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FOAMED ALUMINUM PROPELLANT STUDY

C G BACON
AND
B R WARREN

TECHNICAL REPORT AFRPL-TR-68-232

DECEMBER 1968

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AFRPL-TR-68-232

FOAMED ALUMINUM PROPELLANT STUDY (U)

C. G. Bacon
and
B. R. Warren

[redacted]

FOREWORD

This report presents a summary of work accomplished in Project FAST, 305901AMX, for the period November 1967 to July 1968. The authors wish to acknowledge the contributions of the following AFRPL personnel in the performance of this project:

Mr. L. Sedillo, Project Engineer, for developing the hardware and procedures to mix and cast the grains. Capt J. Vint and Lt C. Hitchcock, for conducting the motor tests and reducing the data.

Capt S. Beckwith, for the mechanical properties determinations.

The authors also wish to acknowledge the cooperation and assistance of Mr. L. Shiverdecker, Mr. H. Anderson, Mr. H. Wadsworth, Mr. E. Kihara, and Mr. R. Bloom. The work could not have been accomplished without their skills and enthusiasm.

This report has been reviewed and approved.

W. H. EBELKE
Colonel, USAF
Chief, Propellant Division

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Chief, Solid Rocket Division
Air Force Rocket Propulsion Laboratory

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CONFIDENTIAL ABSTRACT

(C) This report summarizes the results of an AFRPL feasibility study on the use of a new experimental material, foam aluminum. The chief areas of interest center around the value of this material in high-burn-rate, pulse or end-burning motors and high acceleration/high "Q" loaded anti-missile applications. The addition of the foam aluminum to solid propellants made a significant increase in the burning rates of all formulations tested in this limited program. The burning rates of composite modified double-base (CMDB) propellants were increased two to three times their normal burning rates. No change was made in the control formulations other than the substitution of foam aluminum for an equal weight of the aluminum powder. Problems of processing (e.g., loading the propellant into the foam structure, etc.) were studied and found to be resolvable. The mechanical properties of the samples tested indicate superior strain capabilities over previous reinforced propellant systems. It was concluded that foam aluminum is a promising material for solid propellant applications and should be investigated further in laboratory evaluation.

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GLOSSARY

B-7014 — Propellant based on HC-434 binder

BATES — Ballistic Test, Evaluation and Scaling

$BKNO_3$ — A mixture of boron and potassium nitrate

BMA-7014 — A propellant based on PBAN binder

C-112 — A composite modified double-base propellant, RH-P-112

CP — Center perforated

e_b — Strain at break

E_o — Initial modulus

HC-434 — Carboxyl terminated polybutadiene made by Thiokol Chemical Corporation

Jelly-roll igniter — An igniter made by rolling the igniter powder, mixed with polyisobutylene, in cheese cloth

LPC-557 — An uncured propellant used for nozzle evaluation, made by Lockheed Propulsion Company

PBAN — Polybutadiene, acrylic acid and acrylonitrile terpolymer

RHIM — Rohm and Haas igniter material

S_b — Stress at break

Type A BP — Ball powder made by Olin Mathieson

VS-6814 — A polyurethane propellant based on a Shell Development Company polyether, PTMG

SECTION I

INTRODUCTION

(C) In September 1967, Project FAST (Foam Aluminum Solid Test), was initiated at the Air Force Rocket Propulsion Laboratory (AFRPL) to determine the feasibility of using open-cell foam aluminum as an ingredient of a propellant system to augment the burning rate of solid propellants. The use of metallic wires such as aluminum, copper, silver, etc, for this purpose has been demonstrated both as long strands and in short dispersed lengths such as staples. Considerable effort has been expended to obtain a feasible technique for processing staple-containing propellants; however, the inherent problems of reproducibility, uneven burning and poor processability have proved too difficult for acceptable solutions.

(C) The use of the open-cell foam aluminum offers a means of utilizing the high-burn-rate potential of staples without the deficiencies of the previous staple propellants. The foam aluminum may be regarded, for burning rate concepts, as perfectly distributed and connected staples. Consequently, many of the original concepts developed for staple propellant burn rates are believed to be valid for the foam propellants.

(C) In addition, the structural reinforcement of the foam structure appears to offer potential advantages, particularly in the area of high-acceleration missiles and end-burners if it can be used in conjunction with new, improved methods of relieving stress concentrations at the propellant-case bond line.

(U) The potential advantages of the material seemed great enough to justify an in-house test and evaluation program. The first phase of this effort has been completed and is reported at this time.

SECTION II

OBJECTIVES

The primary objectives of the project were as follows:

(C) 1. To determine the feasibility of using foam aluminum as a means of significantly increasing the burning rate of solid propellants.

(C) 2. To obtain enough preliminary mechanical property data on foam aluminum propellants to ascertain if such propellants are suitable for use in air-launch missiles.

(C) 3. To gain some insight into the basic ignition characteristics of the foam aluminum propellants.

SECTION III

TEST PROGRAM

A. Description of Foam Aluminum

(C) The material being evaluated is manufactured by ERG Inc, Oakland, California. It is a three-dimensional aluminum mesh, containing essentially spheroidal voids. Perhaps its most significant feature is that it can be manufactured reproducibly to within 3 percent of theoretical density. For the purpose of this test program, the material is classed according to the number of voids per inch, i.e., 10, 20, 30, etc. A sample of 20 mesh or 20 voids per inch to be used as an end-burning grain is illustrated in Figure 1. Figure 2 shows a strand of 10-mesh foam.

(C) The machining characteristics of the foam are excellent. It can be cut into intricate and difficult contours by means of a lathe or bandsaw to produce any desired geometry for a propellant grain. In addition, the filled foam can be trimmed easily to procuce a clean grain with close tolerances and well-defined dimensions. No problem areas were discovered in the limited amount of machine work performed on the material at the AFRPL.

B. Test Motors

(U) The test motors used in this program were modified Rohm and Haas 2C1. 5-4 motors. This motor, shown in Figures 3 and 4, is 2 inches in inside diameter and 4 inches in length; its reproducibility and firing characteristics have been well established at both Rohm and Haas and at the AFRPL using a center-perforated (CP) grain of 1-1/2-inch port and 1/4-inch web. However, it was determined that the motor data would be more meaningful if longer burn times could be established. For this reason, the motors were modified from the CP to an end-burning configuration for the first series of tests with double-base propellants. Later, when the slower burning composite propellants were used, CP grains were required in order to achieve a usable mass flow.

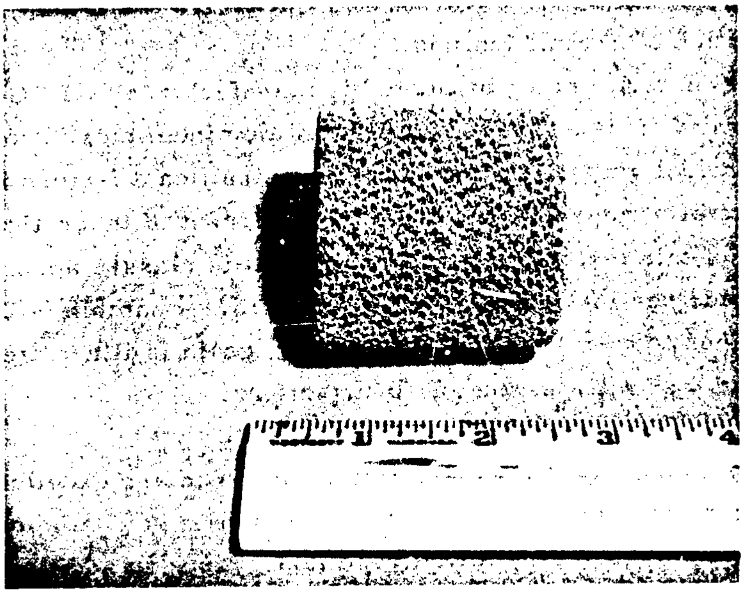

Figure 1. 20 Mesh Foam, End-Burner Configuration

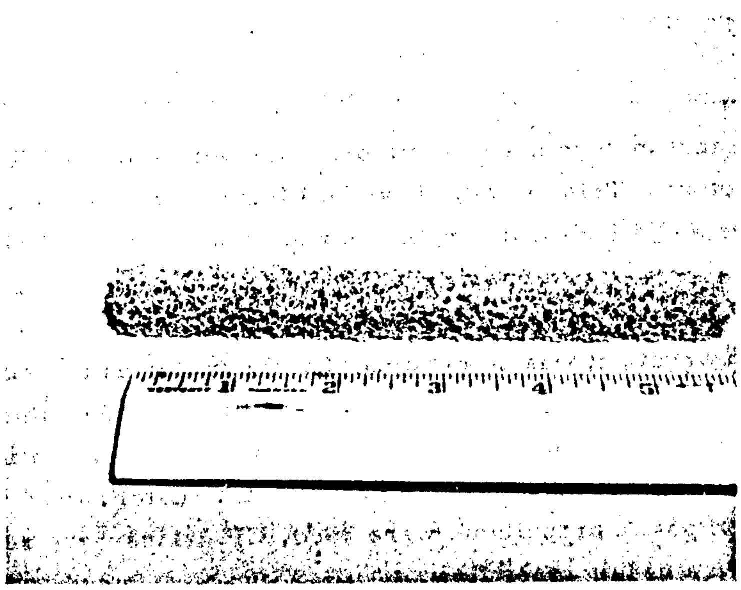

Figure 2. 10 Mesh Foam, 1/2- by 1/2- by 6-inch Strand

Figure 3. Motor Casting Hardware for Standard CP Grain with 1.5-inch Port

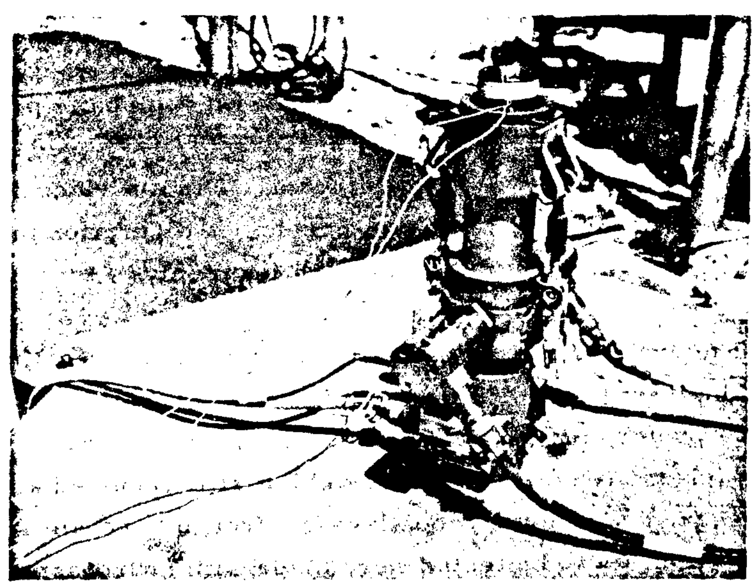

Figure 4. CP Firing Setup

(U) Firing these motors as end-burners required modification to the hardware in order to obtain pressure measurements. The standard CP configuration is shown in Figures 3 and 4 and the modified hardware is shown in Figures 5 and 6. As can be seen, the pressure transducers were moved to the aft closure and the motor cases were notched to allow the chamber pressure to be measured.

C. Propellant Processing

(C) The mesh-like structure of the aluminum foam presented potentially troublesome processing problems, because the large amount of surface area would hinder propellant flow. In anticipation of this, the propellant selected for the first evaluation with the foam was one that had the lowest viscosity and best processing characteristics with which AFRPL personnel were experienced. This propellant, C-112, a composite modified double base, could be poured into the end-burning configuration to give a void-free grain. C-112 was used to process grains with 10, 20, and 30 mesh without difficulty. More time and effort were required for the 30 mesh, however.

(C) In order to obtain preliminary data on composite propellants, samples of uncured propellant LPC-557, produced by Lockheed Propulsion Company, were evaluated in the 10-mesh foam. The low viscosity of this propellant allowed easy pouring into end-burning configuration motors. This propellant was evaluated in the 10-mesh foam only.

(U) The evaluation of burn-rate enhancement was continued with propellants of interest to the Air Force. The first propellant to be tested was VS-6814, a polyurethane derived from a Shell polyether. It was relatively thin (viscosity of 4 to 5 Kilopoise) but still required a slight amount of pressure to force the propellant up through the foam structure. The last two propellants to be tested were made with hydrocarbon binders cured with epoxides. The first formulation, BMA-7014, was made with plasticized PBAN, and the second, B-7014-HC, with a plasticized polybutadiene,

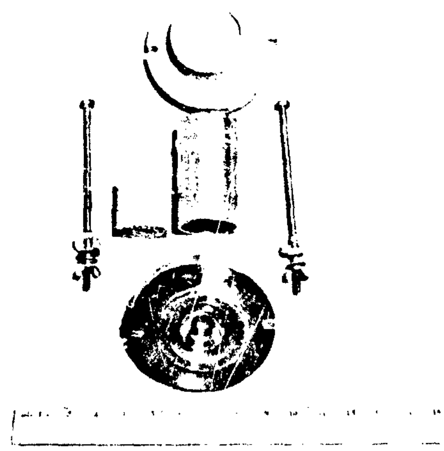

Figure 5. Motor Casting Hardware for End-Burner

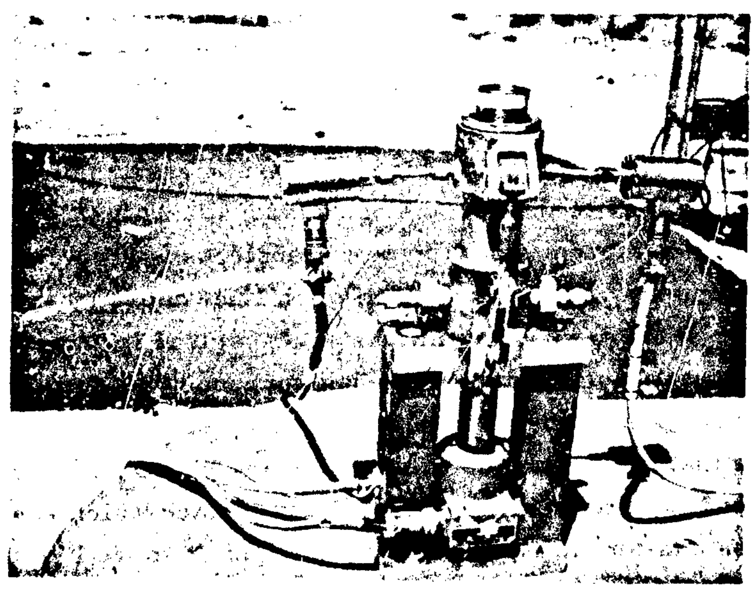

Figure 6. End-Burner Firing Setup

HC-434. These propellants were plasticized to facilitate the casting of the grains which required pressure of up to 35 psig in the apparatus shown in Figure 7.

D. Motor Testing

(U) The motors were tested at the Propellant Evaluation Facility, TS 1-30, a RPL. All of the motors were fired in a vertical position as shown in Figure 6 for the end-burner and Figure 4 for the CP grains. In each firing a dual-bridge load cell was used to obtain two thrust measurements, and two strain-gage pressure transducers were used to obtain duplicate pressure information. The data was converted from analog to digital by an SEL 600 data-acquisition system and recorded on FM tape as well as on an oscillograph. The data was then reduced using a modified Rohm and Haas computer program.

E. Results and Discussion

(C) Progress of the test program was initially hindered by problems with the ignition of the end-burning grains. Misfires, hangfires, and long ignition delays occurred when using either the standard igniter which consisted of 3/4 gm of RHIM igniter powder and an Atlas match or a 3/4-gm jelly-roll igniter. Several approaches were taken to solve the ignition problem: the igniter was increased in size; a boron potassium nitrate ($BKNO_3$) paste was applied to the surface of the propellant; ignition was attempted with a hot wire and a small piece of double-base propellant; and igniters were made using 1/2 to 1-1/2 gram of ball powder (BP) and 1/2 gram of $BKNO_3$ pellets. The hot-wire igniter was successful in igniting the propellant; however, an unpredictable time lag occurred due to the wire heating. This caused some trouble in obtaining photo coverage. The most useful igniter was that made with the ball powder and $BKNO_3$ pellets, as it gave the relatively long heat flux to the propellant surface which seemed to be required for the end-burners. The CP grains ignited more like the standard motors except that the large web thickness prevented uniform ignition of the uninhibited ends. This resulted in many tests with an abnormally long time to equilibrium pressure, and long tail-offs. For this

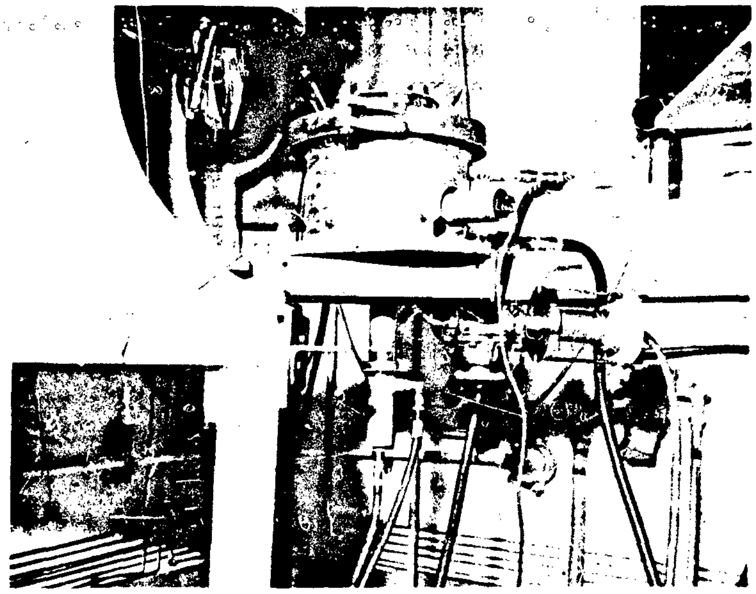

Figure 7. Pressure Casting Apparatus

reason, much of the test data was difficult or quite meaningless to reduce. Figure 8 shows the pressure trace of an end-burner with RH-P-112 propellant which contained the foam structure in one-half of the grain. The transition from the normal propellant to the faster burning foam propellant can be seen after the ignition peak. Tables I and II summarize the results of all the motors tested. Table III compares the burn rate at 1000 psi with the standard propellant of each formulation.

(C) In all of the composite propellants tested, the formulations were fuel-rich, either because that was the way they were designed, as in the case of the LPC-557, or because of a miscalculation in the percentage of aluminum contributed to the propellant by the foam. This was not discovered until the end of the testing and so was included in every formulation, i.e., VS-6814, BMA-7014, and B-7014-HC. The error resulted in approximately a 6 percent excess aluminum content in each formulation. The propellant formulations for all of the propellants tested are presented in the Appendix.

(C) Some of the more significant information obtained in this study was data pertaining to the mechanical properties of Al foam propellants as obtained on test specimens 9/16- by 9/16- by 6-inches long. One test sample consisted of foam aluminum only, without propellant, the others of a polyurethane propellant foam aluminum combination that had 84 percent solids. These data are presented below: *

	E_o psi	S_b psi	e_b percent
Foam only	2441	105.0	26.2
VS-6814 with foam, batch 1	3417	145.4	24.0
VS-6814 with foam, batch 2	2583	167.5	25.0

(C) These mechanical properties are superior to those previously obtained with other reinforcing materials (e.g., wire, reinforced grain)

*Tested at 2 in/min 77^{o} F

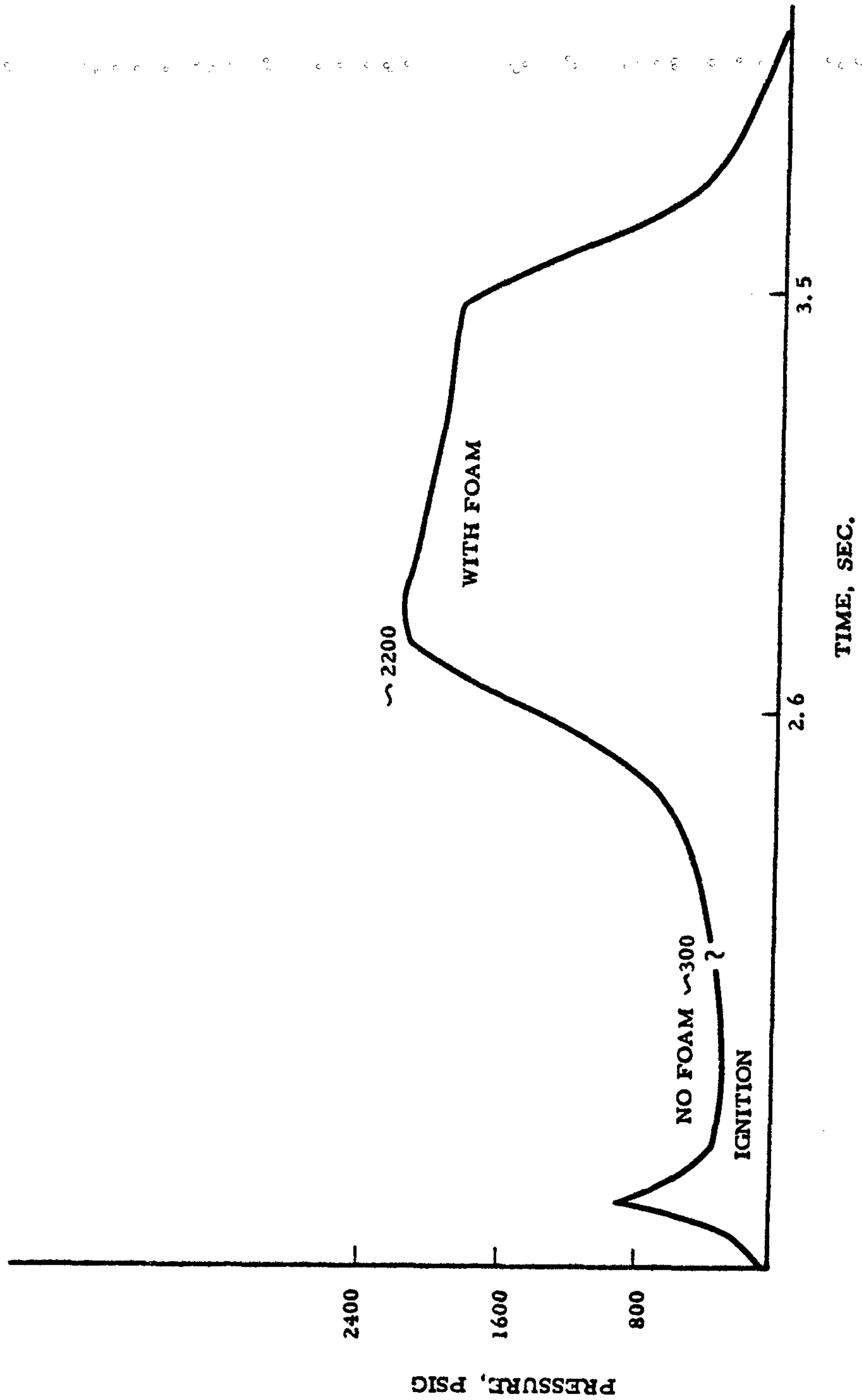

Figure 8. Pressure Trace for C-112 Dual-Thrust End Burner

and are, in fact, better than anticipated with the aluminum foam. These test results indicate that the foam is feasible for use in air-launch missiles in both end-burning and CP designs. As for the temperature-cycling capability of foam propellants, this information should be obtained in a follow-on effort.

SECTION IV

CONCLUSIONS

(U) 1. Feasibility has definitely been demonstrated with regard to the burning-rate augmentation of solid propellants by foam aluminum.

(U) 2. Potential advantages for this material appear in several areas, i.e., high acceleration, boost-sustain, and extended-environment propellants.

(C) 3. Solid loadings of up to 90 percent appear to be feasible for foam propellants, without serious disadvantages.

(C) 4. Preliminary data on the foam propellant mechanical properties show that it can be an acceptable component for air-launched missiles.

(C) 5. Data which should be obtained on foam propellants to complete preliminary evaluation are: combustion efficiency, performance reproducibility, and thermal cycling capability.

SECTION V

RECOMMENDATIONS

(U) The concept for obtaining high solid propellant burn rates presented in this report should be investigated further. A propellant should be demonstrated in a small-scale in-house program and then in a large full-scale industry-conducted program.

(U) A follow-on program should be conducted at the AFRPL to demonstrate the capability of this concept to meet a specific set of motor requirements. A single propellant formulation should be tested to obtain, in 2-inch-diameter motors, data on the burnrate exponent, temperature sensitivity, and ration of burning surface to the nozzle throat area (Kn). After these data are obtained, a series of 6-inch-diameter grains should be tested to obtain data on scaling effects and reproducibility of the propellants.

(U) The above program should be extended by demonstrating the propellant in larger motors. In addition, the motors should be subjected to air-launched environmental testing. This part of the program should most likely be contracted.

(U) These programs should give the Air Force the information it needs to utilize this new concept in future missile programs. The contractual program should also act as a vehicle for familiarizing the industry with the techniques for processing and testing this type of propellant.

(C) Table I. Summary of Motors Tested Without Foam

Run Number	Propellant	Description	Igniter	Nozzle	Closure	Max Pres	Avg Pres	Burn Rate	Remarks
101	Mod C-112	1.373 in Prop & 1.[illegible] in wood	0.1 gm RHIM & Boron Paste		None	850			These 4 motors were tested to determine the durability of the R & H cases in the end-burning configuration. The motors burned for 2 to 4 seconds. All tests were satisfactory.
102	Mod C-112	2.069 i. Prop & 1 in wood	0.16 gm RHIM & Boron Paste		None	1553			
103	Mod C-112	2.075 in Prop & 1 in wood	0.14 gm RHIM & Boron Paste		None	1228			
104	Mod C-112	2.762 in Prop & 1 in wood	0.16 gm RHIM & Boron Paste		None				
105, 109, 117, 124, 127, 128									Standard Double-Base Motors
209	LPC-557	0.5 in Prop	Bag 3/4 gm RHIM	0.200				0.192 in/sec	These 4 motors were tested to obtain baseline burn-rate data for the uncured propellant in the end-burning configuration. All tests were satisfactory. Run 209 had a long ignition delay.
210	LPC-557	0.5 in Prop	Bag 1/2 gm A-BP 1/2 gm $BKNO_3$	0.200	None		150	0.192	
211	LPC-557	0.5 in Prop	Bag 1/2 gm A-BP 1/2 gm $BKNO_3$	0.200	None	2350	186	0.192	
212	LPC-557	0.5 in Prop	Bag 3/4 gm RHIM	0.200	None	960	135	0.135	Baseline Burn rate for BMA-7016
301	BMA-7016	CP-1/2 in Port, 4" long	Bag 3/4 gm RHIM	0.300	0.050		500	0.414	
302	BMA-7016	CP 1 1/2 in Port, 4" long	Bag 0.6 gm RHIM & 0.4 $BKNO_3$	0.250	0.050		1200	0.358	
132	BMA-7014 HCI	CP 1 1/2 in Port, 4" long	Bag 3/4 gm RHIM	0.275	0.050	714	673	0.338	Baseline Burn rate for BMA-7014-HCl
133	BMA-7014 HCI	CP 1 1/2 in Port, 4" long	Bag 3/4 RHIM	0.250	0.050	870	815	0.346	

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(C) Table II. Summary of Motors Tested with Foam*

Run Number	Propellant	Description	Igniter	Nozzle	Closure	Max Pres	Avg Pres	Burn Rate	Remarks
201	Mod C-112	3" end burner, Tandem case	Bag 1/2 gm RHIM	0.275					No data, composite double-base
202	Mod C-112	4" end burner, Tandem case	Bag 1/2 gm RHIM	0.275	0.020	1200			Burned through O-rings
203	Mod C-112	2" end burner, Tandem case	Jelly-roll, 3/4 gm	0.300		600			Burned through O-rings
204	Mod C-112	3" end burner, 1" of foam	Jelly-roll, 3/4 gm Boron Paste	0.250	0.030	700	450	0.98	Motor contained 2 inches of propellant on top of foam propellant
205	Mod C-112	3" end burner, 1" of foam	Jelly-roll, 3/4 gm Boron Paste	0.200	0.025	2300	1300	1.75	Motor contained 2 inches of propellant on top of foam propellant
206	Mod C-112	3" end burner	Jelly-roll, 3/4 gm Boron Paste	0.225	0.035				Motor failed
207	Mod C-112	3" end burner	Jelly-roll, 3/4 gm Boron Paste						Motor hang-fired and then failed
106	Mod C-112	4" end burner	Jellyroll	0.300	0.045	1500			
107	Mod C-112	4" end burner	Jellyroll	0.320	0.045				
108	Mod C-112	4" end burner	Mg/Teflon 3/4 gm	0.300					
110	Mod C-112	1" end burner 20 mesh	Mg/Teflon 3/4 gm	0.320	0.045	400	112	0.610	First test with 20 mesh foam
111	Mod C-112	1" end burner 20 mesh	Mg/Teflon 3/4 gm	0.320	0.045	600	127	0.447	20 mesh foam
112	Mod C-112	1" end burner 20 mesh	Mg/Teflon 3/4 gm	0.300					Did not ignite – 20 mesh foam
113	Mod C-112	1" end burner 20 mesh	Bag, 1/2 gm RHIM $BKNO_3$	0.300	0.045	1450	661	2.29	20 mesh foam
114	Mod C-112	1" end burner 20 mesh	Hot wire & 3.5 g C-112	0.330	0.065	1250	124	0.627	20 mesh foam
115	Mod C-112	1" end burner 20 mesh	Hot wire & 3.5 g C-112	0.330	0.065				No data, no oscillograph trace – 20 mesh foam
116	Mod C-112	1" end burner 20 mesh	Hot wire & 3.5 g C-112	0.300	0.065	1850	595	2.349	20 mesh foam
118	Mod C-112			0.700	0.035				Did not ignite – first test with 30 mesh foam
119	Mod C-112	1" end burner 30 mesh	Hot wire + 3.5 g C-112	0.300	0.065	400	220	0.8	Motor hang-fired – 30 mesh foam
120	Mod C-112	1" end burner 30 mesh	Hot wire + 3.5 g C-112	0.300	0.065	350	180	0.72	Motor hang-fired – 30 mesh foam
121	Mod C-112	2" end burner 30 mesh	Hot wire + 3.5 g C-112	0.275	0.065	650	325	0.975	30 mesh foam
122	Mod C-112	2" end burner 30 mesh	Hot wire + 3.5 g C-112						Motor failed after apparently good start – 30 mesh foam

*All motors have 10 mesh foam unless otherwise noted.

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(C) Table II. Summary of Motors Tested with Foam (Cont'd.)

Run Number	Propellant	Description	Igniter	Nozzle	Closure	Max Pres	Avg Pres	Burn Rate	Remarks
125	Mod C-112		Several tried						No ignition
126	Mod C-112	2" end burner	Hot wire + 3.5 gm C-112	0.275					Motor failed
128	Mod C-112	CP-1/2" Port, 4" long	Hot wire + 6 gm C-112	0.700	None				Low-pressure burn, no data
129	Mod C-112	CP-1/2" Port, 4" long	Hot wire + 2.3 gm C-112	0.700	None				Shear pins in camlocks failed
130	Mod C-112	3" end burner	Hot wire + 2.5 gm C-112	0.250	0.060				Motor failed
131	Mod C-112	3" end burner	Hot wire + 2.5 gm C-112	0.275	0.060				Motor failed on ignition
208	Mod C-112	2" end burner	Bag 3/5 RHIM	0.200	0.035				Motor failed after ignition
213	LPC-557	2" end burner 10 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.200			600	0.7	
214	LPC-557	2" end burner 20 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.200			500	0.54	20 mesh foam
215	LPC-557	2" end burner 20 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.190					Motor failed when ignition plugged nozzle
216	LPC-557	2" end burner 20 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.200			450	0.717	20 mesh foam
217	LPC-557	2" end burner 20 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.200			600	0.777	20 mesh foam
218	LPC-557	2" end burner 20 mesh	Bag, 1/2 gm Type ABP, 1/2 gm $BKNO_3$	0.200			320	0.62	20 mesh foam
303	VS-6814	CP 1/2" Port 4" long	Bag 0.6 gm RHIM + 0.2 $BKNO_3$	0.300	0.050	1260	1000	1.345	Polyurethane
304	VS-6814	CP 1/2" Port 4" long	Bag 0.6 gm RHIM + 0.2 $BKNO_3$	0.310	0.050		780	1.790	
219	VS-6814	2" end burner	Bag 0.6 gm RHIM + 0.2 $BKNO_3$	0.200					Motor failed
305	BMA-7016	CP, 1/2" Port 4" long	Bag 3/4 g RHIM	0.300	0.045		975	0.79	PBAN
220	BMA-7016	2" end burner	Bag 0.6 g RHIM 0.8 g $BKNO_3$	0.200			400	0.484	
221	BMA-7016	2" end burner	Bag 0.6 g RHIM, 0.8 g $BKNO_3$	0.190	Cork		1300	1.912	

[redacted]

(C) Table III. The Influence of Aluminum Foam On Propellant Burn Rate

Propellant	Without Foam	With Foam	Mesh Size	Percent Increase
End-Burner:				
C-112	0.7 in/sec	1.5	10	114
		3.4	20	386
		1.75	30	150
LPC-557	0.46 in/sec	0.94	20	104
BMA-7016	0.38 in/sec	1.51	10	297
B-7014-HC	0.40 in/sec	0.78	10	95
Center Perforate:				
VS-6814	0.42 in/sec	1.5	10	257
BMA-7016	0.37 in/sec	0.78	10	110
B-7014-HC	0.38 in/sec	0.66	10	74

APPENDIX

PROPELLANT FORMULATIONS

	Wt %
(C) RHIM Igniter Powder	
Magnesium (55-100)	60
$KClO_4$ (105)	25
$Ba(NO_3)_2$	15
(C) BMA-7014	
Ammonium perchlorate	70
Aluminum	14
PBAN Binder	14
(C) C-112	
Ammonium perchlorate	30
Aluminum	13
Type B Ball Powder	16.67
DEGDN	37.33
Resorcinol	1.0
(C) LPC 557	
Ammonium perchlorate	68
Aluminum	17
PBAN Binder	14
(C) VS-6814	
Ammonium Perchlorate	68
Aluminum	14
Polyether Binder	16
(C) B-7014-HC	
Ammonium Perchlorate	70
Aluminum	14
HC-434-Binder	14

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13. ABSTRACT

(C) This report summarizes the results of an AFRPL feasibility study on the use of a new experimental material, foam aluminum. The chief areas of interest center around the value of this material in high-burn-rate, pulse or end-burning motors and high acceleration/high "Q" loaded antimissile applications. The addition of the foam aluminum to solid propellants made a significant increase in the burning rates of all formulations tested in this limited program. The burning rates of composite modified double-base (CMDB) propellants were increased two to three times their normal burning rates. No change was made in the control formulations other than the substitution of foam aluminum for an equal weight of the aluminum powder. Problems of processing (e.g., loading the propellant into the foam structure, etc.) were studied and found to be resolvable. The mechanical properties of the samples tested indicate superior strain capabilities over previous reinforced propellant systems. It was concluded that foam aluminum is a promising material for solid propellant applications and should be investigated further in laboratory evaluation.

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