N74-10710

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-649

Alternate Propellents for the Space Shuttle Solid Rocket Booster Motors

Solid Propellant Engineering Section Staff

CASE FILE COPY

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
October 15, 1973

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-649

Alternate Propellents for the Space Shuttle Solid Rocket Booster Motors

Solid Propellant Engineering Section Staff

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
October 15, 1973

Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

ACKNOWLEDGMENT

We thank T. P. Browne, J. P. Coughlin, W. Lambert, A. B. Longyear, P. L. Smith, and R. R. Smith of the Aerojet Solid Propulsion Company; J. Bonin, P. G. Butts, R. J. Pooch, J. G. Seubold, and A. H. von der Esch of the Lockheed Propulsion Company; I. C. Adams, E. G. Dorsey, J. C. Kilminster, L. R. McGee, J. D. Thirkill, and G. Thompson of the Thiokol Chemical Corporation; and S. J. Backlund, J. T. Lee, R. W. Purdy, E. Roberts, and E. J. Walden of the United Technology Center for their cooperation in the accumulation of data contained herein.

CONTENTS

I. Introduction 1

II. Summary 2

III. Discussion 5

A. Possible SRBM Propellants 6

1. Reference propellant 6

2. Propellant A 6

3. Propellant B 6

4. Propellant C 7

5. Propellant D 7

6. Propellant E 8

7. Propellant F 9

8. Propellant G 9

9. Propellant H 9

10. Propellant I 9

11. Propellant J 9

12. Propellant K 9

B. Effect of Using Possible Propellants for the SRBM 9

1. Propellant properties 10

2. HCl, Al_2O_3, and CO emission 10

3. Delivered thrust 11

4. Propellant mass fraction 11

5. Hazard classification 12

6. Development time and cost 12

IV. Conclusions 13

References 14

TABLES

1. Effect of formulation changes in PBAN and HTPB propellants on amount of hydrogen chloride (HCl), aluminum oxide (Al_2O_3), and carbon monoxide (CO) emitted per Space Shuttle launch 15

2. Properties of possible propellants for Space Shuttle solid rocket booster motors 17

3. Percent by weight of HCl, Al_2O_3, and CO in the exhaust of a Space Shuttle solid rocket booster motor using possible propellants 18

4. Total weight of HCl, Al_2O_3, and CO emitted in the operation of a Space Shuttle solid rocket booster motor using possible propellants 19

ABSTRACT

As part of the Shuttle Exhaust Effects Panel (SEEP) program for fiscal year 1973, a limited study was performed to determine the feasibility of minimizing the environmental impact associated with the operation of the solid rocket booster motors (SRBMs) in projected Space Shuttle launches. Eleven hypothetical and two existing limited-experience propellants were evaluated as possible alternates to a well-proven state-of-the-art reference propellant with respect to reducing emissions of primary concern: namely, hydrogen chloride (HCl) and aluminum oxide (Al_2O_3). The study showed that it would be possible to develop a new propellant to effect a considerable reduction in HCl or Al_2O_3 emissions. At the one extreme, a 23% reduction of HCl is possible along with a 11% reduction in Al_2O_3, whereas, at the other extreme, a 75% reduction of Al_2O_3 is possible, but with a resultant 5% increase in HCl.

I. INTRODUCTION

This study was performed by the Jet Propulsion Laboratory as part of the Shuttle Exhaust Effects Panel (SEEP) program for fiscal year 1973. The SEEP was formed by the Office of Aeronautics and Space Technology of the National Aeronautics and Space Administration (OAST/NASA) at the request of the Office of Manned Space Flight of the NASA to investigate and define necessary launch restraints for the Space Shuttle.

The objective of the task was to determine if an alternate solid propellant, other than a well-proven state-of-the-art reference propellant (an 86% by weight solids loaded ammonium perchlorate/aluminum/polybutadiene-acrylic acid-acrylonitrile (AP/Al/PBAN) formulation), could be developed to reduce the potentially hazardous emissions that would result from the firing of the Space Shuttle solid rocket booster motors (SRBMs). The emissions of primary concern are hydrogen chloride (HCl) and aluminum oxide (Al_2O_3). The study has been completed and the results are presented in this report.

The approach that was followed in achieving the objective of the study was to: (1) establish hypothetical solid propellant formulations which could be considered practical and would result in a reduction of one or both of the aforementioned emissions, (2) review the formulations with potential SRBM contractors with respect to processability, performance, cost, and experience, (3) revise the formulations as a result of the review with the potential SRBM contractors, (4) conduct analyses, as required, and (5) estimate the effects of utilizing any one of the propellant formulations as opposed to using the reference formulation in the SRBMs.

Only one area of the Space Shuttle launch vehicle is addressed: namely, the solid propellant that will be used in the SRBMs. NASA has commented (Ref. 1), "Emissions of hydrogen chloride (HCl) from the solid boosters may create potentially hazardous conditions in the immediate vicinity of the launch site for a short period of time. . . . the principal concern. . . . is the possibility of rain scrubbing out the HCl from the exhaust

cloud in concentrations sufficient to have an adverse effect." It is also implied (Ref. 1) that standard operational procedures will have to be adopted to defer launches if weather conditions are such that the predictions of exhaust cloud concentrations, movements, and weather indicate unacceptable environmental conditions. It was therefore deemed worthwhile to investigate the use of alternate propellants to reduce the source quantities of the potentially hazardous pollutants, and, as a result, minimize the constraints that will have to be imposed on the Space Shuttle launches.

II. SUMMARY

A limited study was conducted to determine whether a Class 2[1] solid propellant could be developed and used in lieu of a well-proven state-of-the-art reference propellant (an 86% by weight solids loaded AP/Al/PBAN formulation that contains 16% by weight of Al) in the SRBMs to reduce the amount of HCl and Al_2O_3 that would be emitted during the launch of a Space Shuttle vehicle.

Thirteen different propellant formulations were considered, eleven of which were hypothetical formulations, and two of which were existing limited-experience formulations using a hydroxy-terminated polybutadiene (HTPB) binder. Other than the change of binder, the investigation was concerned with: (1) the use of cyclotetramethylenetetranitramine (HMX), cyclotrimethylenetrinitramine (RDX), and ammonium nitrate (AN) oxidizers, which do not contain chlorine, as a partial substitution of the AP oxidizer, and (2) varying the amount of Al in the formulations. Double base, AN/PBAN, and AN/HTPB propellants were not investigated because (1) the double base

[1] The hazard classification designation of a propellant which burns vigorously with little or no possibility of extinguishment in storage situations. Explosions normally will be confined to pressure ruptures of containers and will not produce propagating shock waves or damaging blast overpressure beyond the magazine distances (quantity-distance storage relationships) that are specified for Class 2 materials (Ref. 2).

propellants are known to be Class 7[2], and therefore do not comply with the present NASA requirement that the SRBM propellant must be Class 2, and (2) an AN/PBAN or AN/HTPB propellant, which contains the maximum amount of AN in the formulation (as constrained by mixing, casting, and physical property requirements), would have a delivered specific impulse and density that are both much too low to allow consideration as a practical alternate propellant. The maximum amount of HMX, RDX, or AN that was used in the formulations was regulated by hazard classification in the case of HMX and RDX, and by processing and performance considerations in the case of AN. Aluminum was retained in all of the propellants because of combustion stability and performance considerations. However, the weight percent of Al was varied from 4 to 20%. Thus, by replacing a part of the AP with HMX, RDX, or AN, a reduction would result in the total amount of HCl that would be emitted during the launch of a Space Shuttle vehicle. Also, by reducing the weight percent of Al in the formulation, a reduction in the amount of Al_2O_3 would be effected.

The propellant formulations that were investigated are tabulated in Table 1. The formulation designated as the reference propellant is representative of a well-proven state-of-the-art propellant and is a prime candidate for the baseline SRBM. The other formulations, designated A through K, are those that were considered for use in lieu of the reference propellant. Formulations E and J are representative of existing AP/Al/HTPB propellants, with which the solid rocket motor industry has limited experience. The rest of the propellants are hypothetical ones, which have been formulated to provide the maximum practical reduction in either HCl or Al_2O_3 emissions.

The confidence level of achieving the established cost-time goals for development, qualification, and initial production of the SRBMs, using the reference propellant, is very high. The confidence level is degraded

---

[2] The hazard classification designation of a propellant, most of the entire quantity of which will explode virtually instantaneously (mass detonate) when a small portion is subject to fire, to severe concussion or impact, to the impulse of an initiating agent, or to the effect of a considerable discharge of energy from without. Such an explosion normally will cause severe structural damage to adjacent objects and the direct propagation of the detonation to other separated explosives and ammunition placed sufficiently close to the initially exploding pile (Ref. 2).

somewhat with the use of propellant J, and still more with the use of propellant E. The cost-time goals established by the Shuttle Project could not be met using any one of the hypothetical propellants.

It is believed that any one of the hypothetical propellants could be developed and qualified for use in the SRBMs. The cost and time required for such a program would depend upon the degree of change and the phasing of the work with the main Shuttle program. It is roughly estimated that the maximum cost and time required for development and demonstration, not including qualification, would be $25,000,000 and 36 months respectively. The demonstration would consist of the static firing of two full-scale SRBMs. An additional cost and time would be required to qualify the new SRBM design for use in the production SRBMs. The program that would be required to qualify the new SRBM design would depend upon many factors, which cannot be ascertained at this time; therefore, no estimates were made of qualification cost and time.

The weight of each propellant that is required per launch of a Space Shuttle vehicle, as shown in Table 1, was derived on the basis of providing the same delivered total impulse as two SRBMs, which each contain 544,311 kg (1,200,000 lb)[3] of the reference propellant. A vehicle optimization study would be the accurate approach to follow to determine the weight of propellant required per launch; however, such a study was not required to make a qualitative assessment of the relative differences in HCl and Al_2O_3 emissions.

The total weights of HCl, Al_2O_3, and CO[4] that would be emitted per Space Shuttle launch with SRBMs that contain each alternate propellant, in order to deliver the same impulse as SRBMs that contain the reference propellant, are tabulated in Table 1. It is clearly shown that the total weight of HCl that is emitted can be reduced by approximately 10% by using propellant

---

[3] The weight of propellant which was estimated to be required at the time this study was initiated (Ref. 1). (In this report, values in customary units are included in parentheses after values in International System units if the customary units were used in the measurements or calculations.)

[4] The weight of CO emission was included because it is an emission of secondary importance (Ref. 1). No consideration was given in this study to the reduction of the CO emission.

formulations that contain HMX or RDX (propellants B, G, and K vs the reference propellant). It is further shown that the total weight of HCl can be reduced in the order of 23%, with an 11% decrease in the total Al_2O_3 emission, by using a propellant formulation that contains AN (propellant D vs the reference propellant). The total weight of Al_2O_3 that is emitted can also be reduced in the order of 75% (propellant C vs the reference propellant), at the expense of 5% increase in the total weight of HCl that is emitted. Also, the use of propellant J (an 88% by weight solids loaded AP/Al/HTPB propellant) would result in about a 1 1/2% reduction of the total weight of HCl that is emitted during a launch of a Space Shuttle vehicle as compared to the amount of HCl that would be emitted using the reference propellant.

As a result of this limited study, it is concluded that a Class 2 solid propellant can be developed, demonstrated, qualified, and used in Space Shuttle production SRBMs to effect a reduction of about 10 to 23% in the total amount of HCl, or a maximum reduction of about 75% in the total amount of Al_2O_3 that would be emitted per launch.

III. DISCUSSION

A study which considers the use of possible alternate propellants for the Shuttle SRBMs must be conducted on the basis of a relative comparison with a possible SRBM baseline propellant system (an 86% solids loaded AP/Al/PBAN propellant with 16% Al). Approximately 99.9% of the exhaust that is emitted during the operation of the SRBM, using the reference propellant, consists of a mixture of six different gases (H_2, H_2O, N_2, CO, CO_2, HCl), and one condensed species (Al_2O_3). The remaining 0.1% of the exhaust consists of a large number of chemical species which are present in very small amounts. The only chemical species in the exhaust that are subject to question with respect to possible adverse environmental effects are HCl and Al_2O_3.

Both PBAN and HTPB propellants were included in the study. The HTPB propellants were included not only for the possibility of reducing questionable emissions, but also to offer a propellant system with performance growth potential. It is pointed out, and emphasized, that no attempt was made to optimize any of the propellants from a total vehicle systems

standpoint. A description of each of the alternate propellant formulations, with the reasons for its selection as a possible propellant for the SRBMs follows.

A. Possible SRBM Propellants

The propellants that could be realistically considered for utilization in the Space Shuttle SRBM are listed in Table 1. The reference propellant is representative of what could be the baseline SRBM propellant. The propellants that are designated A through K are those that are considered to be feasible systems that could be developed and qualified for use in the SRBM. All of the propellants, with the exception of the reference propellant (a well-proven low-cost, low-risk propellant) and propellants E and J (low-cost, limited-experience propellants), are hypothetical formulations.

1. Reference propellant. The reference propellant is a fully developed, well characterized, "off-the-shelf," PBAN propellant that contains 86% by weight total solids (70% AP and 16% Al) in a PBAN binder.

2. Propellant A. The propellant designated as A uses the same ingredients as the reference propellant, but contains only 4% by weight of Al to minimize the amount of Al_2O_3 that would be emitted in the operation of the SRBM. It was thought to be impractical to eliminate all of the Al, because of combustion instability considerations. Therefore, a reasonable compromise was made, and a formulation that contained 4% Al was selected. Because of the difference in density between the Al and the AP, a total solids loading of 84% was selected.

3. Propellant B. One method which may be employed to either reduce or eliminate the amount of HCl that is emitted in the operation of the SRBM is to use an oxidizer, such as HMX or RDX, which does not contain chlorine. HMX, a high-cost material (approximately 11 times that of AP), has been used extensively in double-base propellants, but there is only limited experience with the use of HMX in composite propellants. RDX is also a high-cost material (approximately three times the cost of AP), and there is very limited experience with the use of RDX in composite propellants. HMX could not be made available in the quantity required (4.5 to 6.8 million kilograms per year) to support the expected production (Ref. 3) of SRBMs for the Space Shuttle program, without adding additional production facilities;

however, RDX could be made available without the necessity of providing additional production facilities. The availability of HMX and RDX and the relative cost of HMX and RDX to AP are based upon a cursory investigation. A thorough investigation may yield different results.

The possibility of replacing various amounts of the AP in the reference propellant formulation with either HMX or RDX was investigated by discussion with experienced propellant personnel in the propellant industry. It was concluded that the replacement of more than 20% by weight of the AP in a formulation with either HMX or RDX would certainly result in a Class 7 propellant, but that the substitution of up to 10% by weight of the AP with either HMX or RDX would very likely result in a Class 2 propellant. Therefore, to be relatively certain that the propellant would be Class 2, propellant B was formulated to be a modification of the reference propellant by the replacement of only 10% by weight of the AP with either HMX or RDX.

4. Propellant C. The propellant formulation designated as C is a modification of propellant A, in which 10% by weight of the AP has been replaced with HMX. The modification was made to reduce the amount of HCl that would be emitted, as compared to that which would be emitted with the use of propellant A.

5. Propellant D. Another oxidizer, which does not contain chlorine, that was considered to reduce the amount of HCl in the exhaust of an operating SRBM, is ammonium nitrate (AN). AN is a low-cost material (approximately 1/3 that of AP), but has a major disadvantage of being hygroscopic. AN also has lower energy and density than AP. It is believed that difficulty may be encountered in effecting complete combustion of the Al in propellants that contain AN as a part of the oxidizer. The Al combustion efficiency is believed to be a function of the weight fraction of AN in the total oxidizer. It is theorized that the Al combustion efficiency decreases with an increase in the weight fraction of AN. A reasonable upper limit of AN was therefore assumed to be 25% of the total oxidizer, and the weight fraction of Al in the total propellant was set at 14%. The weight fraction of total solids in the formulation, which was set at 85%, is believed to be the maximum that could be achieved with the 25% AN/75% AP oxidizer in a PBAN binder and still possess adequate processing properties. Thus the formulation designated as propellant D is a best estimate of a feasible AN/AP/Al/PBAN propellant

formulation to provide a maximum decrease in HCl emission. There is, however, a strong possibility that it would be found necessary to reduce the AN/AP weight fraction ratio to achieve the processing and physical properties or performance (especially burn rate) required for use in the Space Shuttle SRBMs.

6. Propellant E. In addition to the propellant formulations that used PBAN as the binder, formulations which employed HTPB as the binder were considered. It is recognized, from the standpoint of processing limitations, that the HTPB binder can incorporate a higher solids loading than is possible with the PBAN binder. It was expected, and was confirmed, that the resulting HTPB propellant formulations, using relatively the same percentage ratios of AP/Al, HMX/AP/Al, and AN/AP/Al that were used in the PBAN formulations, would result in higher performance (delivered specific impulse × density) than the PBAN propellants. Therefore, it may be possible to reduce the amount of propellant required, as compared to that needed for an SRBM using the reference propellant, and thereby effect a reduction in the amount of the HCl, Al_2O_3, or CO that is emitted in the operation of an SRBM. Propellant E is a 90% by weight solids HTPB formulation that contains 20% by weight of Al. The formulation is not considered to be optimum with respect to performance or cost. A lower weight fraction of solids, and a different ratio of AP to Al in the formulation, could result from a detailed Space Shuttle systems optimization study. The propellant industry has considerably less experience with HTPB propellants than it has with PBAN propellants. To date, less than 450,000 kg of HTPB propellant has been processed, and a few large motors, which contained up to 17,237 kg of HTPB propellant, have been fired. In contrast, over 77,000,000 kg of PBAN propellant has been processed. The PBAN propellant has been used in many successful motors; for instance, forty 3.048-m (120-in.) diameter motors, which each contained about 192,777 kg (425,000 lb) of propellant, have been used, without a single failure, in 20 operational flights of the Titan III-C and D launch vehicles. Also, three 6.604-m (260-in.) diameter motors, which each contained about 725,748 kg (1,600,000 lb) of propellant, have been fired in ground level tests.

7. Propellant F. The formulation designated as propellant F is the HTPB counterpart of propellant A, and is formulated to reduce the Al_2O_3 that is emitted. It is a 86% by weight solids loaded propellant.

8. Propellant G. The formulation designated as propellant G is a 90% by weight solids loaded formulation like propellant E; however, the formulation has been modified to reduce HCl emission by replacing 10% by weight of the AP with HMX.

9. Propellant H. The formulation designated as propellant H is the HTPB counterpart of formulation C and is formulated to reduce both the Al_2O_3 and HCl emissions as compared to that associated with the use of the reference propellant. The formulation has a 2% by weight higher solids loading (86% vs 84%) than its PBAN counterpart.

10. Propellant I. The formulation designated propellant I is formulated to perform the same function as its PBAN counterpart (propellant D). It has, however, only 1% by weight more total solids loading than propellant D.

11. Propellant J. The formulation designated propellant J is an 88% by weight solids loaded HTPB formulation. The formulation is included in the list of propellants because it is believed that it could be developed for use in the SRBM with less difficulty than that associated with the development of propellant E. Propellant J is considered to be the most probable choice of an HTPB propellant for use in the SRBM.

12. Propellant K. The formulation designated as propellant K is a modification of propellant J, in which 10% by weight of the AP has been replaced with either HMX or RDX.

B. Effect of Using Possible Propellants for the SRBM

The effect of utilizing any one of the propellants, as listed in Table 1, on (1) propellant properties, (2) HCl, Al_2O_3, and CO emission, (3) delivered thrust, (4) propellant mass fraction, (5) hazard classification, and (6) development time and cost for the SRBM were ascertained by analysis, estimated, or at least considered in this limited study. The effects are discussed in the ensuing text.

1. Propellant properties. A tabulation of the pertinent theoretical and predicted properties of each propellant is shown in Table 2, where T_f is the theoretical, adiabatic combustion flame temperature at $689.5 \times 10^4 N/m^2$ (1000 psia) and $I_{sp}°$ is the theoretical standard specific impulse, calculated by assuming equilibrium conditions throughout, and expanding from a chamber pressure of $689.5 \times 10^4 N/m^2$ (1000 psia) down to $101 \times 10^3 N/m^2$ (14.7 psia) (i.e., sea level optimum). The density of each propellant was calculated from the known densities of the individual propellant ingredients. The term η, defined as the specific impulse efficiency, is the ratio of the measured specific impulse to the theoretical equilibrium-flow specific impulse, calculated at the motor firing conditions, multiplied by 100. It is derived from the following equation:

$$\eta = \lambda - K\alpha - Q$$

where

λ = nozzle efficiency

K = an empirically derived constant

α = the mass fraction of condensibles in the exhaust

Q = heat loss

I_{sp} (del) is the predicted delivered specific impulse for the respective propellant fired under standard conditions : $689.5 \times 10^4 \rightarrow 101 \times 10^3 N/m^2$ ($1000 \rightarrow 14.7$ psia), using a 15° half-angle nozzle. The I_{sp} (del) value is derived by multiplying $I_{sp}°$ by η. The equation has been used extensively at the Jet Propulsion Laboratory to predict the potential performance of different propellant systems in a number of different motors, and the agreement between predicted and measured values has been excellent. As a case in point, the predicted I_{sp} value for the reference propellant, obtained by use of the equation above, is 2,400 N-s/kg (244.7 lbf-s/lbm). The reference propellant is essentially the propellant used in a currently produced large solid rocket motor, which has a delivered specific impulse of approximately 2,403 N-s/kg (245.0 lbf-s/lbm) at standard conditions.

2. HCl, Al_2O_3, and CO emission. The percent by weight of HCl, Al_2O_3, and CO of the total weight of emissions from a solid rocket motor, using each of the propellants, is shown in Table 3. The data shown in

Table 3 were used in the calculation of the total weight of HCl, Al_2O_3, and CO that would be emitted in the operation of an SRBM using each of the propellant formulations. The resulting data are tabulated in Table 4. The total weight of propellant that is required for an SRBM, using each propellant, was assumed to be that needed to deliver a total impulse of 130.62×10^7 N-s (293.64×10^6 lbf-s) (the delivered total impulse of a hypothetical SRBM, which contains 544,308 kg (1,200,000 lb) of the reference propellant). The weight of each propellant required by the SRBM to deliver the required total impulse was calculated using the delivered I_{sp} data in Table 2. It is recognized that the method used to calculate the total weights of HCl, Al_2O_3, and CO that would be emitted in the operation of an SRBM, using each propellant formulation, is oversimplified and does not result in an absolute evaluation from a Space Shuttle system point of view. However, an absolute evaluation was not required to make a qualitative assessment of the relative differences in HCl or Al_2O_3 emissions. The data contained in Table 4 clearly show that it is possible to reduce the total amount of HCl or Al_2O_3 that is emitted either by modifying the reference propellant formulation or by using HTPB propellant formulations in lieu of the PBAN formulations. The type and extent of emission reductions are discussed in Section II (Summary).

3. Delivered thrust. No attempt was made in this limited study to evaluate the variation in delivered thrust of the SRBM, using any of the possible propellant formulations, with respect to that delivered using the baseline propellant formulation. It was assumed that the burn rate of each possible propellant could be adjusted to the required burn rate by proper oxidizer particle size selection and/or use of a burn rate catalyst.

4. Propellant mass fraction. The propellant mass fraction that could be realistically achieved in the SRBM, using any of the possible propellant formulations, was not determined in this limited study. The determination of the optimum propellant mass fraction for the SRBM, using any of the propellants that were considered, would involve detailed design evaluations beyond the scope of this study. It is of interest, however, that an SRBM using propellant B, which is considered a feasible approach to reducing the amount of HCl emitted per launch, could have a propellant mass fraction equal to that of an SRBM employing the reference propellant.

This is true because (1) the delivered specific impulse, (2) the adiabatic flame temperature, and (3) the density of propellant B are all about the same as those of the reference propellant.

5. Hazard classification. The ground rule with respect to propellant hazard classification employed for this study was that only Class 2 propellants would be considered. Therefore, all propellant formulations listed in Table 1 are believed to be Class 2 propellants. There is, however, some doubt with respect to the classification of the propellants that contain either HMX or RDX. The amount of either HMX or RDX contained in propellants B, C, G, H, and K are within the limit established by consultation with experienced propellant personnel. Little or no experimental work has been conducted by industry to establish the hazard classification of either HMX or RDX propellants as listed in Table 1. It may be possible to increase the HMX/AP or RDX/AP ratio over that shown for propellants B, C, G, H, and K and still retain the Class 2 classification. The critical diameter[5] of grains made from any of the propellant formulations listed in Table 1, with the possible exception of the reference propellant, is not presently known. It will be necessary to conduct experimental (possibly full-scale) tests to establish the critical diameter. These tests may show that the critical diameter, using any of the propellants, including the reference propellant, is smaller than that of the propellant grains presently contemplated for use in the SRBM (Ref. 4).

6. Development time and cost. All of the possible alternate propellants listed in Table 1 can be developed, demonstrated, and qualified for

[5]The critical diameter is the diameter of a right solid circular cylinder of propellant (grain), which if subjected to sufficient shock, impact, fire, and mechanical failure (either individually or in any combination) will result in steady-state detonation and/or thermal explosion of the grain. Detonation is an exothermic reaction characterized by a rapid combustion or thermal decomposition reaction zone, which is preceded by a shock wave and propagates through the material at a velocity greater than the sonic velocity in the material. An essential feature of detonation is the movement of product gases toward the burning surface and unreacted material. The propagation mechanism is shock compression. Steady-state detonation proceeds at a constant velocity. Thermal explosion is the violent consequence of an exothermic reaction that releases heat at a greater rate than the rate of heat loss from the reacting medium, reaching the point where the reaction produces an explosion because of the increasing temperature and reaction rate (Ref. 4).

use in the SRBM. The maximum estimated time and cost for development and demonstration would be that required to develop and finally demonstrate, in two full-scale SRBM static firing tests, the propellants that contain either AN or RDX. It is roughly estimated that the development and demonstration efforts could be accomplished in 36 months at a cost of $25,000,000. It is also roughly estimated that the propellants which contain HMX could be developed and demonstrated in two full-scale SRBM static firings in 24 months at a cost of $22,000,000. The latter program would not be as difficult to accomplish as the AN or RDX propellant program, in that a moderate amount of effort is in progress within the solid propellant industry to develop 88 to 90 percent solids loaded AP/HMX/Al/HTPB propellants for use in solid rocket motors. Further discussion on the subject of time and cost required to develop, demonstrate, and qualify the alternate propellants for use in production Space Shuttle SRBMs is included in Section II (Summary).

IV. CONCLUSIONS

As a result of the limited study, the following conclusions are drawn:

(1) It is possible to develop a new propellant that could be utilized in lieu of an assumed baseline SRBM propellant to effect a considerable reduction in the amount of HCl or Al_2O_3 that would be exhausted into the atmosphere during the operation of the SRBMs in the Space Shuttle program. At the one extreme, a 23% reduction of HCl is possible along with an 11% reduction in Al_2O_3, whereas, at the other extreme, a 75% reduction of Al_2O_3 is possible, but with a resultant 5% increase in HCl.

(2) The estimated maximum cost and time that would be required to develop and demonstrate, in two full-scale SRBM firings, any one of the new propellants that were considered are $25,000,000 and 36 months respectively. The cost could be reduced considerably if the development and demonstration program were conducted by the selected SRBM contractor concurrently with the design, development, and qualification of the baseline SRBM.

REFERENCES

1. Environmental Statement for the Space Shuttle Program, Final Statement, National Aeronautics and Space Administration, Washington, D.C., July 1972.

2. DOD Ammunition and Explosives Safety Standards, Manual No. DOD 4145.27 M, Department of Defense, Office of The Assistant Secretary of Defense (Installations & Logistics), Washington, D.C., March 1969.

3. Request For Proposal 8-1-4-94-98401, Space Shuttle Program Solid Rocket Motor Project, Volumes I and II, National Aeronautics and Space Administration, George C. Marshall Space Flight Center, July 16, 1973.

4. Elwell, R. B., Irwin, O. R., and Vail, R. W., Jr., Project Sophy-Solid Propellant Hazards Program, Technical Report AFRPL-TR-67-211, Volume I, Air Force Rocket Propulsion Laboratory, Research and Technology Division, Edwards Air Force Base, Calif., August 1967.

Table 1. Effect of formulation changes in PBAN and HTPB propellants on amount of hydrogen chloride (HCl), aluminum oxide (Al_2O_3), and carbon monoxide (CO) emitted per Space Shuttle launch

Propellant designation	Propellant formulation	Propellant weight[h] required per launch kg (lbm)	Weight emitted per launch kg (lbm)		
			HCl	Al_2O_3	CO
Reference	70[a] AP[b]/16 Al[c]/14 PBAN[d]	1,088,622 (2,400,000)	236,231 (520,800)	328,981 (725,280)	247,553 (545,760)
A	80 AP/4 Al/16 PBAN	1,101,678 (2,428,784)	273,547 (603,068)	83,287 (183,616)	188,828 (416,294)
B	7 HMX[e]/63 AP/16 Al/14 PBAN or 7 RDX[f]/63 AP/16 Al/14 PBAN	1,085,516 (2,393,154)	212,110 (467,622)	325,872 (718,424)	280,823 (619,108)
C	8 HMX/72 AP/4 Al/16 PBAN	1,105,335 (2,436,846)	246,932 (544,392)	83,564 (184,226)	228,694 (504,184)
D	17.75 AN[g]/53.25 AP/14 Al/15 PBAN	1,102,133 (2,429,788)	182,072 (401,400)	291,514 (642,678)	258,451 (569,786)

(a) Percent by weight
(b) Ammonium perchlorate
(c) Aluminum
(d) Polybutadiene/acrylic acid/acrylonitrile
(e) Cyclotetramethylenetetranitramine
(f) Cyclotrimethylenetrinitramine
(g) Ammonium nitrate
(h) To deliver the same total impulse

Table 1. (contd)

Propellant designation	Propellant formulation	Propellant weight[h] required per launch kg (lbm)	Weight emitted per launch kg (lbm)		
			HCl	Al_2O_3	CO
E	70[a] AP[b]/20 Al[c]/10 HTPB[d]	1,095,336 (2,414,802)	232,320 (512,178)	413,380 (911,346)	(426,696)
F	82 AP/4 Al/14 HTPB	1,096,238 (2,416,790)	278,992 (615,072)	82,876 (182,710)	172,877 (381,128)
G	7 HMX[e]/63 AP/20 Al/10 HTPB	1,089,066 (2,400,980)	212,259 (467,950)	411,014 (906,130)	221,299 (487,880)
H	8.2 HMX/73.8 AP/4 Al/ 14 HTPB	1,098,022 (2,420,724)	251,453 (554,358)	83,012 (183,010)	206,433 (455,106)
I	17.75 AN[f]/53.25 AP/15 Al/ 14 HTPB	1,099,404 (2,423,772)	181,732 (400,650)	311,681 (687,140)	261,438 (576,372)
J	70 AP/18 Al/12 HTPB	1,089,512 (2,401,962)	233,047 (513,780)	370,107 (815,947)	233,809 (515,460)
K	7 HMX/63 AP/18 Al/12 HTPB or 7 RDX[g]/63 AP/18 Al/12 HTPB	1,084,191 (2,390,232)	211,634 (466,574)	368,517 (812,440)	261,398 (576,284)

(a) Percent by weight
(b) Ammonium perchlorate
(c) Aluminum
(d) Hydroxy-terminated polybutadiene
(e) Cyclotetramethylenetetranitramine
(f) Ammonium nitrate
(g) Cyclotrimethylenetrinitramine
(h) To deliver the same total impulse

Table 2. Properties of possible propellants for Space Shuttle solid rocket booster motors

Property	Propellant											
	Ref	A	B	C	D	E	F	G	H	I	J	K
Adiabatic flame temperature T_f, K	3,549	3,071	3,499	3,002	3,230	3,736	3,042	3,737	3,017	3,200	3,572	3,564
Theoretical standard specific impulse $I_{sp}°$, N-s/kg (lbf-s/lbm)	2,580 (263.1)	2,460 (250.9)	2,588 (263.9)	2,452 (250.0)	2,535 (258.5)	2,598 (264.9)	2,472 (252.1)	2,612 (266.4)	2,468 (251.7)	2,550 (260.0)	2,595 (264.6)	2,608 (265.9)
Specific impulse efficiency η, %	93.0	96.4	93.0	96.4	93.5	91.8	96.4	91.8	96.4	93.2	92.4	92.4
Standard delivered specific impulse I_{sp} (del), N-s/kg (lbf-s/lbm)	2,400 (244.7)	2,371 (241.8)	2,407 (245.4)	2,363 (241.0)	2,370 (241.7)	2,385 (243.2)	2,383 (243.0)	2,399 (244.6)	2,379 (242.6)	2,376 (242.3)	2,398 (244.5)	2,409 (245.7)
Density[a] ρ, kg/m^3 (lbm/in.^{3})	1,755 (0.0634)	1,672 (0.0604)	1,752 (0.0633)	1,669 (0.0603)	1,694 (0.0612)	1,849 (0.0668)	1,705 (0.0616)	1,840 (0.0664)	1,694 (0.0612)	1,708 (0.0617)	1,802 (0.0651)	1,791 (0.0647)

(a) Calculated density using the density of each ingredient. The density of the cured propellant will be slightly higher due to volume change in the binder during cure.

Table 3. Percent by weight of HCl, Al_2O_3, and CO in the exhaust of a Space Shuttle solid rocket booster motor using possible propellants

Propellant	Weight percent of total emission at $101 \times 10^3 N/m^2$ (14.7 psia)		
	HCl	Al_2O_3	CO
Reference	21.70	30.22	22.74
A	24.83	7.52	17.14
B	19.54	30.02	25.87
C	22.34	7.56	20.69
D	16.52	26.45	23.45
E	21.21	37.74	17.67
F	25.45	7.56	15.77
G	19.49	37.74	20.32
H	22.90	7.56	18.80
I	16.53	28.35	23.78
J	21.39	33.97	21.46
K	19.52	33.99	24.11

Table 4. Total weight of HCl, Al_2O_3, and CO emitted in the operation of a Space Shuttle solid rocket booster motor using possible propellants

Propellant	Propellant required per SRBM kg (lbm)[a]	Weight emitted per SRBM kg (lbm)		
		HCl	Al_2O_3	CO
Reference	544,311 (1,200,000)	118,115 (260,400)	164,491 (362,640)	123,776 (272,880)
A	550,839 (1,214,392)	136,774 (301,534)	41,643 (91,808)	94,414 (208,147)
B	542,758 (1,196,577)	106,055 (233,811)	162,936 (359,212)	140,411 (309,554)
C	552,667 (1,218,423)	123,466 (272,196)	41,782 (92,113)	114,347 (252,092)
D	551,067 (1,214,894)	91,036 (200,700)	145,757 (321,339)	129,225 (284,893)
E	547,668 (1,207,401)	116,160 (256,089)	206,690 (455,673)	96,773 (213,348)
F	548,119 (1,208,395)	139,496 (307,536)	41,438 (91,355)	86,438 (190,564)
G	544,533 (1,200,490)	106,129 (233,975)	205,507 (453,065)	110,649 (243,940)
H	549,022 (1,210,387)	125,726 (277,179)	41,506 (91,505)	103,216 (227,553)
I	549,702 (1,211,886)	90,866 (200,325)	155,841 (343,570)	130,719 (288,186)
J	544,756 (1,200,981)	116,523 (256,890)	185,053 (407,973)	116,904 (257,730)
K	542,096 (1,195,116)	105,817 (233,287)	184,258 (406,220)	130,699 (288,142)

(a) To deliver the same total impulse.

NASA — JPL — Coml., L.A., Calif.