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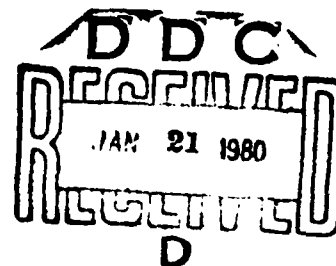BURNING OF SOLID PROPELLANTS

Merrill K. King

Research and Technology Division
Atlantic Research Corporation
5390 Cherokee Avenue
Alexandria, Virginia 22314

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

At Atlantic Research, erosive burning characteristics of eleven composite propellants were measured and found to agree well with predictions of a simplified first-generation model under most conditions. A second-generation more fundamental model for predicting burning rate versus pressure and cross flow velocity, given only compositional data, also yield predictions in close agreement with data. The most important parameter affecting crossflow sensitivity was no-cross flow burning rate, erosion sensitivity decreasing with increasing base rate. ARAP completed modifications to its SPEC model to enable calculation of cylindrical →over

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flows and performed preliminary evaluation for cold-flow simulations and erosive burning. Motor port diameter was identified as a key erosive burning scaling parameter through its effect on threshold conditions, and a simplified scaling relation was developed and verified. In addition, ARAP investigated the effects of combustion-turbulence interaction on predicted erosive burning. Penn State measured erosive burning rates of three AP-composite formulations in a device designed to give a well-defined turbulent boundary layer. The data agreed well with predictions made using a Penn State model based on a 2D turbulent boundary layer approach. Correlations relating burning rate to free stream velocity, and pressure were developed. The model was also extended to axisymmetric cylindrical port flow.

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INTRODUCTION - RESEARCH OBJECTIVES

Erosive burning, the augmentation of solid propellant burning rate by the flow of products across a burning surface, is becoming increasingly important with use of lower port-to-throat area ratio motors and nozzleless motors, both of which result in high velocity crossflows. The response of various propellants to such crossflows must be known by the motor designer in order for him to perform adequate motor design. In addition, it is important that the propellant formulator understand the effect of various formulation parameters on the sensitivity of a propellant to crossflows so that he may tailor his propellants to the desired characteristics. For example, in a nozzleless rocket motor, the decrease in pressure from the head end to the aft end of the grain tends to result in slower burning at the aft end in the absence of erosive effects. Depending upon the sensitivity of the formulation to crossflow, the increasing Mach number along the grain port may lead to undercompensation, exact cancellation, or overcompensation of the pressure effect. A detailed discussion of the effects of erosive burning on solid propellant rocket interior ballistics for low port-to-throat area ratio motors and nozzleless motors was presented by this author in Reference 1. During the past four years, experimental and analytical studies of erosive burning have been conducted at Atlantic Research and Pennsylvania State University along with additional modeling efforts at Aeronautical Research Associates of Princeton (ARAP), all under AFOSR sponsorship. Atlantic Research is currently prime contractor on a three-year (FY78 through FY80) erosive burning program being conducted for AFOSR with ARAP and Penn State as subcontractors. A comprehensive list of research objectives for this three-year program is presented below:

A.   Atlantic Research Objectives (Task A)

1.   Develop a theoretical model of steady state erosive burning to permit prediction of composite propellant burning rate as a function of pressure and crossflow velocity, given only propellant composition and particle size distribution, and extend this model to handle cases involving multimodal oxidizer (ammonium perchlorate) and metalized propellants.

2.   Work on development of an improved theoretical model of the effects of oscillatory crossflow on composite propellant combustion.

3. Conduct approximately 50 testing firings with approximately 10 different composite propellant formulations in the erosive burning test apparatus.

4. Formulate suitable quantities of composite propellants of various types to perform the erosive burning test program of Task A (3) in an experimental apparatus developed by Atlantic Research under AFOSR Contract F44620-76-C-0023.

5. Gather and correlate burning rate versus pressure versus crossflow velocity data from the tests of Task A (3).

6. Make continuing comparisons between experimental data and the developed erosive burning theoretical model, using these comparisons to upgrade the model as needed.

7. Incorporate in theoretical modeling of erosive burning by flame bending the effects of high blowing velocities and increased turbulence, characteristic of cylindrically performated motors as opposed to test devices.

8. Develop at least a preliminary model for erosive burning of double-base propellants.

9. Investigate the need for modeling erosive burning in HMX-oxidized propellants.

10. Perform special motor tests to investigate the change in erosive burning sensivity caused by a large change in the ratio of blowing velocity to crossflow velocity.

11. Perform preliminary design for a cold-flow test apparatus to study boundary layer shapes and turbulence distributions in internally perforated solid propellant grains.

12. Proceed with final design, construction and use of the cold flow apparatus for the purpose shown in Item A (11) above; or alternatively, perform 30 additional tests in the Atlantic Research erosive burning hardware, using about five selected HMX and double-base formulations.

B. <u>Aeronautical Research Associates of Princeton Objectives</u> (Task B)

1. Improve the grain port or test section flowfield modeling part of the erosive burning model located at Aeronautical Research Associates of Princeton, by removing the inviscid outer boundary layer assumption, and compare the results with existing flow experimental data.

2. Implement at least one commonly used composite propellant combustion model, and compare the results with appropriate data.

3. Remove the Shvab-Zeldovich assumptions from the Aeronautical Research Associates of Princeton erosive burning model and ascertain the limits of insensitivity to driver propellant temperature.

4. Develop a computer code with the ability to perform a quasitime dependent analysis of the burning of cylindrical and two-dimensional grains, depending upon the model's satisfactory performance under task B (1) and (2).

5. Parameterize the velocity profile results form the SPEC model in graphical or algebraic form.

6. Formulate the system of equations necessary to model particulate behavior and turbulence interaction within the grain port.

7. Incorporate the modeled particulate fow equations of subparagraph (6) into the SPEC code and demonstrate their solution.

8. Assess the effects of tubular motor length to diameter ratio and turbulence on particulate number-density profiles within the grain port.

9. Include an imposed acoustic field in the SPEC model and assess the effects of frequency and velocity on propellant burning.

C. <u>Pennsylvania State University Objectives</u> (Task C)

1. Perform checkout tests of the erosive burning model computer program located at Pennsylvania State University.

2. Perform a set of "computer experiments" to determine the best set of coefficients for turbulence correlations in the Pennsylvania State erosive burning model.

3. Perform a set of parametric calculations with the resulting final erosive burning model to study the effects of conditions such as gas velocity, flame temperature, chamber pressure, pressure gradient, and oxidizer particle size on erosive burning.

4. Investigate possible improvements in the turbulence closure procedures involved in the Pennsylvania State erosive burning model.

5. Use the resulting computer program to generate an erosive burning formula of use to propellant grain designers.

6. Perform a series of erosive burning experiments in a test apparatus, located at Pennsylvania State University. Parameters to be varied in this study include free-stream velocity, pressure, pressure gradient, oxidizer particle size, and propellant types.

7. Further improve the Pennsylvania State erosive burning model by improving the way reaction rate is included, and by taking account of high Mach number flow and surface roughness.

8. Extend the erosive burning model from flat-plate geometry to axisymmetric flow.

9. Validate the 2-D model of erosive burning by experimental firings and measurements.

10. Incorporate the erosive burning model into an existing rocket performance prediction code and test the resulting coupled erosive burning rocket performance code.

The status of the research effort being conducted at Atlantic Research, along with a list of publications and a description of interactions with other activities is presented in the following sections. Similar presentations of the status of the Penn State and ARAP efforts are presented in Appendices A and B.

STATUS OF ATLANTIC RESEARCH EFFORTS

A major portion of the Atlantic Research effort in the current reporting period has centered around Tasks A1 and A7, involving upgrading of the second generation erosive burning model for prediction of propellant burning rate as a function of pressure and crossflow velocity for unimodal, non-metallized composite formulations, given only composition, along with extension of this model to handle multimodal oxidizer and metalized formulations. Included in this effort has been a thorough review of the literature regarding turbulent transpired boundary layers followed by a major revision of the crossflow analysis originally built into the second-generation model.

As discussed in detail in Reference 2, several variants (IIIA, IIIC, and IV) of the second-generation model of erosive burning were found to give satisfactory results when tested against no-crossflow burning rate data for a series of four unimodal oxidizer composite propellants. Although Variant IIIC is the most appealing to this author on a physical basis, the considerably lower computational complexity associated with Variant IV led to its selection for extension to multimodal oxidizer cases. This extension was carried out in a straightforward manner using Glick's "petit ensemble" approach[3], in which a propellant containing oxidizer particles of different sizes is broken into a

series of subpropellants or "pseudopropellants", each of which contains oxidizer of only one size. These subpropellants were assumed to burn non-interactively with the unimodal oxidizer model being used to calculate a mass flux for each, and straightforward averaging then being used to obtain an overall propellant average linear regression rate. The only manner in which oxidizer of one size was allowed to affect the burning of a subpropellant containing oxidizer of another size was through possible influence on the assignment of fuel to that subpropellant. That is, rather than fuel being assigned to each oxidizer size category in direct proportion to the amount of oxidizer in that category, the capability of allowing uneven assignment of fuel to various oxidizer size subpropellants was allowed by means of a power law:

$$V_{f,d_i} = C_2 (D_o)^{XEXP}$$

where V_{f,d_i} is the volume of the fuel assigned to a particle of diameter $(D_o)_i$, XEXP is an arbitrary input power law constant, and C_2 is a constant determined by application of overall continuity. It may be easily shown that XEXP=3 will result in each subpropellant having the same oxidizer/fuel ratio as the overall propellant O/F ratio. XEXP <3, on the other hand, will result in subpropellants with small oxidizer being more fuel-rich than the overall propellant and subpropellants with large oxidizer being more fuel-lean, with the reverse occurring for XEXP>3.

Thus the modification of Variant IV of the Generation 2 burning rate model to handle multimodal oxidizer cases consisted of adding a package at the front of the program to define the subpropellants, using the existing program to calculate burning rates for each subpropellant, and properly averaging these rates. Two options for averaging the rates were built into the program. The first of these is a straightforward geometrical area averaging procedure, while the second allows for the fact that slower-burning subpropellants will spend a longer time burning than faster-burning ones. Thus, in the second procedure a residence-time-weighted averaging procedure is employed. The second procedure appears at this time to yield slightly better results.

Variant IV of the second generation erosive burning model was also modified during the current reporting period to treat the effects of metal additives (thus far limited to aluminum) on propellant burning rate. The metal was allowed to effect burning rate through its heat sink effects within the condensed phase propellant and additionally via conductive and radiative feedback from particles burning above the propellant surfce. Among the phenomena treated in this model were aluminum agglomeration, particle velocity lag relative to the gases leaving the propellant surface, particle ignition delay, particle combustion rate, conductive feedback from incremental heat release zones at various distances from the propellant surface, and radiative feedback. In the case of multimodal oxidizer propellants, the assignment of various fractions of the aluminum to the various subpropellants was treated in the same manner as the assignment of fuel (binder) to these subpropellants.

Use of the erosive burning package originally built into the different Generation 2 model variants led in all cases to major underprediction of the effect of crossflow on burning rate, indicating that the originally proposed flame-bending mechanism,was by itself insufficient. Accordingly, during the current reporting period, a second possible mechanism augmentation of turbulence transport properties in the region between the propellant surface and the gas-phase flames was invoked and combined with the flame-bending mechanism. In this approach, it was assumed that both the effective thermal conductivity (governing feedback from the various gas flames) and the effective mass diffusivity (an important parameter in determining the thickness of the diffusion flame) were increased in crossflow situations by crossflow-inducted turbulence. A flow profile analysis permitting calculation of eddy viscosity (and, by analogy, total effective thermal conductivity and diffusivity) as a function of distance from the propellant surface for a given crossflow velocity, transpiration velocity (determined by the propellant burning rate), and temperature field (dependent on the location of gas-phase heat release zones) was developed and coupled with the Variant IV combustion model for erosive burning calculations. An improved calculation of diffusion flame-bending angle was also incorporated in this analysis.

Details of the flow profile analysis procedures are presented in
Reference 2. The outputs from this analysis were used to calculate:

$$\lambda_{effective}/\lambda_{laminar} = D_{effective}/D_{laminar} = 1 + \rho \epsilon \mu = f(y)$$

That is, the ratio of transport total properties to laminar properties were
calculated as a function of distance from the surface. Average total
transport property values between appropriate zones were then calculated and
substituted for the laminar values in the diffusional mixing equations and the
heat feedback equations in the original model, revised burn rates and flame
distances were calculated, and the procedure was repeated until convergence
was achieved. As might be expected, this looping procedure is considerably
more complex in the case of multimodal propellants than for unimodal
propellants since solution of the individual subpropellant cases becomes
interactive in the case of crossflow. This interaction occurs because there
is only one boundary layer for the overall propellant (that is, one cannot
calculate a different boundary layer profile for each subpropellant) with the
boundary layer details being controlled by the average transpiration velocity,
flame height, surface temperature, etc. for the overall propellant rather than
by the individual values of these parameters for each subpropellant.

As an adjunct to the modeling effort, a literature survey on the subject
of cold-flow test devices for studying boundary layer shapes and turbulence
profiles in transpired boundary layers has been carried out (Task A11). As a
result of this study, it has been concluded that any experimental effort we
could carry out in this area would only duplicate other efforts, notably those
of Moffat and coworkers at Stanford University. (For example, see Reference
4.) Accordingly it has been decided that the second option of Task A12,
conduct of 30 additional tests in the Atlantic Research erosive burning
hardware (in addition to the 50 called out for Tasks A3 - A6) is the more
appropriate one.

As regards Tasks A3 - A6 and A12, fifteen tests were carried out during
the current reporting period, bringing the cummulative number of tests
conducted on this program to 45. In addition, grains, insulators, windows,

etc. have been prepared for 15 additional tests which are currently underway. At the conclusion of these tests, a total of fourteen different formulations will have been characterized in the Atlantic Research test apparatus, ten on the current program and four on the predecessor Contract F44620-76-C-0023. A summary of trends observed regarding the effects of various formulation parameters on sensitivity of propellant burning rate to crossflow and comparison of model predictions with data is given in the following paragraphs. In this discussion, for sake of clarity and completeness, reference will be made not only to data obtained during the current reporting period, but also to earlier data. For figures presenting detailed comparisons of data with predictions made using the first and second generation erosive burning models, the reader is referred to Reference 5.

In Table I, the propellant matrix being tested is described and the rationale behind the choice of these formualtions is summarized. To date Test Sets 1 - 9, 11 and A1 have been completed, although the data from Test Set A1 have not yet been analyzed. Test Sets 10, A2 and A3 are currently being carried out.

A rather complete set of data, covering a pressure range of 10 to 50 atmospheres and a crossflow velocity range of 600 to 2200 ft/sec has been obtained for the baseline propellant, Formulation 4525. Agreement between first generation model predictions and data is resonably good though the predicted curves for burning rate versus pressure at various crossflow velocities do tend to group more tightly than the data. That is, the model tends to slightly overpredict the burning rate at low crossflow velocities and slightly underpredict it at the higher velocities tested. As with the other propellants studied, theory and data both indicate increasing erosive burning sensitivity with increasing pressure over the range of conditions studied. The data also agree well with predictions made with the second generation model. (Recall here that this model is used for the prediction of the no-crossflow burning rate versus pressure curve along with the erosive burning curves.) If anything, this model slightly underpredicts the erosive burning sensitivity at the lower crossflow velocities studied while providing excellent agreement with data at a crossflow velocity of 2000 ft/sec.

TABLE I. PROPELLANT MATRIX BEING TESTED.

TEST SET	FORMULATION	COMPOSITION	RATIONALE
1	4535	73/27 AP/HTPB, 20μAP	BASELINE FORMULATION. T = 1667 °K
2	5051	73/27 AP/HTPB, 200μAP	COMPARE WITH 1 FOR AP SIZE EFFECT
3	4685	73/27 AP/HTPB, 5μAP	COMPARE WITH 1 AND 2 FOR AP SIZE EFFECT
4	4889	72/26/2 AP/HTPB/Fe₂O₃, 20μAP	COMPARE WITH 1 FOR BR EFFECT AT CONSTANT AP SIZE
5	5542	77/23 AP/HTPB, 20μAP	COMPARE WITH 1 FOR MIX RATIO (TEMPERATURE) EFFECT AT CONSTANT AP SIZE. T = 2065 K
6	7523	70/28/2 AP/POLYESTER/Fe₂O₃ (20μAP)	BASELINE POLYESTER FORMULATION. T = 2250°K. AP SIZE CHOSEN TO MATCH BR OF NO. 4. COMPARE WITH NO. 4 FOR BINDER EFFECT.
7	5565	82/18 AP/HTPB, BIMODAL AP (68.33 % 200μ, 13.65% 90μ)	MEDIUM TEMPERATURE HTPB FORMULATION. AP SIZES CHOSEN TO MATCH BR OF NO. 1. COMPARE WITH NO. 1 FOR TEMPERATURE EFFECT T = 2575°K.
8	5555	82/18 AP/HTPB, BIMODAL AP (41 % 1μ, 41 % 7μ)	COMPARE WITH NO. 7 FOR BR EFFECT. T = 2575°K.
9	7605	78/20/2 AP/POLYESTER/Fe₂O₃, BIMODAL AP (23.4 % 20μ, 54.6 % 200μ)	MEDIUM TEMP. (2800°K) SMOKELESS POLYESTER FROMULATION. COMPARE WITH NO. 6. ALSO COMPARE WITH NO. 5 FOR BINDER EFFECT AT NEARLY CONSTANT BR.
10	7758	88 AP/12 HTPB, MULTIMODAL AP	ARCADENE 368 (OPERATIONAL SMOKELESS PROPELLANT)
11	6626	74 AP/21 HTPB/5 Al, MULTIMODAL AP TO MATCH BR OF NO. 7.	SAME TEMPERATURE AS NO. 7. COMPARE WITH NO. 7 FOR ALUMINUM EFFECT.
A1	7768	82/18 AP/HTPB, BIMODAL AP (41 % 7μ, 41 % 90μ)	
A2	7748	82/18 AP/HTPB, BIMODAL AP (41 % 20μ, 41 % 20μ)	FURTHER STUDY OF AP SIZE AND BASE BURNING RATE EFFECTS
A3	7750	82/18 AP/HTPB, TRIMODAL AP (27.3 % 1μ, 27.3 % 20μ, 27.4 % 200μ)	

Formulation 5051, which differs from the baseline formulation through use of 200 micron AP oxidizer in place of 20 micron oxidizer, is predicted by both models to be somewhat more sensitive to crossflow than the baseline formulation. With respect to the first generation model predictions, agreement between predicted and measured augmentation ratio is fairly good except at low pressure, high crossflow velocity conditions, where the measured burning rates considerably exceed the predicted values. However, the second generation model does not exhibit this difficulty, with good agreement between theory and data being obtained over the entire range of test conditions. Breakdown of the first generation model in the low pressure, high crossflow velocity region is not particularly surprising since, in this region, the composite propellant begins to behave more like a homogeneous propellant than a heterogeneous propellant, and this model only considers effects of crossflow on the diffusional mixing processes of oxidizer and fuel streams. In order for the model to be useful in low pressure, high crossflow velocity regions, it appears that an additional mechanism beyond that of flame-bending must be invoked. With the second generation model, this additional mechanism, crossflow-induced turbulence augmentation of transport properties has been included, with the aforementioned beneficial results.

Formulation 4685, which differs from the baseline formulation by replacement of 20 micron oxidizer with 5 micron oxidizer, exhibits considerably less sensitivity to erosion than that baseline formulation, as predicted. Agreement between predicted and observed burning rates appears to be good except, again, with the first generation model in the low pressure, high crossflow velocity regime. With Formulation 5542 (analogous to the baseline formulation but with higher oxidizer/fuel ratio and consequently higher temperature and base burning rate, oxidizer size being held constant) the first generation model appears to slightly overpredict the sensitivity of the burning rate to crossflow while the second generation model does an excellent job of matching data with predictions.

With Formulation 4869, which differs from the baseline formulation through addition of two percent iron oxide catalyst, theoretical predictions have been made only with the first generation model since the second

generation model has not yet been expanded to include the effects of burn-
ing rate catalysts. Data and theoretical predictions agree fairly well at
high crossflow velocities, but not nearly as well at low crossflow velocities
where the predictions of erosive burning rate augmentation are somewhat higher
than observed in the experiments. An explanation of this discrepancy has not
yet been developed.

Theoretical predictions have been made with both the first and second
generation models for two additional non-metalized formulations, both
consisting of 18 percent HTPB binder and 82 percent bimodal ammonium
perchlorate (Formulations 5555 and 5565). Formulation 5555, a high burning
rate formulation, is predicted by both models to be rather insensitive to
crossflow: the data corroborate this prediction. With Formulation 5565,
which has approximately the same base (no-crossflow) burning rate-pressure
behavior as the baseline formulation but a considerably higher oxidizer/fuel
ratio and flame temperature, good agreement is found between data and the
first generation model predictions, the formulation being fairly sensitive to
crossflow. However, the second generation model badly overpredicts this
sensitivity. The cause of this problem has not yet been positively identified,
but it appears likely that it is associated with inaccurate modeling of the
effect of the flow field on either the flame-bending or the turbulence
augmentation of transport properties at large distances from the propellant
surface. (The combination of the very large 200 micron ammonium perchlorate
particle size in this formulation and relatively high burning rate, at least
as compared to the other large oxidizer formulations tested to date, leads to
very large predicted no-crossflow diffusion flame heights for this
formulation.) This possibility is currently being examined and a resolution of
the problem sought.

Experimental erosive burning rate data for Formulation 6626, the only
metalized propellant tested to date, have been compared to predictions from
both the first and second generation models. Although the data are somewhat
sparse, the agreement between experiment and predictions made using the first
generation model is excellent. This is particularly interesting since the
first generation flame-bending model does not include any specific mechanism

involving the aluminum: the excellent agreement with data suggests (though it certainly offers no rigorous proof) that the aluminum, at least at the relatively low level of 5 percent, does not directly affect the erosive burning of composite propellants. The second generation model, which also does not include any direct interactive crossflow-aluminum behavior mechanisms, yields excellent agreement between theory and data for the no-crossflow case, while tending to slightly overpredict the effects of crossflow on burning rate.

Since there is currently an insufficient data base for generation of the optimum values of the three free constants in the second-generation model for the polyester binder/AP/Fe_2O_3 family, the data from tests with Formulations 7523 and 7605 have only been tested against the first generation model. The agreement between theory and experiment is not particularly good for these formulations, especially at high pressure. In both cases the dependence of burning rate on pressure at fixed crossflow velocity seems to be somewhat larger than predicted.

Next, let us compare results for the various formulations to identify parameters which influence the sensitivity of composite propellants to crossflows. Between Formulations 4525, 5051, and 4685, the only independent variable changed is the oxidizer particle size, composition being held constant. The change of oxidizer size, of course, leads to a change in base (no crossflow) burning rate versus pressure characteristics. Formulation 5051, containing 200 micron diameter AP, is the slowest burning of the three formulations, with Formulation 4685 (5 micron AP) being the fastest and Formulation 4525 (20 micron) AP being intermediate. For instance, at 5 MPa (50 atmospheres) the base burning rate of 5051 is 0.47 cm/sec, that of 4525 is 0.68 cm/sec and that of 4685 is 1.15 cm/sec. The sensitivity of burning rate to crossflow was found to increase with increasing particle size (decreasing base burning rate). For example, at a crossflow velocity of 200 m/sec (650 ft/sec) and a pressure of 5 MPa (50 atmospheres), the augmentation ratio for 4685 is about 1.10, that for 4525 is 1.65, and that for 5051 is 2.0.

Comparison of data for 4525 and 4869, two formulations of essentially the same oxidizer/fuel ratio, flame temperature, and oxidizer particle size, with

the base burning rate being varied through use of catalyst in 4869, again shows an increase in sensitivity of burning rate to crossflow with a decrease in burning rate. At 5 MPa (50 Atmospheres) the base burning rates for 4869 and 4525 are 1.30 cm/sec and 0.68 cm/sec, respectively. At this pressure, with a crossflow velocity of 200 m/sec (650 ft/sec), their r/r_0 values are 1.10 and 1.65 respectively, while at 600 m/sec (1950 ft/sec), the r/r_0 values are 1.75 and 2.3. Thus base burning rate is seen to affect the erosion sensitivity of composite propellants even at constant oxidizer particle size, erosive effects increasing with decreasing base burning rate.

Formulations 4685 and 4869 have approximately the same base burning rate at 8 MPa (80 atmospheres) with catalyst and oxidizer particle size effects on base burning rate roughly cancelling. Thus comparison of erosion sensitivity of these formulations at this pressure is of interest in that oxidizer particle size is varied (5 micron diameter for 4685, 20 micron diameter for 4869) while base burning rate is held constant. Such comparison indicates that these formulations have roughly the same sensitivity to the lower crossflow velocities tested at 8 MPa (80 atmospheres), with the catalyzed propellant being slightly more sensitive at the higher crossflow velocities tested. Thus it appears that it is the base burning rate rather than the oxidizer particle size per se which dominates the sensitivity of composite propellants to erosive burning, though oxidizer size does have some further residual effects, erosion sensitivity decreasing with decreasing particle size at constant base burning rate.

Comparison of test results for Formulations 4525, 5542 and 5565 permits study of the effect of oxidizer/fuel ratio (and thus flame temperature) on erosion sensitivity, both at constant oxidizer particle size (5542 and 4525) and at constant base burning rate (5565 and 4525). Formulation 5542 differed from 4525 in oxidizer/fuel ratio (77/23 versus 73/27) and consequently flame temperature (2065°K vs 1667°K). Since the oxidizer particle size was the same for both propellants, the higher oxidizer/fuel ratio for 5542 led to higher base burning rate (1.14 cm/sec vs. 0.68 cm/sec at 5 MPa). Examination of the data reveals that the erosion sensitivity of 5542 is considerably less than that of 4525 over the entire range of crossflow velocities studied

(e.g., r/r_0 = 1.10 for 5542 and 1.65 for 4525 at 200 cm/sec, 5 MPa; and r/r_0 = 1.7 for 5542 and 2.9 for 4525 at 800 m/sec, 5 MPa). Thus we see that changing oxidizer/fuel ratio from very fuel- rich to less fuel-rich, with accompanying increase in flame temperature and burning rate, leads to decreased sensitivity to erosive burning. Comparison of results for 5565 and 4525, which differ in oxidizer/fuel ratio but not in base burning rate (oxidizer particle size having been adjusted to compensate for the burning rate change with changing oxidizer/fuel ratio) permits separation of the effects of varying oxidizer/fuel ratio (and thus flame temperature) from the effects of base burning rate. Such comparison indicates that the sensitivity of Formulations 5565 and 4525 to crossflow are nearly the same. For instance, at 200 m/sec (650 ft/sec) crossflow velocity and 5 MPa (50 atmospheres), the augmentation ratios for 5565 and 4525 are 1.50 and 1.65, respectively, while at 800 m/sec (2600ft/sec) and 3 MPa (30 atmospheres), they are 2.65 and 2.50. Accordingly, we may tentatively conclude that oxidizer/fuel ratio (and consequently flame temperature) does not directly affect the erosion sensitivity of the compositions studied to date, but only affects it through its effect on base burning rate.

Formulations 5555 and 5565 had the same composition, differing only in oxidizer particle size, which was adjusted in 5555 to give a very high burning rate. Again, a strong dependency of erosion sensitivity on base burning rate was observed. At 5 MPa (50 atmospheres), the base burning rates of 5555 and 5565 are 2.94 and 0.70 cm/sec, respectively. At 200 m/sec (650 ft/sec) crossflow velocity, the respective values of r/r_0 are 1.0 and 1.5, while at 700 m/sec (2300 ft/sec), they are 1.2 and 2.4. Thus, once again, erosion sensitivity is seen to decrease with increasing base burning rate.

Formulation 6626, the only metalized formulation tested to date, was tailored to have essentially the same base burning rate versus pressure characteristics as Formulations 4525 and 5565 and, moreover, to have approximately the same flame tmeperature as 5565. It has already been pointed out that formulations 4525 and 5565 have nearly identical erosive burning behavior. Testing with Formulation 6626 revelaed further that this formulation has essentially identical erosive burning behavior as the other

two formulations. For example, at a crossflow velocity of 700 m/sec (2300 ft/sec) and a pressure of 2.8 MPa (28 atmospheres) the augmentation ratios for 4525, 5565, and 6626 are 2.05, 2.20, and 2.05; while at 245 m/sec (800 ft/sec) and 4.0 MPa (40 atmospheres), they are 1.80, 1.63, and 1.71. Thus, we are again drawn to a conclusion that the dominant factor affecting the sensitivity of burning rate of a composite propellant to crossflow is the base burning rate, largely independent of the various factors going into determining that base burning rate.

With respect to the effect of binder type on erosion sensitivity, it is useful to compare data obtained with Formulations 4869 and 7523 and data obtained with Formulations 5542 and 7605. With Formulations 4869 and 7523, the base burning rate and oxidizer size were held constant while the binder was changed from HTPB to polyester (the latter yielding a higher flame temperature). Study of the data indicates that at low pressure the erosion sensitivities of these two formulations were essentially equal but that at higher pressures the polyester formulation was more sensitive to crossflow. A similar conclusion is drawn from comparison of data for Formulations 5542 and 7605. Between these latter two formulations, base burning rate was again held essentially constant though in this case the oxidizer particle size(s) did vary.

Summarizing the results obtained in Task Categories A3 – A6 and A12, nine AP/HTPB propellants and two polyester/AP formulations with systematically varied compositions and ingredient paricle sizes have been characterized with respect to erosive burning over a wide range of pressures and crossflow velocities. The erosive burning data have been compared with predictions made using a simplified first-generation model in which it is postulated that erosive burning is caused solely by bending of columnar diffusion flames by a crossflow. In general, the model was found to reasonably well predict the observed results except at low pressure, high crossflow velocity conditions where the composite propellant heterogeneity is relatively unimportant. A considerably more sophisticated model, capable of predicting burning rate as a function of pressure and crossflow velocity (including the limiting case of zero crossflow velocity) given only propellant compositional and ingredient

particle size data has been tested against data obtained for seven of the AP/HTPB formulations. In all cases, the model predicts the no-crossflow results quite well, and in six out of seven cases it additionally does a good job in predicting erosive burning characteristics, even in the low pressure, high crossflow velocity regime (due to inclusion of a second erosive burning mechanism, crossflow-induced turbulence augmentation of transport properties). Data obtained to date support the following general conclusions regarding the effects of various parameters on the sensitivity of composite propellant burning rate to crossflow:

(1) The severity of erosive burning (augmentation ratio) is most strongly dependent on base (no-crossflow) burning rate, augment- ation ratio increasing with decreasing base burning rate.

(2) There is a small residual effect of oxidizer particle size at fixed base burning rate, erosion sensitivity decreasing with decreased particle size.

(3) Oxidizer/fuel ratio (and thus flame temperature) appears to affect the augmentation ratio for HTPB systems only through its effect on the base burning rate.

(4) At fixed base burning rate, aluminum has no effect on erosive burning, at least at the low (5 percent) aluminum loading tested thus far.

(5) The interaction of effects of crossflow velocity and pressure on burning rate appears to be different for polyester and HTPB binder systems, the polyester formulations being more sensitive to crossflow at high pressure.

During the current reporting period, no work was accomplished on Tasks A2 and A8 - A10.

References:

1. King, M. "Effects of Crossflow on Solid Propellant Combustion: Interior Ballisticc Design Implications", 1976 JANNAF Propulsion Meeting, Atlanta Georgia, December 1976, CPIA Publc. 280, Vol. V, p. 342.

2. King, M.K., "A Model of the Effects of Pressure and Crossflow Velocity on Composite Propellant Burning Rate, "AIAA/SAE/ASME 15th Joint Propulsion Conference, Las Vegas, Nevada, June 2976, AIAA Paper No. 79-1171.

3. Glick, R.L. and Condon, J.A., "Statistical Analysis of Polydisperse, Heterogeneous Propellant Combustion: Steady-State", 13th JANNAF Combustion Meeting, Monterrey, Calif., Sept., 1976, CPIA, Publ.281, Vol II, p. 313, Dec. 1976.

4. Moffat, R.J., et al., The Behavior of Transpired Turbulent Boundary Layers, Report HMT-20, Stanford University, 1975. NTIS Acquisition No. ADA 016096.

5. King, M.K., "An Investigation of the Effects of Formulation Parameters on Erosive Burning of Composite Propellants", 16th JANNAF Combustion Meeting, Monterey, Calif., Sept., 1979. To be post printed in an upcoming CPIA Publication.

PUBLICATIONS GENERATED BY ATLANTIC RESEARCH UNDER

CONTRACT F49620-78-C-0016*

King, M. K., "Model for Steady State Combustion of Unimodal Composite Solid Propellants," AIAA 16th Aerospace Sciences Meeting, Huntsville, Alabama, January 1978, AIAA Paper No. 78-216.

King, M. K., "Erosive Burning of Composite Solid Propellants: Experimental and Modeling Studies," AIAA/SAE 14th Joint Propulsion Conference, Los Vegas, Nevada, July, 1978. Also, Journal Of Spacecraft and Rockets, 16, 3, May-June, 1979. p. 154.

King, M. K., "Erosive Burning of Composite Solid Propellants," 15th JANNAF Combustion Meeting, Newport, R.I., September, 1978, CPIA Publication 297, Vol. II, pp. 179-88, Feb., 1979.

King, M. K., "A Model of the Effects of Pressure and Crossflow Velocity on Composite Propellant Burning Rate," AIAA Paper 79-1171, AIAA/SAE/ASME 15th Joint Propulsion Conference, June, 1979, Las Vegas, Nevada.

King, M. K., "An Investigation of the Effects of Formulation Parameters on Erosive Burning of Composite Propellants," 16th JANNAF Combustion Meeting, Monterey, California, Sept., 1979. To be postprinted in CPIA Publication.

*See Appendices A and B for Publications Generated by Penn State and ARAP Under Contract F49620-78-C-0016.

PROFESSIONAL PERSONNEL ASSOCIATED WITH

ATLANTIC RESEARCH EFFORT UNDER CONTRACT F49620-78-C-0016*

1. Dr. Merrill K. King - Principal Investigator, Analytical Modeling, Test Selection, Data Analysis

2. Mr. Stephen Kunkel - Test Direction

3. Mr. Phillip Graham - Propellant Formulation

4. Mr. Merlin Larimer - Propellant Formulation

5. Mr. Robert Wallace - Testing

*See Appendices A and B for similar information regarding The Penn State and ARAP subcontracts.

INTERACTIONS (COUPLING ACTIVITIES) INVOLVING
ATLANTIC RESEARCH PERSONNEL*

1. Dr. King participated in the Velocity-Coupled Combustion Instability Workshop held at the US Naval Postgraduate School during the 16th JANNAF Combustion Meeting, September, 1979.

2. Dr. King had several conversations with Dr. Robert Hermsen (CSD) during August-September, 1979, regarding both the first and second generation erosive burning models and the Atlantic Reseasrch erosive burning data base developed under this program, with the object of incorporating this information into the Solid Rocket Performance Program being developed by CSD and Software Engineering Associates for AFRPL.

3. H. P. Sauerwein, A. Lampert, and R. H. Schmucker (Bayern Chemie, West Germany) have incorporated our first generation erosive burning model into an interior ballistics code to very successfully predict performance of small tactical rockets. Results of this work were presented at the 53rd AGARD Propulsion and Energetics Symposium in Oslo.

4. Atlantic Research, teaming with Software Engineering Associates, anticipates receiving award of a contract from AFRPL to develop a Nozzleless Motor Performance Comptuer Program. A major portion of this effort will be devoted to incorporating an accurate fast algorithu for calculating burning rate as a function of pressure, crossflow velocity, and position within the solid grain port: Dr. King will be responsible for this phase of the program.

5. Atlantic Research has agreed to carry out 16 tests in its erosive burining test device for Hercules Aerospace Division (Cumberland) in the event that they are successful in their bid on an AFRPL program entitled, "Nonlinear Stability for Tactical Motors."

*See Appendices A and B for similar information regarding the Penn State and ARAP subcontracts.

APPENDIX A

ANNUAL REPORT FROM PENNSYLVANIA STATE UNIVERSITY
TO ATLANTIC RESEARCH CORPORATION

TURBULENT BOUNDARY-LAYER ANALYSIS AND EXPERIMENTAL INVESTIGATION
OF
EROSIVE BURNING PROBLEM IN SOLID-PROPELLANT ROCKET MOTORS

Annual Report

October 1, 1978 to September 30, 1979

Sponsored by

Prepared by

Mohan K. Razdan and Kenneth K. Kuo
Dept. of Mechanical Engineering
The Pennsylvania State University
University Park, Pennsylvania

November 1979

ABSTRACT

A theoretical model for erosive burning study has been developed by formulating an axisymmetric turbulent boundary-layer flow inside the cylindrical port of a composite solid-propellant rocket motor. Experimentally, erosive burning rates of three types of Ammonium-Perchlorate-based composite propellant formulations have been measured by using a high-speed motion picture method. Experiments were conducted in a test rig which was designed so that a well defined turbulent boundary layer was developed by the flow of combustion gases over two-dimensional propellant samples. Experimental data for burning rate, free-stream velocity and pressure have been obtained for the verification of an erosive burning model of solid propellants based on a 2D turbulent boundary-layer approach. Erosive burning rate correlations have been developed relating the burning rate to freestream velocity and pressure. The comparison of experimental data and theoretical results obtained from the erosive burning model developed at The Pennsylvania State University showed a close agreement.

I. INTRODUCTION

Under the previous AFOSR grant and the current subcontract from Atlantic Research Corporation, authors have conducted basic research on the erosive burning of Ammonium Perchlorate (AP) composite Solid Propellants. During earlier part of the research program, a theoretical model was formulated by considering a steady, two-dimensional, compressible, chemically reacting turbulent boundary layer over a flat propellant sample (see M.K. Razdan and K.K. Kuo, AIAA Paper No.78-978). In the experimental area, a test-rig was designed and fabricated so that a turbulent boundary layer is formed over a test propellant surface by the flow of high-velocity combustion gases. Erosive burning tests were conducted with propellant slabs, and the test data showed a close agreement with the predicted results from the theoretical model (see M.K. Razdan and K.K. Kuo, AIAA Paper No. 79-1172).

The objectives of the current continuing research program at The Pennsylvania State University are:

1. To extend the erosive-burning model from two-dimensional to axisymmetric geometry in order to simulate actual flow configurations in rocket motors.

2. To solve the theoretical model and to study the effects of gas velocity, pressure, pressure gradient, and propellant physiochemical characteristics under various rocket motor conditions.

3. To establish a data base by conducting erosive-burning tests at various pressures and free-stream velocities for two-dimensional flat AP-based composite solid propellant slabs. The data can be used to make further comparison with the

predictions from the erosive-burning model based on a turbulent boundary-layer approach.

4. To develop the erosive burning rate correlations which can be used by grain designers.

II. STATUS OF THE RESEARCH EFFORT

A. Theoretical Work

The physical model considered in the theoretical analysis consists of an axisymmetric flow of gases inside a cylindrical solid propellant grain. The gases form a turbulent boundary layer over the burning surface of the propellant. Both the developing and fully-developed portions of the boundary layer are considered in the theoretical analysis.

The theoretical model is formulated by starting with the general conservation equations in terms of cylindrical coordinates for a reacting compressible turbulent flow. Following the Reynolds time-averaging procedure and an order-of-magnitude analysis, a set of partial differential equations for time-averaged flow properties of the axisymmetric turbulent boundary-layer is obtained. These equations consist of: (1) continuity equation, (2) momentum equation, (3) species equations, and (4) energy equation. In order to achieve the closure of the turbulent flow problem two additional conservation equations are considered for turbulent kinetic energy and the turbulence dissipation rate. In the freestream of the developing portion (potential core region) of the axisymmetric flow field, inviscid equations are also considered for the conservation of mass, momentum and energy. These equations are used together with boundary-layer equations to solve for downstream flow properties.

The gas-phase chemical reaction rate is modeled with the eddy-break-up (EUB) concept of Spalding. The chemical reaction between fuel and oxidizer gases is assumed to be diffusion limited. The rate of depletion

of the fuel and oxidizer species is controlled by the rate of mixing of fuel and oxidizer, which in turn is related to the level of turbulence intensity in the flame zone.

At the present time, the formulation of the model has been completed. The implementation of the finite-difference equations into a computer code is in progress. Numerical solution of the theoretical model is anticipated in the near future.

To improve the predictive capability in terms of surface roughness effect, the 2D theoretical model for erosive burning has been modified to incorporate the Cebeci and Chang formula. Theoretically predicted AP particle size effect compares well with experimental data if the average surface roughness height is considered to be 10% of the initial AP particle size.

B. Experimental Work

A series of erosive burning test firings has been conducted on two-dimensional flat AP-based composite solid propellant slabs. The experiments were designed for verification purposes, so that erosive-burning rates at various freestream velocities and pressures can be compared with theoretical predictions from the 2D model based on turbulent flow analysis. High-speed motion picture method was used to determine the burning rates of test propellant samples.

Erosive burning characteristics of three types of AP-based composite solid propellants have been studied. These propellants are (I) 73/27/ AP/HTPB with 20 μm AP, (II) 73/27/AP/HTPB with 200 μm AP, and (III) 75/25/AP/PBAA-EPON with 76 μm AP. Propellants (I) and (II) are the same as used by M. King at ARC (see M.K. King, AIAA Paper No. 78-216). Pressure and velocity ranges covered in the experiments were: 2 to 6 MPa

for pressure, and 200 to 700 m/s for freestream velocity. Both pressure
and velocity were altered by using different sized exit nozzles. The
measured erosive-burning rates were compared with the theoretical pre-
dictions of the two-dimensional turbulent boundary layer model of erosive
burning developed at The Pennsylvania State University. The comparisons
for all three propellants showed good predictability of the model. Cor-
relations between erosive burning rate, freestream velocity, and pressure
were developed by conducting a multi-regression analysis of the measured
data.

Currently, a supersonic nozzle is being fabricated which is to be
used in experiments to achieve supersonic gas velocities over test-
propellant samples for studying erosive burning effect at high Mach
numbers. More tests under various flow conditions are planned. Also an
additional propellant formulation ($72/26/2/AP/HTPB/Fe_2O_3$ with 20 μm AP)
having higher strand burning rate will be tested to further study the
strand burning rate effect on the erosive burning.

III. SUMMARY AND CONCLUSIONS

The erosive burning problem of composite solid propellants has been
modeled by considering either a 2D or an axisymmetric, chemically reacting,
turbulent boundary layer inside a solid propellant grain of a rocket motor.
The erosive burning behavior of three types of composite solid propellants
was studied by burning test propellant slabs in turbulent boundary layers,
formed by the flow of hot combustion gases over the propellant samples.
The burning rates at various pressures and freestream velocities were
measured by a high-speed motion picture technique in which the burning
propellant surface was photographed during a test firing. The following
observations and conclusions can be made from the present study:

1. The predicted results show that propellants with lower strand burning rates are more sensitive to erosive burning than those with higher strand burning rates.

2. By increasing oxidizer particle size of a composite propellant, the erosive burning effect becomes more pronounced.

3. The erosive burning rate correlates well with chamber pressure and freestream velocity. Correlations were developed from the measured burning-rate data. These types of correlations can be used conveniently in the design considerations of a solid-propellant rocket motor.

4. The experimental data are in close agreement with the predicted results from the erosive burning model based on the turbulent boundary-layer approach, developed at The Pennsylvania State University.

IV. WRITTEN PUBLICATIONS IN TECHNICAL JOURNALS

1. Razdan, M.K. and Kuo, K.K., "Erosive Burning Study of Composite Solid Propellants by Turbulent Boundary-Layer Approach", accepted for publication in Nov. 1979 issue of AIAA Journal.

2. Razdan, M.K. and Kuo, K.K. "Experimental Measurements and Model Validation for Composite Solid Propellants Burning Under High Cross-Flow Velocities," accepted for publication in AIAA Journal.

V. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

1. Research so far has resulted in the award of one Ph.D. degree with the thesis entitled: "Erosive Burning Study of Composite Solid Propellants by the Reacting Turbulent Boundary-Layer Approach".

2. The remainder part of the research effort is expected to result in the award of a M.S. degree.

VII. INTERACTIONS

A. Spoken Papers at Conferences:

1. Razdan, M.K. and Kuo, K.K., "Erosive Burning Study of Composite Solid Propellants by Turbulent Boundary-Layer Approach," Presented at AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nev., July 25-27, 1978, AIAA Paper NO. 78-978.

2. Razdan, M.K. and Kuo, K.K., "Experimental Measurements of Erosive Burning Rates of Composite Solid Propellants," Presented at AIAA/SAE/ASME 15th Joint Propulsion Conference, Las Vegas, Nevada, June 18-20, 1979, AIAA Paper No. 79-1172.

B. Consultive and Advisory Functions

Some research results obtained on erosive burning study were presented as a part of a 5-day summer course conducted by Professor K. Kuo at the Research Center of Societe Nationale des Poudres et Explosifs (SNPE), Le Bouchet, France, in September 3-7, 1979.

APPENDIX B

ANNUAL REPORT FROM AERONAUTICAL RESEARCH ASSOCIATES
OF PRINCETON
TO ATLANTIC RESEARCH CORPORATION

DEVELOPMENT OF A SECOND-ORDER
CLOSURE MODEL OF
SOLID PROPELLANT EROSIVE BURNING

Robert A. Beddini

Aeronautical Research Associates of Princeton, Inc.
50 Washington Road, P.O. Box 2229
Princeton, New Jersey 08540

November 1979

Interim Scientific Report
For the Period 1 October 1978 - 30 September 1979

Prepared for

ATLANTIC RESEARCH CORPORATION
5390 Cherokee Avenue
Alexandria, Virginia 22314
ARC P.O. 12181

I. INTRODUCTION

Burning rate augmentation due to erosive combustion must be accurately accounted for in the prediction of solid-propellant motor performance. The problem is particularly serious in high length-to-diameter ratio tactical motors--a class which includes the cost-effective nozzleless motor. For such motors, burning rates of two or three times the normal (strand) burning rate have been observed. In attempting to predict this behavior, the designer is today compelled to use heavily empiricized theories of erosive burning which almost universally require correlation to data obtained under actual erosion conditions. Even when correlations have been calibrated to subscale motors, gross errors have appeared in application of the correlations to the erosive burning of large, strategic motors.

It is generally accepted that erosive burning is caused by the interaction of the propellant flame with a high-speed, cross-flowing boundary layer. In most prior theoretical treatments, the fluid-dynamics of the boundary layer have been substantially over-simplified. Inadequate treatment of the fluid-dynamics is one probable reason for the failure of prior erosion models and their subsequent rejection by the propulsion community. The experience and current, fundamental research activities of Aeronautical Research Associates of Princeton, Inc. (A.R.A.P.) in the areas of turbulent combustion and turbulent fluid-dynamics uniquely complement the AFOSR program in erosive burning. Further, since the internal fluid-dynamics of the motor (e.g., velocity, temperature, and turbulent diffusivity profiles) play an important role in problems of aluminum combustion and aeroacoustics, the A.R.A.P. theoretical research program is highly relevant to these areas as well.

II. RESEARCH OBJECTIVES

The following research objectives were established for the 1979 contract year. The extent to which these objectives have been completed is described in the next section.

1) Determine if the detailed results from specific calculations performed with A.R.A.P.'s SPEC model can be used to provide relatively simple parametric correlations for design work.

2) Complete the modifications to the SPEC model to enable it to calculate axisymmetric (cylindrical) as well as planar grain-port flowfields.

3) Determine if combustion-turbulence interaction is an important additional mechanism of erosive burning and determine if it can account for "negative erosion."

4) Develop and implement a model of composite propellant combustion applicable to the erosive burning problem.

III. STATUS

A. Background

The A.R.A.P. research effort in erosive burning was initiated in October, 1975 under AFOSR Contract No. F44620-76-C-0016. In October, 1977, this effort was continued under subcontract to Atlantic Research Corporation (AFOSR Prime Contract No. F49620-78-C-0016). It is therefore advisable to briefly review the overall progress and major achievements before presenting a discussion of the most recent research.

FY 1976 - Research initiated. Development of a theory
to predict erosive burning in solid rocket motors
utilizing second-order turbulence closure. Preliminary
results and objectives reported at the 1976 JANNAF
Workshop on Erosive Burning.

FY 1977 - Development of the first reacting turbulent
boundary-layer model of erosive burning. Successful
prediction of several erosive burning scaling features
including burning rate sensitivity, pressure sensitivity,
threshold behavior, and dependence on geometry. The
following deficiencies were noted in the model:

a) quantitatively, it underpredicted the erosion
   of typical propellants.
b) it did not account for the heterogeneous flame
   structure of composite propellants.
c) it neglected the effects of combustion-turbulence
   interaction (i.e., reaction rate fluctuations)
   on erosive burning.
d) results indicated that the flowfield in actual
   rocket motors was more complicated than could
   be described by a boundary layer description.

FY 1978 - Deficiencies (a) and (d) above were given the
greatest attention to improvement. Propellant surface
roughness was accounted for and the flow in a two-
dimensional grain port was modeled in detail. Consideration
of propellant roughness appeared to remedy the under-
prediction problem, as was demonstrated for a particular
motor. Further, the flowfield results yielded the most
theoretically comprehensive description of the port
flowfield yet available, and indicated that the ability
to calculate cylindrical-port flowfields would be a
desirable enhancement. The intimate connection between
calculated velocity-profile transition and the threshold
condition of erosive burning was demonstrated.

B. Performance During the FY 1979 Year

The attributes and deficiencies in the SPEC model and interactions with various members of the propulsion community have led to the list of research objectives described in Section II. A detailed discussion follows.

Objective 1: This objective was established for two reasons. The first reason was that ongoing and prospective 6.2 research programs sponsored by AFRPL were directed to employ applicable, recently-developed basic research results. The second reason was to demonstrate that the SPEC model, though still under development, can yield practical design information.

To satisfy the technical requirements of the objective, the problem of scaling the threshold condition of erosive burning was examined in detail. The results of prior calculations were used as a guide in formulating a simple scaling relation for the threshold condition. The "mass velocity" at threshold was shown to be a function of burning rate (as was well-known) and also a function of motor diameter and surface roughness. The latter two parameters have been inconsistently accounted for in prior studies, and the diameter scaling is particularly important for large motors. These results were reported in the Proceedings of the JANNAF Combustion Meeting (December, 1978).

Objective 2: The qualitative and quantitative successes of the SPEC model with regard to predicting two-dimensional port flowfields in FY 1978, indicated that modification to compute cylindrical-port flowfields would be an important and necessary enhancement. This objective was completed during FY 1979.

The calculations were compared with cold-flow simulation data (Dunlap, 1974). As with the 2-D flow, agreement between

4

data and calculation was obtained for the flow regime
experimentally investigated. Transition to a turbulent
velocity profile is again predicted to occur downstream
of the measurement stations, and to occur in actual
solid rocket motors which exhibit erosive burning.

Calculations of erosive burning were performed
for a specific cylindrical-port motor and compared with
corresponding results for a 2-D motor. It was found
(quite surprisingly) that the model predicted the
erosion scaling between the 2-D and cylindrical port
results to be in terms of absolute port height or
diameter, and not hydraulic diameter as expected. To
partially verify this observation, calculations were
performed to obtain the skin friction in simple,
incompressible pipe and channel flows. In these cases,
the SPEC calculations were able to reproduce the expected
hydraulic-diameter scaling to within a few percent.

The implications of the flowfield behavior predicted
by the theoretical model are of great importance to both
the erosive burning and acoustic stability problems.
However, at the present time, there is insufficient
experimental data (from cold flow simulations, for
example) to verify theoretical predictions in detail.
Unless additional experimental data becomes available
during the early part of FY '80, work will proceed on
evaluation of the model for erosive burning under the
assumption that the flowfield description is essentially
correct.

Objective 3: This objective was posed to investigate
the largely unknown consequences of combustion-turbulence
interaction on propellant combustion (viz., temperature
fluctuations which can induce large deviations in reaction
rate). This effect has been neglected in prior work

(see deficiency (c) above) and in other erosive burning
models. In the Soviet literature, combustion-turbulence
interaction has been suggested as a candidate mechanism
for "negative erosion."

To investigate these effects, a complete interaction
model was posed and applied to the combustion of ammonium
perchlorate (AP). Ammonium perchlorate was selected
because of its role as oxidizer in composite propellants
(see Objective 4) and because it has been extensively
investigated for its normal (nonerosive) burning behavior.
The AP combustion models of Beckstead, Derr and Price
(1968) and Guirao and Williams (1971) were evaluated for
normal burning and predicted erosive burning with and
without combustion-turbulence interaction.

The investigation yielded the following results:

a) Combustion-turbulence interaction can appreciably
   alter the reaction rate and turbulent diffusivity
   profiles.

b) These effects tend to cancel each other in the
   evaluation of burning rate. That is, the
   erosive burning results for both the BDP and
   Guirao-Williams combustion models with combustion
   turbulence interaction were nearly the same as the
   results obtained without interaction.

c) No evidence of "negative erosion" was obtained.
   This may, however, be model dependent and further
   research should be performed on this topic in
   the future.

d) The Guirao-Williams combustion model yielded a
   much lower flame-height than the BDP model.

e) As a consequence of the much larger flame-height
   yielded by the BDP ammonium perchlorate combustion
   model, AP could appreciably contribute to the
   overall erosive burning of typical composite

propellants. The Guirao-Williams model, on the
other hand, is less susceptible to erosive
burning.

f) The results suggest that the erosive burning
response of a propellant can be used as an
approximate combustion diagnostic technique
for determining an unknown propellant flame-
height relative to a standard propellant flame-
height.

The preceding results have been reported at the
1979 JANNAF Combustion Meeting.

Objective 4: Although the results from Objective (3)
are applicable to the modeling of unmixed combustion
processes occurring during composite propellant combustion,
no new results in this area have been obtained. The problem
lies with the lack of a continuous "field" description of
combustion in contemporary composite propellant models.
Although some new concepts have been formed to improve
existing models and allow them to be consistently applied
to the erosive burning problem, a substantial effort would
be required to develop these new concepts. It has therefore
been decided that, at least for FY 1980, composite pro-
pellant erosive burning will continue to be simulated with
a homogeneous combustion model.

VI.   INTERACTIONS - FY 1979

1) Mr. Beddini presented results from the combustion-turbulent
interaction phase of research at the 16th JANNAF Combustion
Meeting, Naval Postgraduate School, Monterey, CA, Sept. 10-14,
1979.

2) While at that meeting, he discussed various aspects of flowfield-interaction effects on velocity coupling. The individuals principally involved in the technical discussion were Mr. Jay N. Levine of AFRPL and Dr. Ronald Derr of NWC/China Lake.

3) Dr. Robert Hermsen (of United Technologies/Chemical Systems Div.) and Mr. Beddini had several discussions during July - September, 1979. Dr. Hermsen forwarded a revised copy of a graph showing the scaling of the erosive burning threshold condition that was previously published by Mr. Beddini. Dr. Hermsen had added new data from several CSD motors and indicated that this provided further support for the scaling relation developed under AFOSR sponsorship. Dr. Hermsen was investigating the implementation of the threshold criterion in the Solid Rocket Performance Program being developed by CSD for AFRPL.

4) While at the AFOSR/RPL Research Meeting (March 20-22, 1979), discussions were held with Dr. Daweel George of AFRPL concerning the applicability of the SPEC model to the upcoming RPL "Nozzleless Performance Program." Mr. Beddini indicated that direct incorporation of the SPEC model in the NPP would be somewhat premature in the time-frame of interest to AFRPL. However, results from the SPEC model could be used as a guide in the selection of suitable erosive burning models.

IV. LIST OF PUBLICATIONS

Publications which have resulted from the work performed under AFOSR contracts F49620-78-C-0016 (ARC P.O. 12181) and F44620-76-C-0016 are:

Beddini, R.A. and Varma, A.K., "Analysis of Combustion-Turbulence Interaction with Application to the Deflagration of a Solid Monopropellant," in preparation. Probable submission to Combustion Science and Technology in December, 1979.

Beddini, R.A. and Varma, A.K., "Analysis of Ammonium Perchlorate Combustion in a Turbulent Flow," to be published in the Proc. of the 16th JANNAF Combustion Meeting, Naval Postgraduate School, September, 1979.

Beddini, R.A., "On the Scaling of Erosive Burning: The Threshold Condition," Proc. of the 15th JANNAF Combustion Meeting, December, 1978.

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V. PERSONNEL

The principal investigator for the A.R.A.P. effort is
Mr. Robert A. Beddini. During the FY 1979 performance period,
he has been assisted by Drs. Ashok K. Varma and Guido Sandri.