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R. Geisler and C. Beckman "The History of the BATES Motors at the Air Force Rocket Propulsion Laboratory"
AIAA **(Statement A)**

AIAA-98-3981

The History of the BATES Motors at the Air Force Rocket Propulsion Laboratory

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THE HISTORY OF THE BATES MOTORS AT THE AIR FORCE ROCKET PROPULSION LABORATORY

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Abstract

This paper presents the history of the Ballistic Test and Evaluation System (BATES) at what was then the Air Force Rocket Propulsion Laboratory (AFRPL) over the past 40 years. The system maintains the highest accuracy possible (0.2 % on thrust) and has become the equivalent of Bureau of Standards for measuring and comparing solid propellant performance. The BATES database covers several thousand firings with several hundred parameters reported per firing. The paper also discusses methodologies developed with the system, scientific discoveries made with the system, and the key role it has played in shaping the entire ballistic testing and analysis efforts in this and other countries.

Figure 1. Post-firing, First Bates Test, Sept. 1961

Introduction

In the summer of 1959 the nucleus for what was to become the Air Force Rocket Propulsion Laboratory was established as a tenant of Edwards AFB, CA by a contingent of scientists and engineers from the Aeropropulsion Laboratory at WPAFB, OH. One of the major objectives of the move was to establish a more vigorous in-house program. When asked for an initial list of potential programs, the Solid Rocket Division proposed establishing a high-precision ballistic testing capability that could rank vendors propellant performance and provide an estimate of full-scale motor performance using the minimum motor size possible to limit the quantity of scarce advanced propellants needed. The original project engineer was Mr. Wilbur Andrepont who was supported by Lt. Harold Gale. The first BATES motor firing was successful and was accomplished on 8 September 1961. Figure 1 shows the design team of Mr. Andrepont and Lt. Gale conducting a postfiring inspection of the test hardware with the lead mechanic Mr. Bill Sando.

Since the knowledge of ballistic testing, scaling, and performance prediction were in their infancy, the engineers surveyed the state of the art and found that the Rohm and Haas company at the Army Redstone Arsenal were the most experienced in this field. Consequently much of the motor design was based on their advice. At the time, it was thought that a motor with a propellant weight approaching 100 lb. would produce specific impulse efficiency nearly the same as any larger size motor. This, of course, was not totally true because of our lack of understanding of two-phase-flow and how to scale for such a parameter. We did understand the need for as neutral a trace as possible and the minimization of heat-loss and mass addition in the motor design. The result was the design of the Seventy-pound BATES motor. In subsequent years the Fifteen-pound motor was added to aid scaling studies and ultimately the Super BATES motor using 800 pounds and more of propellant was added to approximate the gas and particle residence time of a large motor. In addition, a whole host of modifications of the motors took place over the years to study such

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special problems as effect of multiple chamber lengths, nozzle submergence, end burners, motor spin rate, nozzle erosion rate, vacuum testing, and insulation. Each of the major BATES motor designs will be discussed in detail later in this paper.

As the program progressed it became clear that we were dealing with a system and series of methodologies to evaluate performance and not just the design of a motor. Our approach became one of maintaining the maximum measurement accuracy possible while stressing design features, which presented the most analyzable and measurable possibility for evaluating performance effects such as combustion completeness, heat loss, and two-phase-flow effects. We also felt compelled to become the leader in this field since our measurements would become the basis for important contract awards and final propellant selection for major vehicles and weapon systems. We always maintained maximum participation in the relevant JANNAF panels for setting standards of measuring and reporting performance and we also used their corporate recommendations in prioritizing improvements to the system.

Over the next 40 years the BATES system and our understanding of it and the motor area grew. The BATES system became the universally accepted basis for performance measurement and is accepted by U.S. manufacturers and some abroad. On the order of 4,000 motor tests have been conducted by the laboratory and many more by industry. In addition, all of the laboratory firings have been meticulously documented over the years and are available for continued use to study new problems.

Description of the BATES Motors:

Seventy-Pound BATES Motor:

The first motor designed and used was the 70-pound motor and its constant internal design and present overall design is shown in Figure 2 and Table I. The grain is a double end burning center-perforated grain

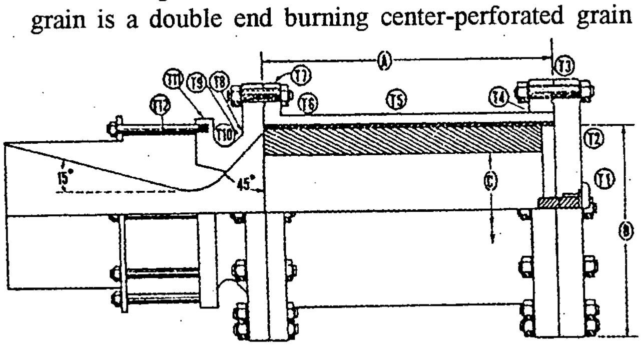

Figure 2, 15/70 Pound BATES (Ref Table I)

designed for maximum neutrality, minimum sliver, and minimum mass addition from insulation and for manufacturing simplicity.

Table I, 15-Pound and 70-Pound BATES Motor Characteristics

Motor Size	15-Pound	70-Pound
Pressure (psi)	1000.	1000.
Nozzle Diameter (in)	2.	1.
Gas Residence Time (Msec)	8.	17.
Grain Length (in) (A)	20.	12.
Grain Bore (in) (B)	8.	4.6
Grain Diameter (in) (C)	12.	7.

Figure 3 shows the theoretical burning area vs. time for the BATES grain design. The Seventy-Pound motor has the 1.86-inch web and the Fifteen-pound motor has the 1-inch web. The Fifteen-pound history is offset for comparison.

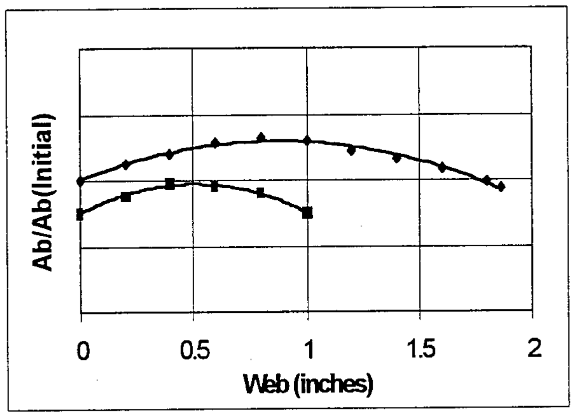

Figure 3, Fifteen-Pound and Seventy-Pound BATES Burnback History

The grain is cartridge loaded in a phenolic tube. The motor also has a very low web fraction, which combined with the cartridge design places very low requirements on propellant properties. Fortuitously, this motor turned out to have sufficiently large residence time (~17 milliseconds) to burn most of the aluminum in most propellants. The head closure, case, and aft closure are high strength steel. The aft-closure is lined with a graphite liner to prevent closure erosion. The nozzle and expansion cone is a single graphite part, which is normally Great Lake Carbon HLM-85 material. Thermocouples are instrumented on the Fifteen-pound and Seventy-pound motors at twelve positions. The heat loss determined is part of the routine data analysis. The air calorimetry correlates with oil calorimetery conducted early in the motor development. Testing is conducted on high accuracy thrust stands that have Bureau of Standards traceable dead weight calibrators. The thrust stands have 0.1 percent thrust measurement for the Seventy-pound motor and 0.25 percent for the Fifteen-pound motor. Test matrices require three motors per pressure and preferably six for the Seventy-pound motor and six motors per pressure and preferably nine for the Fifteen-pound motor with new nozzles. This allows delivered specific impulse to be determined within 0.25 seconds. The standard igniter for the Seventy-pound motor is the JATO igniter, which contains forty-five grams of ALCO pellets that initiate with a black powder squib. The Fifteen-pound motor uses a Laboratory design of an aluminum basket and a black powder squib with a nominal eighteen grams of BKNO3 pellets. MAG-Teflon pellets are used for reduced and minimum smoke propellants to facilitate better plume monitoring. Figure 4 shows a typical BATES firing trace for a hydroxyl-terminated polybutadiene binder, ammonium perchlorate oxidized, aluminumized or nonaluminized propellant. The mid-web deviation or ballistic anomaly is often observed in the BATES and other motors and has been referred to as "Hump and BARF". We have used BATES to study this anomaly[1,2,3,4].

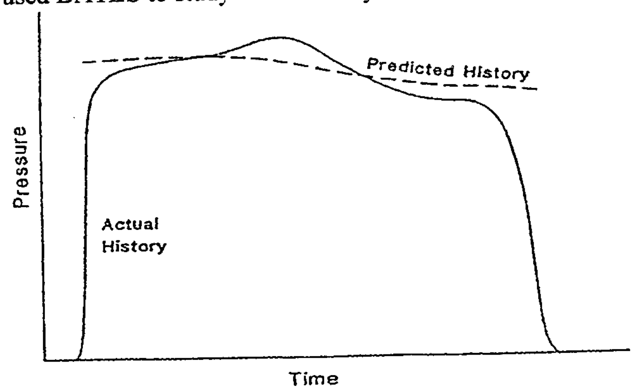

Figure 4, BATES Pc History (90/21 AP Formulation)

Fifteen Pound BATES Motor:

A few years later the Fifteen-pound motor was designed. It's need was several fold, we needed a second size motor to facilitate and validate scaling predictions. We needed a motor that used a smaller quantity of propellant since many experimental formulations that had limited availability or contained ingredients that were scarce and expensive. An interesting feature of this motor is that its design is essentially a photo-reduction of the Seventy-pound motor. This approach helped in the scaling studies and was a very good motor for tactical propellant assessment especially reduced smoke and minimum smoke formulations since the nozzle geometries were very similar. We later learned that this motor's gas residence time (~ 8 milliseconds) was not quite large enough to burn all of the aluminum in the heavily aluminized propellants

Super BATES:

Considerably later in the game we introduced the Super BATES Motor[5]. The concept was to approximate the mass flow and gas residence time of a large motor but with a very thin web and short burn time to minimize the amount of propellant required. We selected the third stage of Minuteman III for the mass flow, throat diameter and gas residence time to be simulated. The motor was designed and checked-out by UTC under contract. Motor design and characteristics are shown in Figure 5.

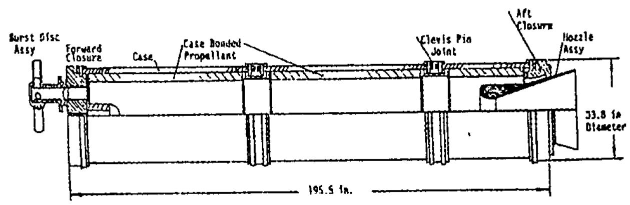

Figure 5, Tandem Super BATES Configuration

Multiple chamber design was developed permitting a number of larger sized motors (800-pounds to 2200-pounds). The nominal 800-pound motor has been the most utilized design. The basic concept is to simulate the nominal burn properties of a very large residence time motor to provide confidence in the specific impulse scaling measurements and also to provide test cases for analyses programs that have a reasonable size.

Description of the BATES Methodology:

The careful, methodical collection of several thousand test results for a wide variety of propellants and conditions eventually led to a methodology and philosophy that viewed the overall effort as one to completely understand and experimentally validate all of those parameters that make up the overall performance. This procedure of prediction and experimental validation became very useful in advancing our understanding of the complexities of motor operation. Many theories were not borne out in tests and had to be modified to represent reality. It became surprising to see how much fundamental understanding could be studied in a seemingly mundane series of motor tests. For example, we were able to investigate many research issues on ballistic anomalies, rheology[1,2,3,4], combustion, plumes, nozzle recession, kinetics, and flow. We also developed a first hand understanding of motor design, high pressure effects, non-destructive testing (all motors were xrayed) and human error was minimized by checking the data in a number of independent ways. The motors have a nominal neutrality of 1.03, which results in the predicted firing history indicated. The actual firing history from the motors produces the ballistic anomaly shown previously in Figure 4. Understanding and resolution of the pressure excursion was possible with the BATES data analysis. This is a normal characteristic of ammonium perchlorate containing composite propellants. Significant effort has been expended to eliminate the phenomena in operational motors because of the deviation from predicted maximum pressure it causes.

An example of our evaluation of a new propellant family is illustrated by what we affectionately referred to as the "ARC series" as shown in Table III

Table III. Propellant Formulations and Properties

	1	2	3	4	5	6
Wt% Al	15	18	21	24	27	30
Wt% AP	75	72	69	66	63	60
Wt% HTPB	10	10	10	10	10	10
Rb 1000 psia	0.56	0.55	0.56	0.46	0.51	0.50
η^{15} (ISP)15-lb	92.3	91.27	90.48	89.59	89.11	88.89
η^{15} (ISP)70-lb	93.38	92.84	92.03	91.31	90.92	90.51
Tc(K)@1000psi	3602	3682	3746	3784	3787	3743
T*(K) no Al	2859	2791	2705	2605	2494	2376
Moles/100 gm. Al_2O_3 at Thrt	0.269	0.319	0.362	0.396	0.413	0.415

This effort was part of the evaluation and introduction of HTPB propellants in the early 1970's [6]. To fully characterize the HTPB propellant we had six compositions formulated at 90 % solids by ARC, carefully tailoring the burning rate and, therefore, the mass-flow rate to be nearly constant. The aluminum level starts at 15% and is raised in 3% increments by displacing ammonium perchlorate oxidizer until it reaches 30% by weight. The tests were conducted at constant conditions as shown in Table IV. The motors were expanded to sea-level conditions (14.7 psia) which is close to ambient pressure (~13.3 psia) with a nominal chamber pressure of 1000 psia. Three Seventy-pound and six Fifteen-pound motors were tested at identical conditions for each aluminum level. Even though attempts were made to formulate to a constant burning rate, it did vary enough to cause small variations in throat diameter to maintain the desired 1000 psia chamber pressure. We did not allow variations in the ammonium perchlorate particle size or the particle size ratio to maintain chamber pressure. They were tested in rotation to prevent any bias due to firing a formulation in different time periods.

Table IV. Test Motor Characteristics

Parameter	70-lb Motor	15-lb Motor
Chamber Pressure (psi)	1000	1000
Propellant Charge wt (lb)	75	15
Nozzle Throat Diameter(in)	2	1
Nozzle Area Ratio	9.5	9.5
Gas Residence Time (Msec)	20	11
Divergence Angle (deg.)	15	15
Tests per Formulation	3	6

The data in Table III was used to evaluate the completeness of metal combustion and scaling effects in these motors. The results of this effort were validated by other sources[7].

Another series was the minimum smoke series where we learned that their combustion efficiency rolls off dramatically below 500 psi. This evaluation supported the minimum smoke motor development program. The propellant was evaluated in the Fifteen-pound motor and temperature sensitivity was determined in addition to the low-pressure combustion assessment. This evaluation established the credibility of the "dark zone" theory.

Specialty and Scientific Uses of the System:

Particulate was caught from the motor exhaust for particle size measurement for metallized propellants. The results of this effort were used for many years to verify the results of two-phase-flow analyses and performance prediction programs. This series also served as the basis for determining the recession rate of graphite as a function of propellant composition[7].

Two-Phase-Flow Losses

In the late 1960's we also collected particulate from every sized rocket from test motors to the NASA 260-inch booster and motors nationwide at the request of Dr. Larry Delaney of the Aerospace Corporation to support his maximum stable droplet size theory[8]. This was accomplished for the 260-inch motors by flying a RB-57 through the exhaust plume upon motor shutdown. Based on the confirmation of our collections from this motor and the 156-inch motors, this theory became the basis for our scaling work that evolved into the Solid Propellant Performance Prediction (SPP) code. These efforts became the future for two-phase-flow modeling of metallized fueled rockets. The sized particles helped confirm the relationship between motor size two-phase flow losses. The major findings of this effort showed particle size was dependent on motor throat size and independent of aluminum loading. This is consistent with Dr. Delaney's theory. We also participated in laser Doppler measurements with Stanford University[9]. The measurement technique was based upon the Doppler-shifted scattering of a focused laser beam by the particle matter in a flow. The absolute value of frequency is converted into velocity information by a Fabry Perot interferometer. This was one of the first attempts to nonintrusively measure the velocity of the aluminum oxide particles in a rocket exhaust plume and correlate these findings with our two-phase-flow calculations. It was concluded that the particle density was too high in the core of the flow to make measurements. However, measurements of small particles in the edge of the plume revealed that they were traveling at precisely the calculated gas velocity for the exhaust.

Radar Attenuation and Cross-Section Studies:

In the mid-60's several problems arose regarding the radar attenuation of the solid rocket exhaust plumes. Some air launched missiles lost contact with the guiding aircraft avionics and flew off-course. Additionally, some space and ballistic missile vehicles experienced communication and telemetry blackouts when microwave signals passed through large lengths of the plume. Once again, BATES was employed as the vehicle to study the problem. The Exhaust Plume Interference Characterization (EPIC)[10] program was created using the BATES motor.

The Seventy-pound test pad was modified to accommodate a cart with a trench and a rail track down stream from the motor exit plane. The cart was designed to encircle the exhaust plume during the firing with microwave transmitters and receivers 180^{o} apart. Two frequencies (X-Band and K-Band) were transmitted at 90^{o} to the plume to receivers on the other side as the cart was rolled down the track from the exit plane; it traversed the plume thus permitting an accurate measure of attenuation for each section of the plume. We screened a number of additives and confirmed that it is the after-burning at the shocks that creates electrons and ions and attenuates the signal. We found that the more aluminum the propellant contained, the higher the signal attenuation because the aluminum ties up the oxygen in the propellant and leaves more fuel-rich gasses to mix with air and after-burn upon ignition from the first shock behind the rocket motor.

As concern grew about reducing the radar cross-section of missiles, the same stand was used to study the problem since we could measure use the two-frequency data to solve for electron density and collision frequency in the plume and these parameters can be used to calculate the cross-section. The plume characterization effort expanded into distinct IR and UV capabilities with the motor that are still in use today.

Motor Spin Rate Effects Studies:

When a notation problem arose on the spin stage of the GPS launcher, we developed a spin stand for the BATES motor and studied the effect of levels up to 6 to 9 radial g's on the motor slag retention and performance. We observed an "order of magnitude" increase in slag at a nominal 6 g's that resulted in a similar performance penalty. We screened new formulations and additives to reduce the problem. We found that our upper g levels were just below particle retention at the burning surface, beyond which burning rate augmentation starts. We also found that agglomerate and slag retention is primarily affected by the amount of radial running surface and allowing the g forces to trap slag. The spin BATES motor tests tended to leave a band of slag on each end of the motor where it was centrifugally cast between the closures and the ends of the grain.

Nozzle Throat Recession and Graphite Kinetics:

In the late 1970's the failure of graphite nozzle parts was of great concern. Once again, the BATES system was used to gain insight to this problem. It was noted that there were several thousand firings of a wide variety of propellant compositions in the database. It was also noted that they all had a common denominator of a Great Lakes Carbon HLM-85 graphite throat. Thus, correlations of throat recession of a function of propellant composition and firing condition could be made for this throat material as shown in Figure 6. The additional element required was a method to derive throat recession rates for these short burn times (less

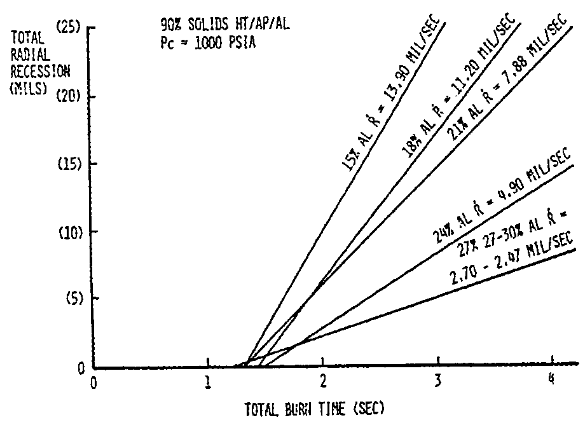

Figure 6, Recession versus Time for ARC Series

than five second) motors. It was discovered that for these small motors a highly amplified and filtered thrust over pressure (F/P) plot could be used to estimate real-time throat diameters to less than one mil (0.001inches) as shown in Figure 7.

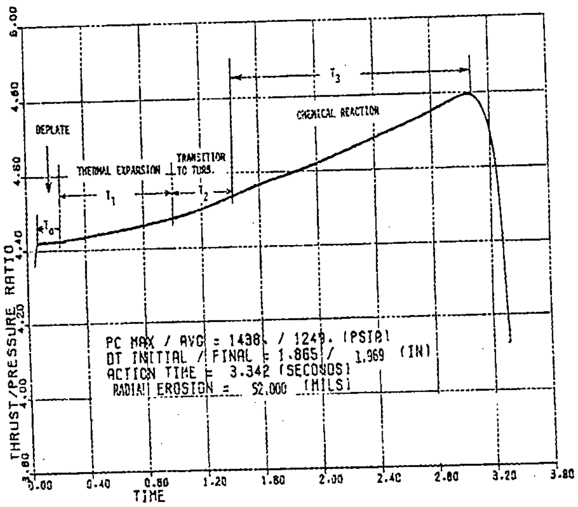

Figure 7, Thrust /Pressure Nozzle Erosion Analysis

The subsequent correlations indicated that recession in solid rocket motors is due to a diffusion limited chemical attack of oxygen species on the graphite surface and not due to mechanical impingement[11]. Furthermore, the attacking oxygen comes primarily from the thermal dissociation of water to the attacking –OH and the surface decomposition of graphite to a material called carbyne which is the C-triple bond-C product of graphite above 2600 K. Since it is a diffusion limited reaction, the surface roughness greatly affects the Reynolds number and hence the reaction rate. For this reason, bulk graphite out performs the more coarsely bound carbon/carbon structures. The overall recession rate is approximated for bulk and woven graphites by the following equation:

$$R=0.58\ Mw\ (Pc/1000)^{0.8}$$

R is recession rate in mils/sec, Mw is mole percent water in the free-stream, and Pc is the chamber pressure. This correlation assumes the surface temperature of the graphite is above the 2600 deg K point where carbyne forms, that Cf and C* are constant, and that the surface roughness is small. Throat recession was found to the surprise of some to decrease as the aluminum content is increased. This is because the aluminum scavenges oxygen and leaves less in the free-stream to attack the graphite. The use of small solid ballistic test motors for nozzle recession measurements and the very simple recession equation were great cost and time saving discoveries provided through the BATES system. The method of estimating instantaneous throat diameter also set the stage for the measurement of instantaneous specific impulse in solid rocket motors.

Hydrogen Augmentation of Solids:

The concept of augmenting the performance of the Space Shuttle solid boosters with leftover hydrogen from the liquid SSME was evaluated in BATES[12]. The tests proved that very good mixing and performance is easily achieved with this approach. There was no erosive burning or change to normal ballistics other than that associated with mass addition. The hydrogen is very benign to the throat erosion as well. The hydrogen addition can reduce nozzle erosion depending on the location of the hydrogen insertion. At a mass addition of as little as 4% of the motor mass flow, a specific impulse increase of over 18 seconds was realized. This performance enhancement can be even more significant as shown in Figure 8. This is in the regime that might be expected for the shuttle using surplus hydrogen from the SSME hydrogen tank. This propellant is normally jettisoned into the Indian Ocean and not utilized to the Shuttle's advantage.

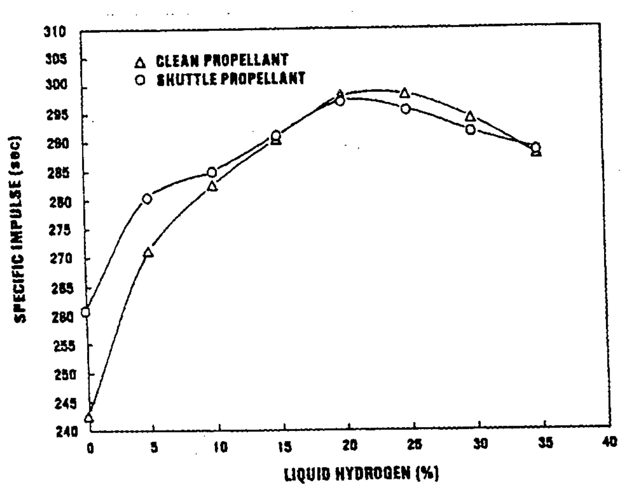

Figure 8,Specific Impulse versus Hydrogen Addition

Conclusions:

In conclusion, what started out as a simple requirement to measure delivered specific impulse turned out to be a gold mine for understanding the performance of solid rockets in general. The concepts of precision measurement coupled with analyzable hardware proved to be the key to success. Measurement and analysis were iterated until our ability to understand and analyze were sufficiently high to abandon experimentation. Once a baseline of understanding was achieved, the motors were profitably used to evaluate a wide range of problems and new ideas ranging from nozzle recession to hydrogen augmentation. It is unfortunate that we may not be able to continue this type of effort under today's diminished rocket propulsion effort. It would be particularly disconcerting to lose the BATES database, which contains 40 years of performance data worth untold tens of millions of dollars. Lacking the necessary funds and manpower this may well happen soon.

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