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INTRODUCTION TO THE PROBLEM

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General Background

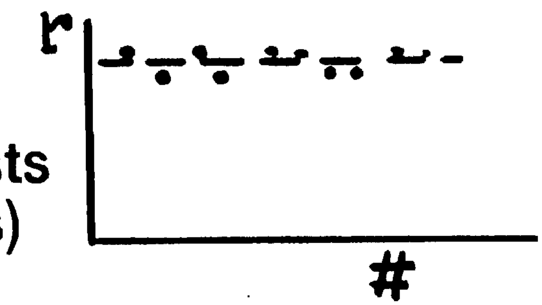
The United States of America entered space with Explorer I, whose success was ensured through highly reliable solid propellant rockets in the second, third, and fourth stages; the use of clusters of identical motors (eleven, three, and one) is a characteristic typical of solid motors, namely the ease of "mass production" after development. Solid propellant rockets have been used extensively in space missions ranging from large boosters to orbit-raising upper stages. The smaller motors find exclusive use in various earth-based applications. The advantages of the solids include simplicity, readiness, volumetric efficiency, and storability (the advantages in specific comparison with liquid propellant rockets are detailed elsewhere in this report). So long as we continue to use them, and consider them for current and future missions, it is very important to maintain competence in solid propellants. Without such "in-house" capability, costly and wasteful panic solutions become necessary as problems are discovered in the use of newer propellants. Some non-technical solutions have saved the day, but these are temporary solutions at best. These aspects are listed in Fig. 1. Several recent advances in micro-technologies seem to indicate that we may profitably use these developments to economically evolve improvements. Our objectives are outlined in Fig. 2.

- SO LONG AS WE CONTINUE TO USE THEM
  - Important to maintain competence
  - Avoid costly panic solutions
  - Non-technical "solutions" may help in the short run, but do harm eventually
- IMPORTANT RECENT PROGRESS IN RELATED FIELDS
  - Combustion
  - Rheology
  - Micro-Instrumentation/Diagnostics
  - Chaos Theory

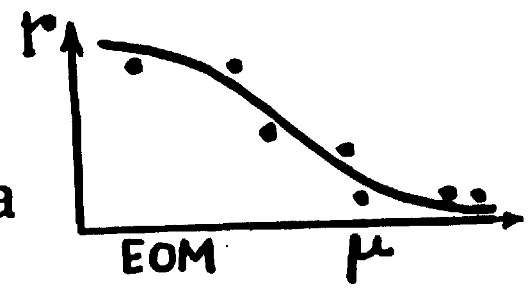
CAN BE APPLIED TO SOLID ROCKETS TO DERIVE MAXIMUM ADVANTAGE AND AVOID WASTE

Fig. 1. Aspects of research on solid propellants.

- ULTIMATE
  - Predictable Solid Rockets
  - Minimum Surprises
  - Economy in Qualification Tests (Scale-up and Modifications)



- SHORT-TERM
  - Identify Critical Parameters
  - Establish Specification Rules
  - Develop Quantitative Criteria



- CONFERENCE (21 April 1989)
  - Learn from Experts
  - Evolve Consensus
  - Document Recommendations

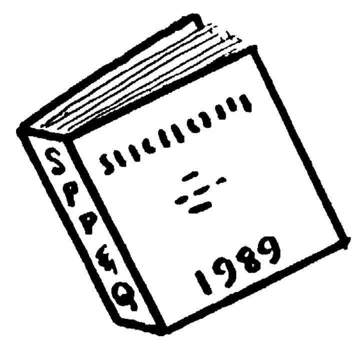


Fig. 2. Objectives of research in solid propellants.

It may be surprising to learn that we do not seem to have a good understanding of the fundamentals of solid propellants, especially after so many successful programs. The sheer bulk of data from almost five decades of (composite) solid propellant rocketry would lead one to suppose that very reliable rockets could be built based upon this data base. The fact that things are not that easy is best summarized by Ed Price, who notes the following:

> An enormous amount of money has been spent during development programs on empirical approaches to meeting program needs for burning rate or mechanical properties. The totality of such efforts contributes very little to understanding or future ability for rational control because the myriad of relevant material, formulation, and test conditions have little commonality from one study to the next. . . .
>
> . . . What they can't do by control of ingredient and processing specifications, they fine tune by testing liquid strands during batch processing and adding catalyst as needed. [His letter is reproduced in its entirety in Appendix D.]

With these clear revelations of the past and present status of solid propellants, one can obtain a better feel for the facts. The advantages of solid propellants have made them so desirable that a large number of these have been built and used without really understanding them well. Instead of a scientific "ground-up" approach, most solid propellant rockets have been built based upon past experience, educated guesses, and extensive corrective procedures during the design evolution. To ensure a sufficiently good understanding that results in verifiable quality and dependability, we will have to do better. The rewards will be substantial.

In the specific context of the Space Transportation System (STS), or the shuttle, we can realistically expect several important advances through a better understanding of solid propellants. These are outlined in Fig. 3. Basically, the payload increases because the liquid propellant margin can be reduced, the thrust vector control (TVC) system used to balance out imbalances in the two boosters can be a lot lighter, and several other systems can be made lighter. All these directly result in a lower cost per pound of material placed in orbit. The indirect cost reductions are far more substantial. These come from decreased **developmental** costs of the future motors.

Motivations

There are at least four important motivations for this scientific approach:

1. *Long-term economy* through *quality, reliability, and safety.* There has been a growing awareness in the rocketry community, and particularly at NASA, that a thorough scientific understanding is the only way to achieve **long-term satisfactory performance and economy**; this awareness was reflected in the formation of Code Q at NASA.

- PAYLOAD INCREASES BECAUSE OF
  - Decreases in the liquid margin
  - Decreases in the TVC system weight needed for the two SRB mismatches
  - Decreases in several other controls/instruments
- COST DECREASES BECAUSE
  - ASRM and RSRM can be better designed
  - HTPB can be used instead of PBAN
  - Clean propellant can be quickly developed
  - Insulation (non-asbestos) can be tailored
  - Alternative propellants can be quickly implemented
- FUTURE NASA DIRECTIONS
  - Can be easily followed

Fig. 3. Advances derived from a better understanding of solid rockets.

2. *New and Revised Designs.* Many advanced designs (e.g., ASRM) and revised designs (e.g., RSRM) are planned or are being executed.[1] Specific examples include (1) the attempts to replace PBAN with HTPB in the STS SRBs and (2) the alternative propellant being considered for pollution reduction through AN instead of AP. Such **new designs** can be economically handled only through a better understanding of the fundamentals. Safety, reliability, and quality cannot be ensured if the general feeling is one of "Don't touch it! We just got it to work with great difficulty. Don't alter anything."
3. *Advanced Process Control.* For safety reasons and also to introduce modern computer-controlled processing, it is very important to understand the fundamental relations among the process variables. It is simply not practical to introduce advanced process control techniques if human monitoring and qualitative judgments (based on experience) are constantly required. This specific aspect of autonomous controls has become very important lately. With the recent NASA (and the USA) thrusts toward space exploration and a permanent presence in space, it is easily recognized that extraterrestrial propellant production is a major enabling technology. This *in situ* propellant production must be demonstrated robotically.

Some of the communication time lags between earth and other planets and asteroids mandate an autonomous processing plant. Such autonomous propellant production at remote sites can only be accomplished through a thorough understanding of the process variables, contingency margins, and "beyond-the-envelope" knowledge. This general area of autonomous propellant production using local resources provides a strong motivation for a better understanding of the fundamentals.

4. *High-Technology Devices.* This decade has seen a rapid advance in **several high technologies.** Microfiberoptics, IR/UV real-time imaging, free radical chemical techniques, *in situ* non-obtrusive sensors, microchips, and microcircuitry provide only a few examples of a wide variety of innovations. Many aspects of solid propellant monitoring and control that were beyond the technologies of the 1970s can be almost routinely handled through state-of-the-art technological advances. These recent high-tech devices and the definite promise of imminent advances provide an important motivation for revisiting many unsolved issues in solid propellant rockets.

Technical Background

The technology of solid propellants and high explosives has developed into a maturing *art* rather than a precise *science*. The variables and factors associated with typical composite propellant processing are so many in number that they may elude traditional, deterministic analyses. Quality control standards have been set based on *known* factors that influence performance, but the unknowns continue to cause surprises. It is not uncommon for propellants with "identical" ingredients processed in "identical" batches to reveal perceptible, and frequently unacceptable, variations in burn rates and mechanical properties (e.g., the tensile modulus). Two typical examples are shown in Figs. 4 and 5. Figure 4 shows a normalized burn rate, while the propellant in Fig. 5 indicates actual burn rates. It is thought that, in both of these cases, the propellants were processed in very similar, if not identical, manners. It is easy to recognize two aspects of this problem. One is the obvious indication that the propellant may not meet the expected performance; the other is the more important, genuine doubt about the performance of future batches. Of course, a major factor that precludes conventional quality assurance analyses and reliability predictions is the fact that usually, especially in larger motors, the number of batches will be too small for a reasonable statistical analysis. Many of these anomalies in recent experiments have been discussed.[2-6] It is clear that, for all the attention the problem has received, attempts at analyses are rare.

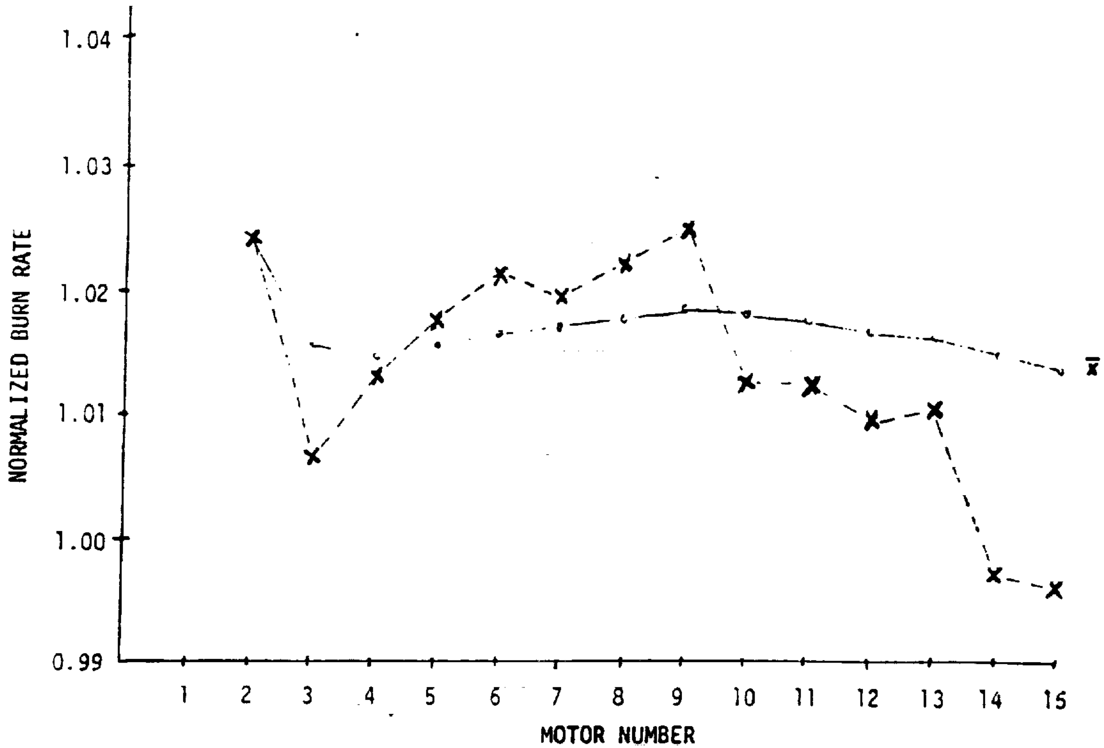


Fig. 4 Normalized burn rate of a solid propellant from batch to batch.

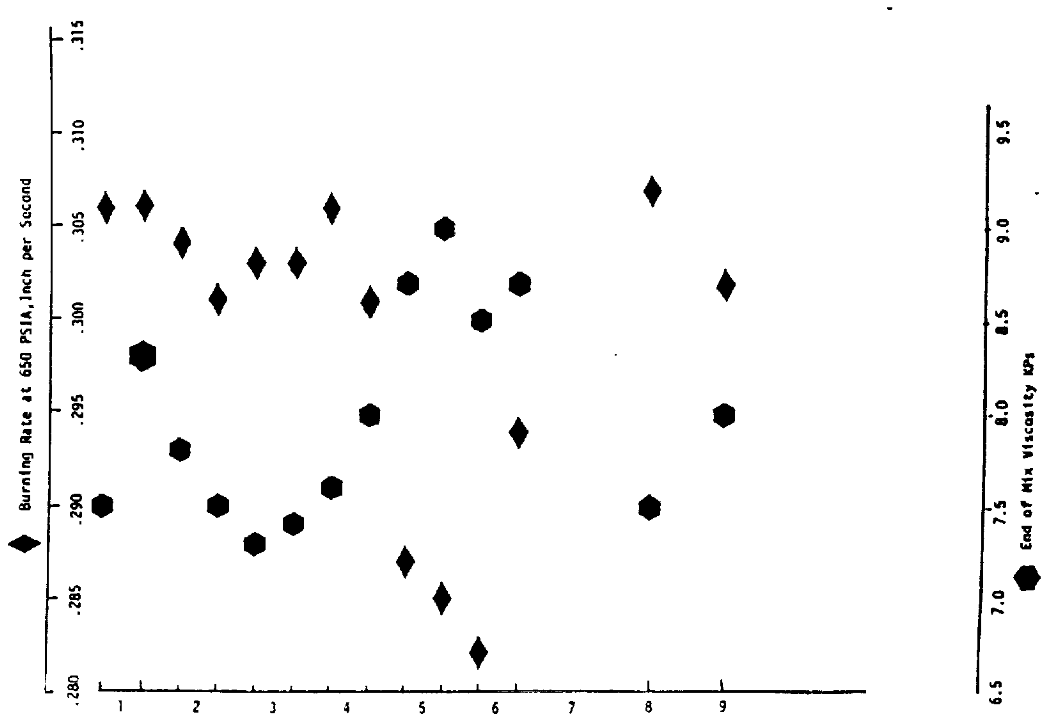


Fig. 5. Actual burn rates of a solid propellant.

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OF POOR QUALITY

Quality control in solid propellant rockets has not been thoroughly understood, mainly because of the very large number of parameters involved in the manufacture of solid propellants. The parameters (Fig. 6) involve the ingredients (at least 10 different ingredients are used, typically; see Table 1) and the processing (at least 30 steps have to be followed, typically; see Fig. 7). The end-use parameters of interest include the steady-state (really, "time-dependent") burn rate, susceptibility to instability or oscillatory combustion, ease of ignition, uniformity of burn rate, completion of combustion (i.e., product distribution), mechanical properties, aging characteristics, environmental effects, and a host of related issues.

The fact that no two batches of solid propellants are identical in performance has been well recognized for many years; it has been thought adequate to maintain quality control standards within, for example, JANNAF recommendations to meet specific needs. Occasional "malfunctions" have not provided sufficiently strong stimuli for a detailed scientific analysis of the problem. A significant shortcoming (12,000-foot altitude loss) in the fourth launch of the STS in 1982 appears to have been the first problem to cause a pink, if not red, flag to be raised[7] (Fig. 8). Subsequent revision of the SRB burn rate downward (Fig. 9) appeared to have solved the problem, at least temporarily.[8] This incident resulted in a thorough examination of the entire burn rate prediction procedures in large SRBs.[9] The general conclusion appears to have been that more work is needed for a better understanding of the mechanics of propellant manufacture, but it is simply not practical to process, cast, cure, and test-fire hundreds of rockets, each containing literally millions of pounds of propellants. Also, as the batch size increases, the potential for non-uniformities in ingredient distribution and processing increases. Better techniques are needed not only to ensure economy and quality control, but also to raise our confidence in the entire manufacturing technique. We simply cannot wait for the "next" firing to provide one more anomalous data point.

The understandable reticence of concerned manufacturers to openly discuss their experiences with malfunctions has not helped to alleviate the problem [however, a good start has been made by one company (see Fig. 10)]. The session organized by Bob Geisler at the AIAA Propulsion Meeting in 1982 appears to be the first to openly describe the experiences.[2-6] No specific recommendations were made, however, to guide future efforts. Two papers[10,11] attempted to isolate one specific subprocess (final mixing time) for a detailed analysis in a carefully controlled experiment where all other parameters were held strictly constant. Use of the same lot numbers for the ingredients minimized ingredient variations. The first theory attempted to relate the progressive grinding of the coarse AP to burn rate and initial tensile modulus. The experimental results were consistent with theory.

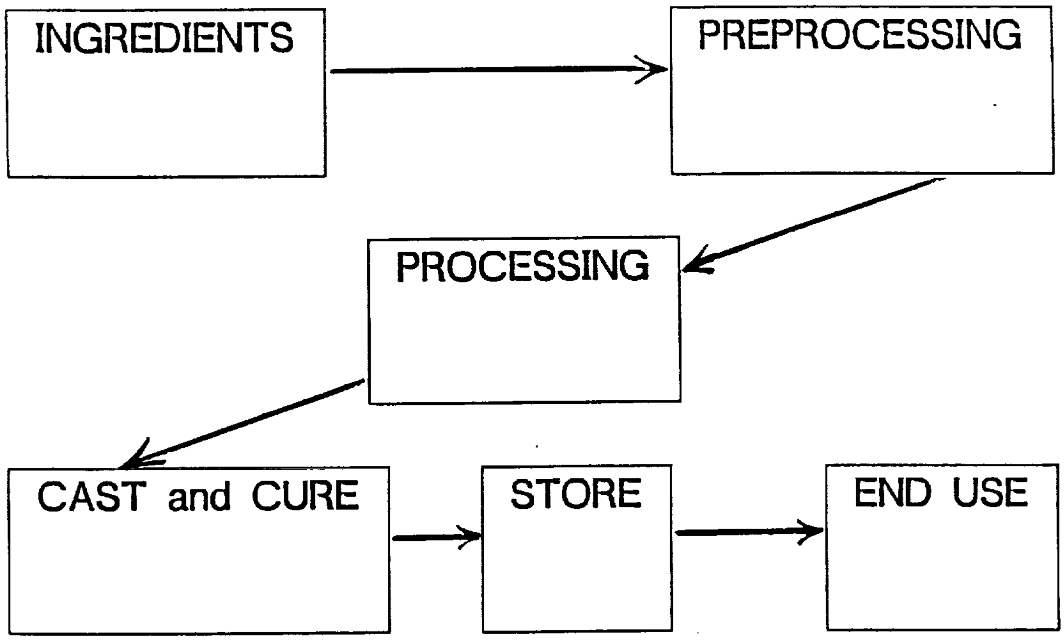
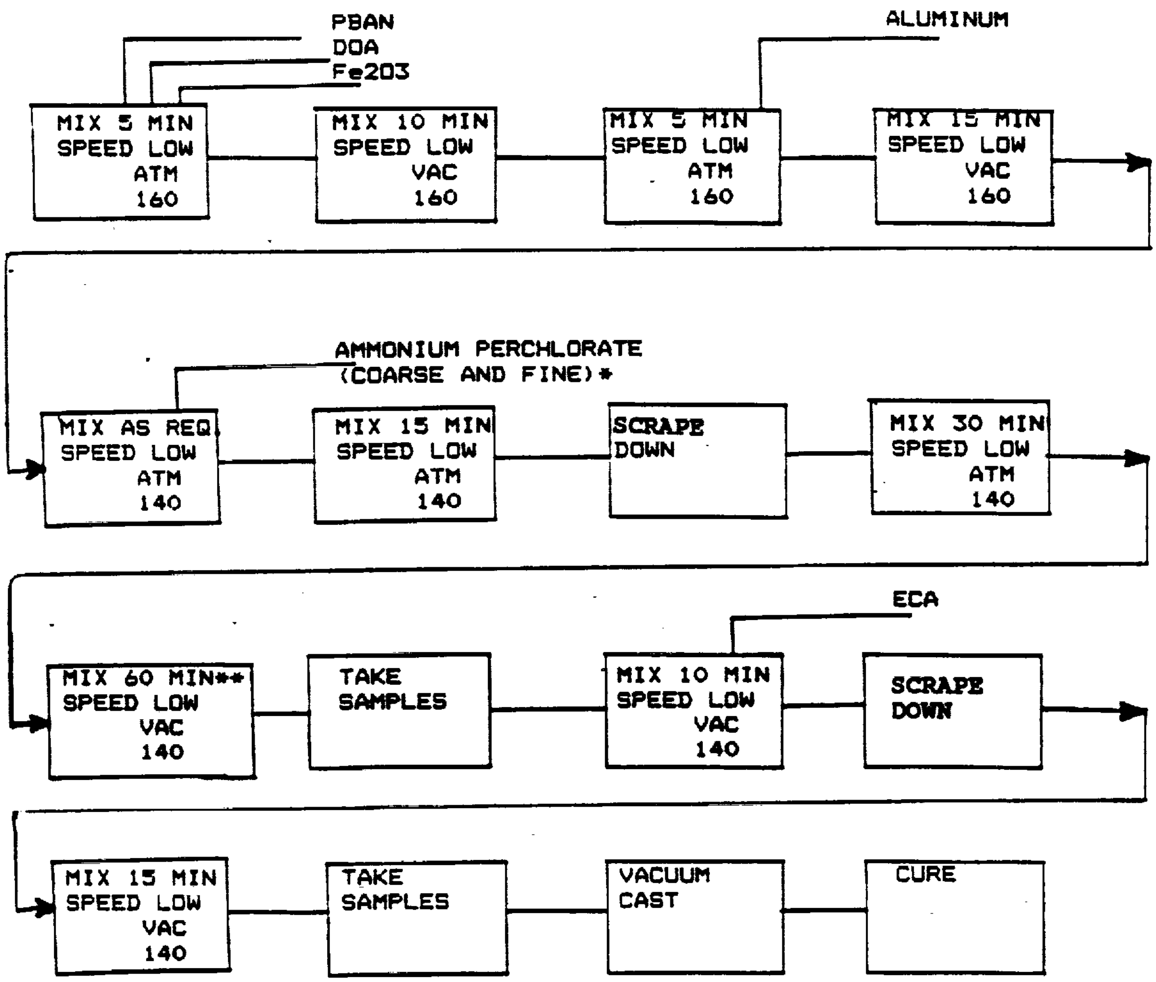


Fig. 6. Parameters involved in the manufacture of solid propellants.

Table 1. Ingredients for a typical propellant (EB-248).

Ingredient	Lot No.	Percentage	Weight (g)
Butarez HT	4760	4.1452	658.050
R45M		7.6395	1212.771
Alrosperse		0.2180	34.6075
Iso Stearyl Alcohol		0.5473	86.8839
A0-2246		0.1400	22.2250
IPDI		1.3100	207.963
MT-4		0.200	31.7500
Al 1230		18.00	2857.50
AP, unground 5272		47.60	7556.50
AP, grind 8		20.40	3238.50
TOTAL		100.200	

[a]Note that the actual numbers seemingly exceed 100% by weight.



*Alternate: Coarse-fine-coarse-...-coarse
**STORED RUNS: Store material at 140 . Mix for 30 min. before adding ECA.

Fig. 7. Mixing procedure for 150 gallons. (The numbers 140 and 160 are temperature in °F.)

Depressed Launch Profile Causes Concern Initially

Kennedy Space Center—Space shuttle's fourth launch, on June 27, caused concern among flight controllers when less-than-planned solid rocket booster performance created a depressed trajectory, lifting the vehicle lower and slower than desired during first-stage flight.

Columbia flew 8,000 ft. below its planned trajectory line, costing a theoretical 2,000 lb. in payload, Johnson Space Center engineers said.

The performance will be an issue for future flights. Engineers are investigating how booster performance is predicted prior to liftoff.

The depressed trajectory did not falter to the point where it seriously affected flight safety. Flight controllers were concerned that it would become a serious problem, but about 30 sec. into the lower trajectory the shuttle began correcting back toward the desired flight path.

Flight controllers said that if they had not seen a similar but smaller solid rocket booster digression on Mission 3, the Flight 4 solid rocket performance would have been even more of a real-time concern. The performance resulted in delayed abort mode calls to the crew and the separation of the solid rocket boosters at a lower altitude and at a slower velocity.

To compensate for the lower performance, the Rocketdyne main engines burned for 2-3 sec. longer than planned, expending about 2,000 lb. worth of the 12,000 lb. of payload performance margin carried by the vehicle.

Maximum Trajectory

Even with the depressed flight path, astronauts Navy Capt. Thomas K. Mattingly and Henry W. Hartsfield piloted the Columbia through its first maximum performance ascent trajectory, verifying the basic flight profile that will be employed most often in the shuttle program.

Mission 4 was the first to fly due east out of Kennedy Space Center, Fla., into a 28.5 deg. orbital incline. It is at this angle that the shuttle can benefit most from the Earth's rotation when boosting payloads into equatorial orbit. About 95% of shuttle missions flown from Kennedy will follow this profile.

Columbia's liftoff weight target of 4,484,585 lb. was about 5,000 lb. heavier than Mission 3. The high-performance trajectory was selected for this flight to assist vehicle propulsion with the heavier mass. The Defense Dept. payload weighed about 8,000 lb.

Immediately after liftoff from Launch Pad 39A, Columbia rolled 90 deg. to the right to establish a 090-deg. due east heading over the Atlantic. This was a departure from earlier missions when a 113-deg. or greater liftoff roll maneuver was used to direct the orbiter northeast into a higher 38-40.3 deg. orbital inclinations.

Columbia's ascent profile was structured using both solid and main engine performance data acquired on the first three missions as opposed to the earlier procedure of using analytical engine performance data. Flight directors expected this to provide a more accurate trajectory compared with predicted values.

A desire to increase the dynamic pressure envelope of the vehicle while at the same time providing a softer ride in the Mach 0.8-1.2 maximum dynamic pressure region, where additional data are needed, also dictated changes between this and previous launches.

Engineers achieved a higher dynamic pressure than during the last flight at a point later in the ascent in order to reduce the loads in the more critical Mach 0.8-1.2 region. The maximum dynamic pressure (Max-Q) for Mission 4 was targeted at 691 psf. compared with 648 psf. on the last flight and a maximum operational dynamic pressure limit of 760 psf.

Almost immediately after liftoff at 11 a. m., the vehicle began exhibiting characteristics indicating lower-than-desired solid motor performance. Main engine throttle down to 65% to reduce loads at Max-Q occurred 2-3 sec. late, and throttle up was also delayed. During first-stage flight the vehicle flies with open-loop guidance, where attitude is a function of velocity. The targeted throttle down from the 100% point was at 13.5 sec.

Vehicle angle of attack at Mach 1 was programed flatter than on Mission 3 to provide a more optimum performance for the heavier ascent mass.

Mission 4 ascent flight test objectives above Mach 1 allowed for a higher dynamic pressure in this regime. This was a change that allowed a higher performance/relative flight path angle in this phase of the flight compared with the first three missions.

At about 1 min. into the ascent, mission control center plots began showing a marked digression from the nominal trajectory line. This started controllers discussing the vehicle's energy state on the ascent flight director's communications loop.

Booster Separation

The flatter programed trajectory for Mission 4 had called for a solid booster separation altitude 5,750 ft. lower than on Mission 3. Actual solid motor performance on the flight, however, resulted in depletion of propellant and booster separation about 2,000 ft. short of that goal at a velocity of 4,293 fps. compared with the 4,336 fps. relative velocity target.

The overall Mission 4 solid booster separation parameters were for a lower altitude and a higher velocity separation in a flatter climb trajectory to provide more performance toward the 55-naut.-mi. main engine cutoff target.

The less-than-expected solid motor performance, however, resulted in a lower and slower situation than desired at this point, affecting abort and other vehicle energy milestones.

This became especially noticeable 2 min. 40 sec. into the flight, when Columbia was scheduled to be capable of achieving a Dakar, Senegal, emergency landing with one engine failed. The milestone passed with no notification of this capability from spacecraft communicator astronaut David Griggs in Houston.

The two-engine Dakar capability expected at 2 min. 40 sec. was not actually attained until about 3 min. 10 sec. Subsequent energy oriented milestones important for abort mode determination were delayed about 15 sec.

Throughout the remainder of powered flight on the main engines, the closed loop guidance phase that adjusts trajectory for the most optimum profile to achieve main engine cutoff targets took out the solid motor performance deficiency. Main engine cutoff was about 2-3 sec. later than planned, but was achieved at the 25,677 fps. velocity predicted.

The 55 mi. engine cutoff point was planned 3 mi. lower than on the last flight and also programed to occur at a higher vehicle flight path angle.

The ignition of the two Aerojet 6,000-lb.-thrust orbital maneuvering system (OMS) engines for the first OMS burn at 10 min. 32 sec. into the flight was observed through the Bermuda tracking station. The 1 min. 37.7 sec. burn provided a 154 fps. velocity change and an initial vehicle orbit of 130 × 33.3 naut. mi.

The second OMS burn was performed 37 min. 40 min. into the flight with the 175 fps. velocity change resulting in a 130 × 130 naut. mi. orbit completing the ascent.

Engineers believe more emphasis will be placed on how the thrust from specific solids can be characterized prior to each flight. ☐

Aviation Week & Space Technology, July 5, 1982

Fig. 8. Article regarding deficiency in solid propellant performance.[7]

Performance of Solids Revised Downward

Kennedy Space Center—Space shuttle solid rocket motor performance is being reduced as a result of the depressed trajectory flown on Mission 4 and new test data showing the motors have a slightly slower burn rate than earlier believed. The change had been a significant prelaunch issue for shuttle Mission 5.

Performance revision considerations were necessary because it meant that software commanding Columbia's Rocketdyne space shuttle main engines had to be reprogramed to provide a throttle schedule different from that originally planned.

The Thiokol motors that make up the United Space Boosters, Inc., solid rocket boosters still fall within specification limits even with their performance revised downward.

Initial shuttle Mission 5 liftoff planning was for throttle commands to reduce the main engines to 68% thrust to reduce accelerations when approaching Max-Q, the point at about Mach I when the vehicle encounters maximum aerodynamic pressure.

After finding the solid motors have a slower propellant burn rate than earlier believed, software commanding the main engines was changed so the oxygen/hydrogen powerplants would throttle no lower than 85% during launch to make up for the performance loss from the solids. This had to be done as a pre-liftoff measure.

During its fourth launch last June, the shuttle experienced what has been dubbed "the great depression," when lower than expected performance resulted in a depressed trajectory that missed solid booster separation altitude targets and affected the dynamic pressure experienced (AW&ST July 5, p. 20).

The boosters performed within specification on Mission 4, but the vehicle's programed trajectory during that launch was based on projections of higher performance. This resulted in a situation where modified vehicle steering and a slightly longer main engine burn time was needed to compensate. The situation was well within vehicle margins but resulted in delaying the availability of critical abort modes.

After that experience, the National Aeronautics and Space Administration and Thiokol started to determine how the motors could be characterized better before launch so the Mission 4 situation would not be repeated.

The earlier preflight characterization method was to use both ground test and flight motor data. These data then were combined with firing tests by several 5 × 12-in. tubes containing propellant from batches being used in the motors flying the upcoming mission. Between 48 and 52 small tube firing tests are done to characterize each motor before flight. The resulting data are used to help structure the trajectory from a performance standpoint.

The motor performance had been showing a slightly decreasing trend between flights one and three, but on Mission 4 the trend was more apparent.

On the last flight the propellant burn rate predicted was 0.366 in./sec. The actual burn rate was 0.359 in./sec., a difference that affected the trajectory significantly.

The NASA/Thiokol effort resulted in a decision to use only flight data in conjunction with the tube firing tests. This changed the scaling factor and has provided new expected burn rates that have been revised downward affecting Mission 5 prelaunch software preparation. Mission 5's original motor burn rate target was 0.368 in./sec. That has now been revised down to 0.365 in./sec.

Fig. 9. Article regarding revision of performance standards for solid propellants.[8]

Parameters Which Have Failed to Scale-up on Occasions	Description of the Specific Problem(s)	Parameter for Scale-up	Controlling Parameters	Propellants	Programs
Mixer power required to mix the propellant in the 600 gallon mixer.	In the scale-up of the [illegible] First Stage propellant, TP-H1207, the mixers kept kicking out on the upper power limit. During one of these occasions, the drive belts were actually burned in half.	To correct this problem, vacuum was pulled on the propellant in a slow stepwise manner. In this manner, the power requirements could be controlled.	Unknown. One theory is that the gas produced by the reaction of [illegible] with the AP adhering to the AP particles [illegible] additional polymer to form bubbles when vacuum is applied.	TP-H1207	[illegible]
Mechanical properties of the propellant failed to match those of the subscale standardization mixes.	During the scale-up of the [illegible] propellant, the stress in the 600 gallon mixes were lower than the one gallon subscale mixes.	The one gallon mixes were processed with a lower sweep rate to match the 600 gallon mixer sweep turnover rate. However, at this low sweep rate, variations were too great so a bias was just applied to the properties of the high sweep rate.	The reaction of the [illegible] with the AP produced [illegible] which adheres to the fine AP particles and cannot be removed without sweep [illegible].	TP-H1175	[illegible]
Mechanical properties of the propellant failed to match those of the vertical mixes processed in the horizontal mixer.	When the igniter propellant, TP-H1137, was scaled up to the 75 gallon mixer on occasion the mechanical properties were greatly reduced even though there was no vacuum mixing in the process.	The Argon sweep used to keep the propellant dry was stabilized at a constant level. This action was based on the effects noted in mixes processed with and without Argon sweep.	Unknown. This propellant contains [illegible]-712 which is not supposed to produce [illegible], however, the propellant acts the same as those which do produce [illegible].	TP-H1137	[illegible], [illegible]
The burn rate of the propellant scaled up to the five gallon mixer was lower than predicted.	When five gallon mixes of [illegible] propellant were processed, we had trouble feeding the AP. When the motors were fired, the burn rate was very low.	We now have weighed requirements on the hot [illegible] AP is screened and weighed up. This action was based on mixes processed in which the AP was screened and weighed in a dehumidified bay.	Unknown. The theory is that the water in the air caused the AP to agglomerate as it was screened.	[illegible]	[illegible]
The viscosity curve of the propellant failed to scale up.	When 600 gallon mixes of TP-H1035 propellant were processed, the low shear rate viscosity was about three times that of the five gallon standardization mixes. This caused the propellant to stick so badly that marginal motors were cast.	None. No more 600 gallon mixes were processed but subscale mixes of the propellant produced the same viscosity curve when exactly the same materials were used.	It was believed that slight changes in the particle size distribution of the [illegible] had caused the slope of the viscosity curve to shift up and cause the problem.	TP-H1035	[illegible]
The propellant casting properties failed to scale up.	When the TP-H1030 propellant was scaled up to the 600 gallon mixer and cast into a 37 in. motor, the aft end of the motor failed to fill in around the fins causing numerous voids.	The propellant AP particle size distribution was changed to reduce the high apparent viscosity at the low shear rates. In addition, the propellant level in the cast funnel was increased to provide a better seal.	It appears that the small changes in fine ground AP used to adjust the burn rate of the propellant has a drastic effect on the viscosity curve.	TP-H1030	[illegible]
The casting rate of the propellant could not be properly predicted.	When casting TP-H1030 propellant into the 37 in. motor from a 600 gallon mix, the casting rate was about twice that predicted.	Casting differential pressure was adjusted to provide a reduced casting rate in the 600 gallon casting system.	Unknown. It was felt that slip at the wall or incorrect extrapolation of the viscosity curve caused the error.	TP-H1030	[illegible]
Cure rate/pot life of propellant.	The mix of TP-H1030 propellant processed in the 600 gallon mixer cured up solid in the mix bowl during the casting operations.	The pot life curves were run at three different temperatures to determine the effect of temperature on the pot life. Following this, the end-of-mix temperature was reduced by 10°F. In addition, the pot life of the propellant was monitored every half hour to catch any step up in the viscosity signaling the onset of cure.	The cooling effect noted on composite 600 gallon mixes didn't take place because the bottom discharge bowl was used. Thus, the pot life being run at 120°F didn't represent the true cure curve of the propellant which was actually 130°F in the mix bowl.	TP-H1030	[illegible]
The burn rate of the propellant in the 600 gallon mixer.	The burn rate measured in the 600 gallon mixer by liquid strands and subscale motors were about 0.030 in./sec less than subscale mixes using the same formulation and materials.	The verification mix will be repeated and the material removed from the bin for subscale mixes will be obtained using a thief sampler.	Unknown. The sampling of the bins used in the 600 gallon mix to obtain raw materials to process the five gallon mixes is the suspected cause. The [illegible] micron AP is noted to [illegible] during grinding with the coarse material going to the side of the bins. It is assumed that the samples for the subscale mixes came from the top of this [illegible].	TP-H1207C	[illegible]
The cure time noted on the early subscale mixes failed to scale up.	The first mixes of TP-H1207C using TPB cured in 4-5 days at 135°F. The time to reach level stress on the 600 gallon verification mix was 12 days.	Investigation is proceeding. To date, additional 600 gallon mixes have not been processed.	Unknown. TPB is known to require an acid environment to chemically change into the species which is the actual catalyst in the polymer reaction.	TP-H1207C	[illegible]
Soft spots and soft streaks were observed in the larger mixes.	When the TP-H1175 propellant was scaled up to the five gallon mixes, soft spots and soft streaks were noted in the mechanical properties samples. This soft, smearing propellant was also found in the 600 gallon mixer.	The bowl sidewalls were scraped all the way to the bottom prior to curative addition in the five gallon mixes. Then later, the mixer blades were replaced with those which provide half the original clearance blade to bowl. In the 600 gallon mix bowl casting system, the propellant from the walls was not sent through the system; they just stop before the wall propellant goes into the casting tube.	The high viscosity of the propellant which formed a film on the bowl wall could not be sheared away once the bulk viscosity was lowered quickly by the addition of [illegible].	TP-H1175	[illegible]
A film of cured-like propellant formed on the surface.	The mix of TP-H1175 was prebatched and sealed with Argon purge. When the mix was final mixed, the process was repeated. When the lid was removed in the casting area, a "cured" film was noted on the propellant surface.	The [illegible] used was allowed plenty of time to cure prior to the part being used around propellant.	The hose and lid used to purge the mix bowl prior to storage and shipping to the casting area had been sealed with [illegible] and the acetic acid involved in the cure of the [illegible] reacted with the propellant ingredients to cause the problem.	TP-H1175	[illegible]
The propellant cured but had soft, tacky areas.	The propellant cast into the first stage slot former area was soft and tacky. There were also "spots" of soft propellant in the aft [illegible] relief ring area.	The [illegible] parts were vacuum dried at high temperature for extended periods of time to allow the alcohol time to diffuse out of the [illegible] part before it was placed in the motor tooling.	The soft propellant areas were caused by the alcohol formed by the cure of the [illegible] in the aft [illegible] relief ring and the slot former. The alcohol then reacted with the curative in the propellant retarding its cure.	[illegible]	[illegible]
Mechanical properties failed to scale-up.	The mechanical properties of the 600 gallon mixes were not as good as the subscale mixes and [illegible] of the propellant solids was [illegible].	The time which the prebatched propellant was stored was increased to a minimum of 24 hours.	The prebatch time serves two purposes. First, it allows the polymers to wet the solids and second, it allows the chemical reactions to proceed to completion.	TP-H[illegible]	Standard Missile
Burn rate of the propellant failed to scale-up.	The burn rate of the Minuteman First stage propellant varied over a considerable range as a function of the time prior to addition of the [illegible].	The mix time of the oxidizer blending step of the mix cycle was tightly controlled to maintain the same burn rate throughout the scale-up process.	The blending of the dry oxidizer in the horizontal mixer was actually grinding the AP by attrition.	TP-H1011	Minuteman I
Burn rate of the propellant.	The burn rate of the Minuteman First Stage propellant, TP-H1011, increased as a function of time the polymer was stored in the tank farm.	New tanks were fabricated from stainless steel to eliminate the corrosion of the mild steel.	The iron from the mild steel tanks in which the [illegible] polymer was stored was acting as a burn rate catalyst.	TP-H1011	Minuteman I

Fig. 10. Discussion of anomalies presented by Thiokol [report to Jet Propulsion Lab].

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More important than the arithmetical accuracy of the results was the first recognition that this complex problem may be amenable to scientific analysis after all. The point to note here is that the importance of such work was recognized long before 1986. The letter from Professor Summerfield (Appendix E) documents this.

A major step toward a scientific delineation of the quality assurance in solid rockets was taken at MSFC via the report "Solid Propulsion Integrity Program Technical Plan" (Preliminary Rept. No. 2-1635-7-14). Clear recognition was made of the fact that

> in process management of particle size distribution, surface area and concentration of critical ingredients such as iron oxide, aluminum oxide and ammonium perchlorate should be developed, or improved. Measurement of in process viscosity is important and needs improvement. Process controls need to be evaluated for the capability of providing control of the important parameters within the necessary limits as they become known.[12]

A briefing to industry by Richard Brown[12,13] also has important details and future plans to minimize surprises.

A program was established at JPL by Code M and MSFC to study these problems. As part of that larger program, one low-level effort in 1984-85 indicated the importance of actual temperatures as contrasted with global mixer jacket temperatures, for example. Especially in a large mix, it was shown that the actual propellant temperature could not only differ from the jacket temperature, but differ at different locations within the mix itself (Fig. 11). A simple Arrehenius rate cure analysis indicated that increases of only one to two degrees Fahrenheit in the mix temperature could result in a decrease of two to three percent in the burn rate of the cured propellant. This simple quantitative estimate was made in an unpublished interoffice memorandum at JPL in 1984. It is likely that one or two degrees difference in the mean temperature could be indicative of five or more degrees difference in local temperatures in the slurry, which could lead to significantly different curing rates, especially if these differences occur after the addition of the curing agent (see Fig. 12). A very careful entry was attempted of literally thousands of data points (mostly from JPL data sources obtained in a nozzle evaluation rocket program) in an unfunded study at the University of Arizona. This data base was generated on a PC by Hal Hikita.

At this point, it would be useful to recall two important aspects of solid propellant predictability. First, the number of parameters is so large that a traditional scientific formulation and analysis may be very difficult, even with the availability of large computers. Second, the key processes that finally result in the cured propellant (and its combustion) must be well understood in order to even look for meaningful trends. What this means is that unconventional approaches may be necessary to obtain a good feel for the variabilities and variations. In other words, we may have to make educated guesses about the probable influences before subjecting the data to a more careful scrutiny.

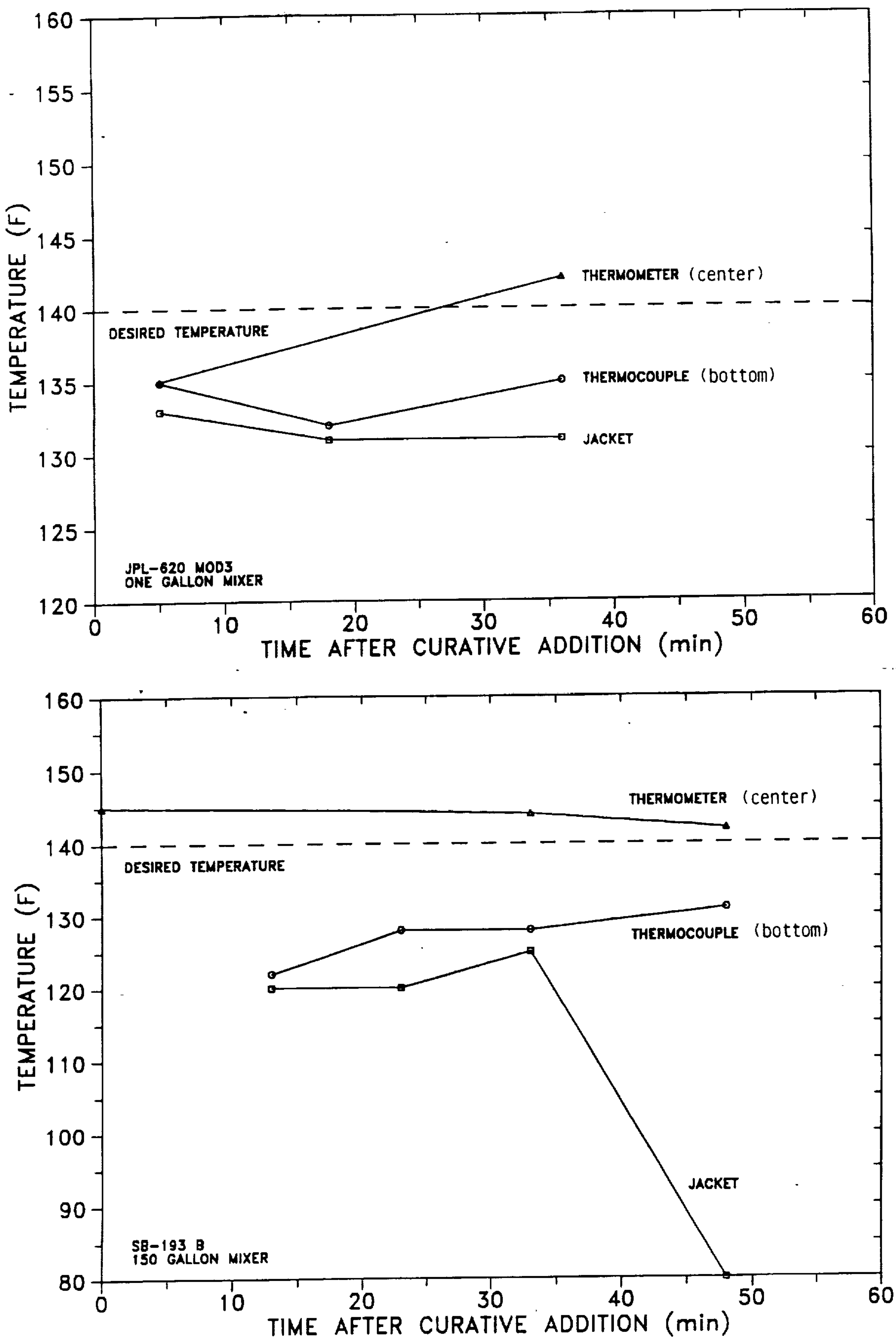

Fig. 11. Actual propellant temperatures in different locations in the mix.

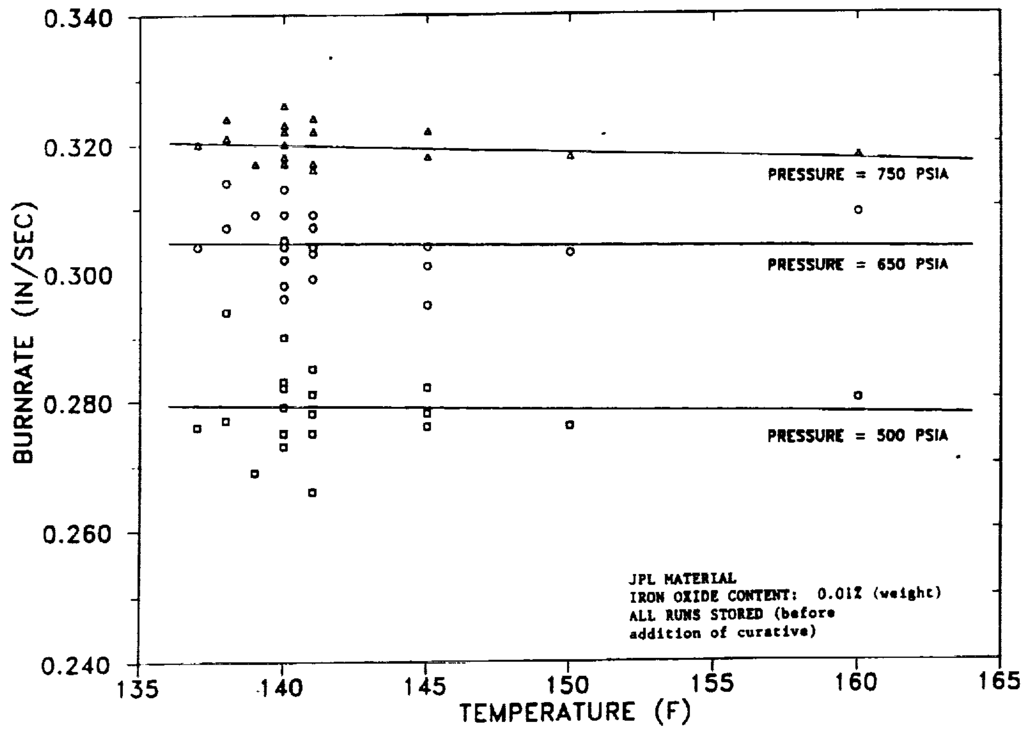

Fig. 12. Burn rate dependence upon maximum last mix stage temperature.

The author feels that it may be instructive to digress here and present two non-technical examples from Sir Arthur Conan Doyle. In the first example, investigators are attempting to reconstruct the events in the night that led to some unfortunate mishaps. Sherlock Holmes guesses that a candle light may have been used in the night, looks for a half-spent candle, and indeed finds it. If he had not looked for it, the candle would not have been found because of all the mud and slush. In another example, he is faced with extracting all the information he can from a small note written hurriedly on the back of a breakfast receipt at a hotel. While Lestrade is preoccupied with the contents of the note, Sherlock Holmes is more fascinated by the very expensive breakfast; this leads him to the hotel where the note was written. That is, what was merely "noise" to Lestrade was indeed the "signal" to Holmes. In a field as complicated as solid propellants, unorthodox and unconventional approaches are necessary to help introduce economical solutions. It is emphasized that such unorthodox approaches should be used only to *narrow down the field of our search* and should not be used as substitutes for scientific and mathematical solutions. End of digression!

Correlations were attempted based on scientific criteria; in the absence of guiding scientific analyses, attempts at obtaining correlations among these extensive sets of data would have been both meaningless and futile. Two of the most important correlations were seen between the end-of-mix viscosity and the burn rate (they are anti-correlated), Fig. 13, and between the shore A hardness and the burn rate (Fig. 14). The significance of these

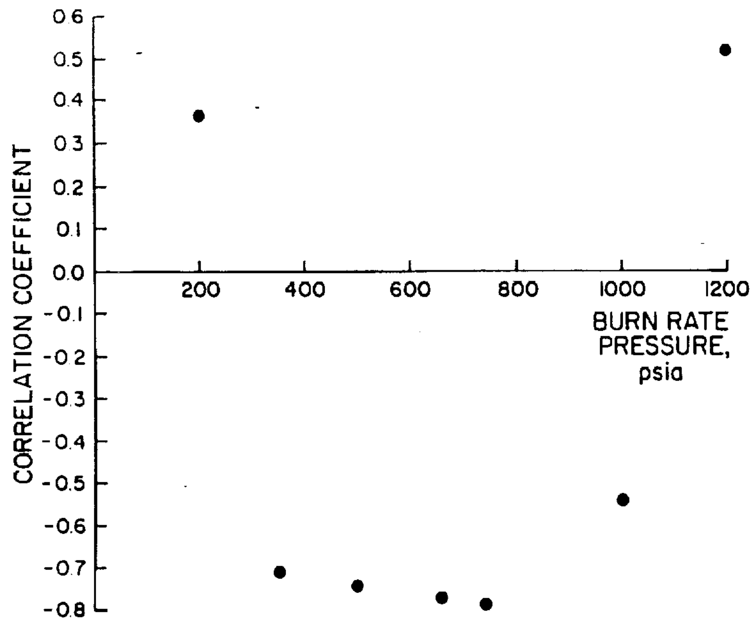

Fig. 13. Burn rate-end of mix viscosity correlation coefficient versus pressure.

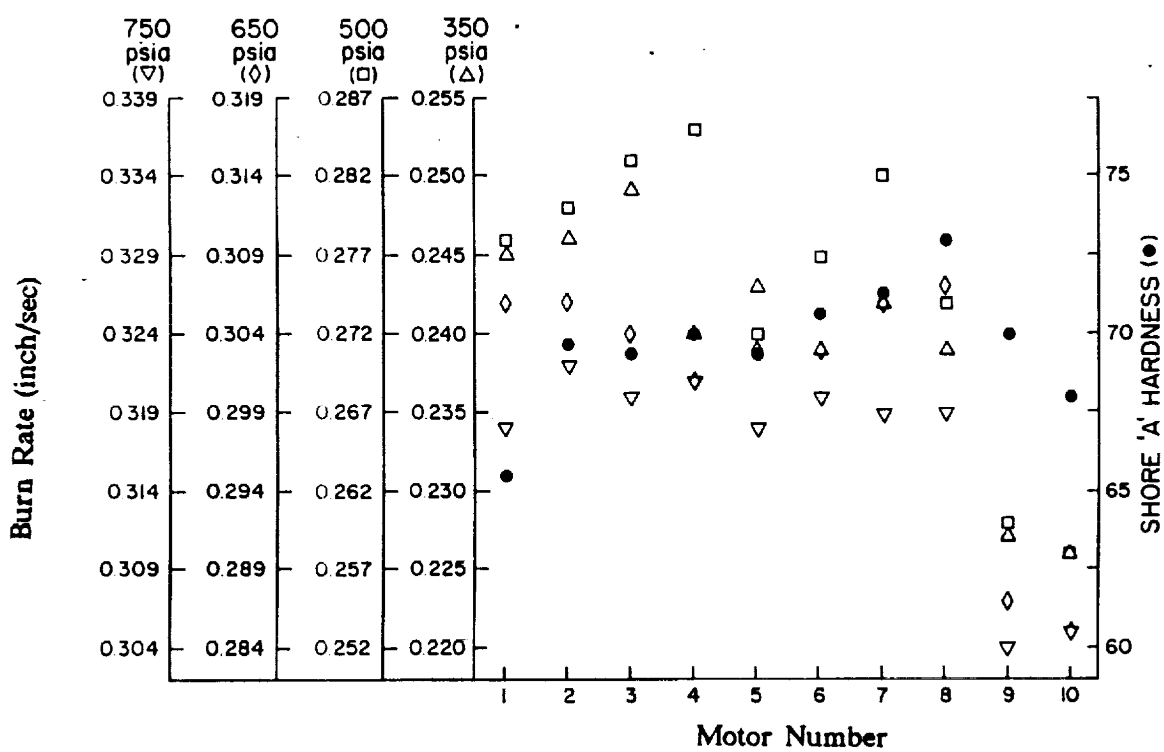

Fig. 14. Shore A hardness/burn rate data.

was described elsewhere.[14] The mention of viscosity as a parameter does not mean that the determination of viscosity is simple, or easy. Measurement (and interpretation) of viscosity of a high solids slurry is by no means well understood. We find that in-situ measurements (where possible), batch-interrupt measurements, and others give different values. The rate of shear is very important. Recent results have also shown that the orifice diameter and edge shape can influence the measured values. In a senior design project, two students built a viscometer that gave continuous real-time viscosity in a mixer that used high-viscosity fluids, simulating propellants. The apparatus was somewhat larger than what could be conveniently included in a practical propellant mixer, but has provided a first step in a highly desirable approach. The main point to note is that the important parameter, namely slurry viscosity, does not appear to be measurable in an unambiguous way at the present time.

More recently, five other plots were discovered to be significant in information content.[15] In Figure 15, we see the non-uniformity of the oxidized particles in the slurry. The composition near the blade is not the same as the bulk values. The basic message is that important pieces of information are available on the manufacturing of propellants. More are needed.

Long-Range and Short-Term Objectives

Development of a fundamental and scientific understanding of the complex processes involved in solid propellant manufacture and end use (combustion in a rocket motor) will need a commitment and should involve a well-coordinated nationwide effort among NASA, DoD, industry, and the universities. Meaningful results that will prove their use in quality assurance and predictability can be realistically expected in ten years after the initiation of such an effort. The results will quantitatively relate the performance of a rocket motor (the thrust time curve, for example) to the ingredients and processing variables; the program will also evolve unambiguous *a priori* rules for **effecting** desired changes in propellant systems. For example, one of the main results will be to evolve a table indicating the effect of propellant (slurry) mix temperature and the end-use burn rate. Another example is the prediction of the burn rate as a function of pressure as the curve is influenced by the variance of the fine particle size distribution from the mean. Yet another example may be the precise prediction of the burn rate when the shape of the coarse particles is specified as a deviation from spheres.

In a field that is as important and current as solid rockets, it would be appropriate to demand more immediate results. Recent work[14] has clearly indicated the definite promise of such results. For example, it was shown that the final mixing time has a measurable

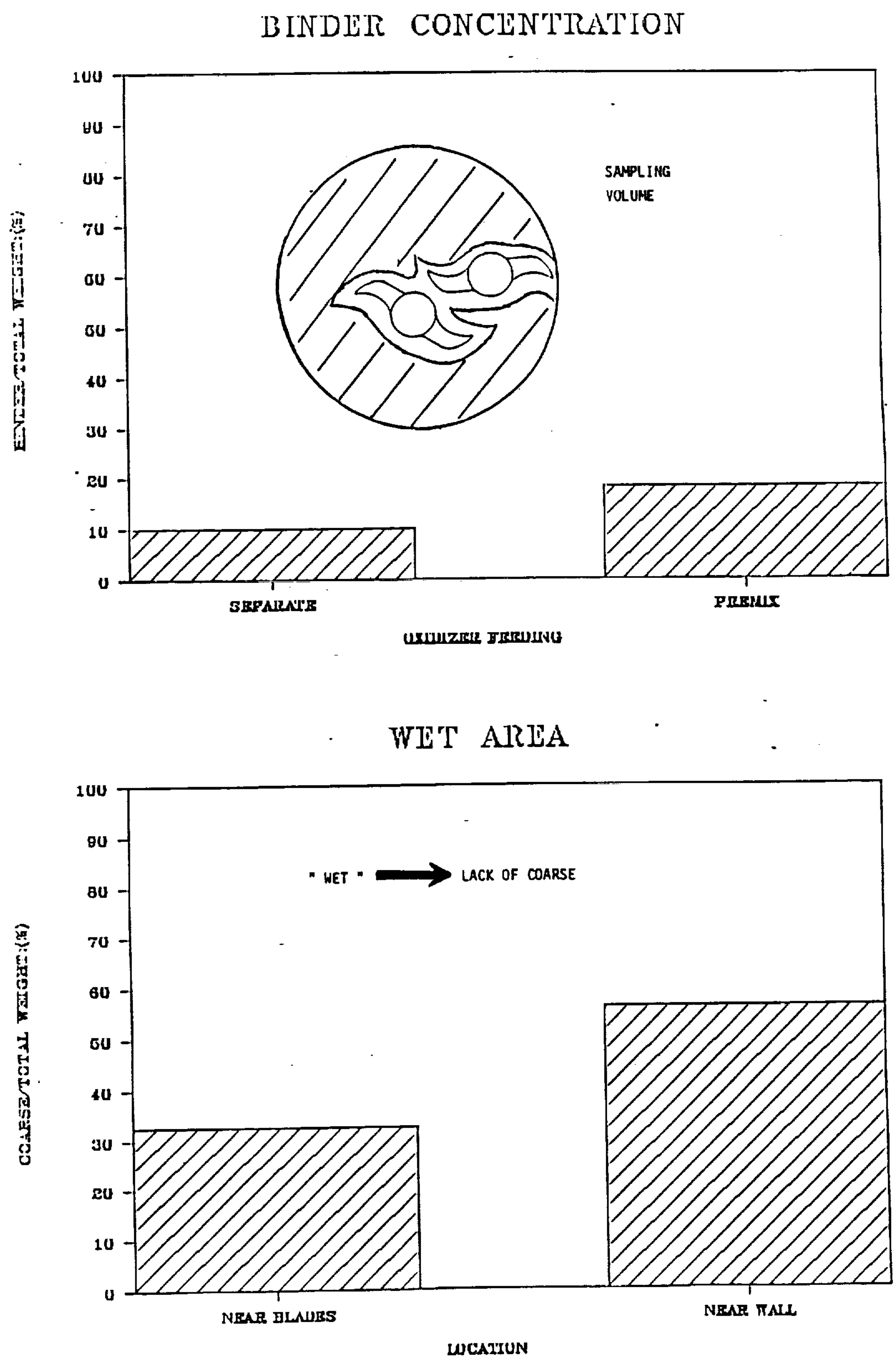

Fig. 15. Non-uniformity of oxidized particles in slurry.

effect upon the burn rate and the Young's modulus of the cured propellant. It was also shown that the end-of-mix (EoM) viscosity is a definite indicator of the burn rate variation of the cured propellant. Such quantitative observations are significant. For example, the processing could carefully monitor the slurry viscosity continuously, and when the viscosity deviates beyond a specified bound, corrective actions would be initiated. This would avoid the costly waste of the production of a full-scale motor of substandard, or unacceptable, quality. To some extent, such observations are indeed in use at the present time. The author admired the judgment of Joe Hance (who, incidentally, directed the processing and production of the T-17 propellant that was successfully used in Explorer I), who would make a decision to stop the processing of propellants based merely on observation of the "quality" of the slurry; the explanation would usually be something like, "the LP-3 had probably deteriorated during storage." This admiration invariably turned quicky into frustration upon realizing that solid propellant quality assurance was not scientifically prescribed, but depended instead on the feel of experience. In the short-term, a program, such as the one discussed in this report, would evolve quantitative, if semi-empirical, rules that will be useful in processing. The qualitative feel of experience will be made scientifically respectable and technologically acceptable through independent verifications. The point is that the benefits of a fundamental program will be felt immediately. These short-term objectives will be to provide clear, dependable guidelines for economical processing and a list of measurable parameters that give a tell-tale signal of the health of the propellant.

The Legacy of Black Art

Solid propellants have also suffered from their legacy of black art. Many of their manufacturing techniques cannot be traced to scientific evolution. The detailed batch sheets and SOPs (Standard Operating Procedures) are usually the result of experience. It would be most useful to revisit some of these.

Solids Versus Liquids

There appears to be a growing feeling among many concerned[16] that eliminating solid rockets altogether, in favor of liquids, would completely "solve" all problems. The absence of a Challenger-class (liquid rocket) catastrophic failure[17] belies the extreme vulnerability of liquid rocket motors. It would be wise to recall that there have been a number of near misses with liquid rockets in recent years. The major problems are systematically outlined by Feynman:[18]

- Turbine blade cracks in high-pressure fuel turbopumps (HPFTP). [May have been solved.]

- Turbine blade cracks in high-pressure oxygen turbopumps (HPOTP).
- Augmented spark igniter (ASI) line rupture.
- Purge check valve failure.
- ASI chamber erosion.
- HPFTP turbine sheet metal cracking.
- HPFTP coolant linear failure.
- Main combustion chamber outlet elbow failure.
- Main combustion chamber inlet elbow weld offset.
- HPOTP subsynchronous whirl.
- Flight acceleration safety cutoff system. [Partial failure in a redundant system.]
- Bearing spalling. [Partially solved.]
- A vibration at 4,000 Hertz making some engines inoperable, etc.

There have also been major catastrophic failures, involving key components, in static tests. The dramatic explosion of Ariane Spot 1's third stage provides a flight example in recent times (November 1986). Another serious problem with liquid propellant rockets is beginning to be recognized lately. This is the potential for **orbital debris** creation. While the exact cause is not yet known, many believe that a debris hit caused the Ariane third-stage explosion in 1986 (Fig. 16): **"Officials believe the most likely cause of the explosion was the detonation of residual oxygen/hydrogen propellants in the vehicle".**[19] This "Ariane Spot 1 rocket body represents the single greatest source of debris now in orbit about the earth."[20] The pressure-fed systems used in liquid rockets are a source of catastrophic explosions upon impact. Many other problems include leaks, toxicity hazards in the vacuum of space, and extreme low temperatures in the vicinity of cryogenic tanks; many serious problems in several operational spacecraft have indeed been traced to these sources. Mechanically, liquid rockets are far more complex than solid rockets--a fact that has frequently forced long dealys in launches due to last-minute repairs. At the fundamental level, the combustion processes of the liquids (providing thrust) are no better understood than those of solids. It would be prudent to keep all options alive at this time, and for the foreseeable future, unless a major advance is made in liquid rocket reliability and safety. After all, it is its intrinsic simplicity that has made the solid rocket so attractive for centuries. This simplicity allows for a great flexibility in the size of the motor at little cost. A well-proved solid propellant can be loaded into motors of any size. In extreme cases, a piece of propellant from a larger motor can be cut, loaded into, and used in a smaller motor. Such flexibility is totally absent in liquids, which still need the full system of components in the smaller motor.

We cannot give up the proven merits of the solid motor simply because some problems remain unsolved; in fact, the merits provide a strong motivation for scientifically solving these few remaining problems.

Used Ariane Stage Explodes, Creating Space Debris Hazard

Washington—A European Ariane booster third stage launched nine months ago exploded in space Nov. 13, creating potentially hazardous orbiting debris and prompting a U. S. request that Arianespace investigate the incident to prevent a recurrence.

The Ariane 1 stage had been used Feb. 22 to launch the French Spot 1 Earth resources satellite (AW&ST Mar. 3, p. 21).

The explosion could result in changes to avoid such incidents and limit the buildup of debris orbiting Earth, according to Frederic d'Allest, president of Arianespace.

The explosion of the spent stage is not believed to be linked to problems experienced in the oxygen/hydrogen system during powered flight. The Ariane third stage has failed three times, most recently on May 30 (AW&ST June 9, p. 21).

Before the explosion, the White House, State Dept. and National Aeronautics and Space Administration had begun an effort to alert international space agencies to the debris issue.

The Ariane stage was orbiting in about a 490-mi. Sun-synchronous polar orbit inclined 98.7 deg. when it exploded. The force of the explosion threw debris into orbits as low as 270 mi. and as high as 840 mi.

The incident occurred at 7:39 p. m. GMT Nov. 13 just after the Ariane stage passed the equator on a northbound path over the central Atlantic between South America and Africa.

Ground Tracking

U. S. Air Force Space Command and Navy Space Surveillance System radars are tracking about 200 pieces of debris one-half inch in diameter or larger. This suggests the presence of several hundred or thousands of smaller particles impossible to track with ground-based radars. Even a small particle orbiting at high velocity could cripple or destroy a spacecraft—manned or unmanned—were a collision to occur.

Officials believe the most likely cause of the explosion was the detonation of residual oxygen/hydrogen propellants in the vehicle. Space Command conducted computer analyses to determine whether the breakup was caused by collision with other space debris. Radar data, however, show no other trackable debris in the area.

Space Command analysts believe that other Ariane third stages launched into geosynchronous orbit may have exploded after long exposure in space. Evidence comes from tracking apparent debris from these vehicles, although such fragments are extremely hard to track since they orbit above the equator, where the U. S. has minimal radar capability. The Spot 1 stage was flying in an orbit where tracking is far easier.

Although the odds of collision with a useful satellite are small, many spacecraft have orbits that pass through the area in which the Ariane debris has dispersed.

There also is significant debris in this area from seven U. S. Delta second stages that exploded years ago after prolonged exposure to the space environment. The Delta incidents created a continuing space debris problem and subsequent Delta stages have been modified to prevent potentially explosive conditions from building. □

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Fig. 16. Article on creation of space debris.[19]

Some Simple Approaches

Composite solid propellant predictability and quality assurance can only come through adequate control of the ingredients and processing. As was evident throughout this meeting, and other information sources, we are beginning to identify some of the more important parameters that one must control and for which specifications must be established. After such specifications are proposed, they must still go through a series of independent verifications, different scales of mixers, different sizes of motors, and different firing conditions before they can be well received, accepted, and followed. In the meantime, some of the more straightforward procedures that the author has followed are described here.

1. Simple Physical and Chemical Examination of the Oxidizer.--Very simple SEM/EDAX examinations of the AP, as received, can be quite revealing. Shown in Figs. 17 and 18 are AP crystals from two sources; Fig. 17 shows AP from a source in the USA, while Fig.18 shows AP from a Japanese source (Nahun Kaleet). The differences are dramatic. Not only are the Japanese AP much more spherical, but their sizes are far more uniform; the particle size seems to approach a unimodal distribution. Prilling produced the near spherical AP in Fig. 18. The precise quantitative influences of this difference in **shape** on the processing, cast, cure, and combustion are not clear. It would seem obvious that there will be substantial differences. While this example is intentionally chosen here to make a point, the utility of simple SEM examination of as-received AP should be obvious, even when the shape differences are not this dramatic. [It is most interesting that nearly three months after these shape influences were discussed at this meeting, a paper discussing very similar concerns and data was presented at the AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey California, July 10-12, 1989.[21]]

2. Simple SEM Examinations of the Cast (Cut) Propellant.--Scanning electron microscopy has been extensively used in the diagnostics of quenched samples from combustion experiments; the pioneering work at NOTS/NWC is most familiar to those in the field of composite propellants. However, the use of SEM for simpler examination of cured propellants is not that prevelant. In one of the programs on low-smoke, high-burn-rate AP propellants, some candidate propellants exhibited unacceptably poor reproducibility (Fig. 19). Pressed for time, we attempted a simple SEM examination of the cured propellants. In Fig. 20, the propellant looks fairly good in terms of mixing, voids, and the coarse/fine distribution; this was indeed the propellant that burned reproducibly. In Fig. 21, we see a very different pattern. The propellant does not appear to have mixed well, voids are present, and the coarse/fine distribution does not appear to be uniform. This was indeed a

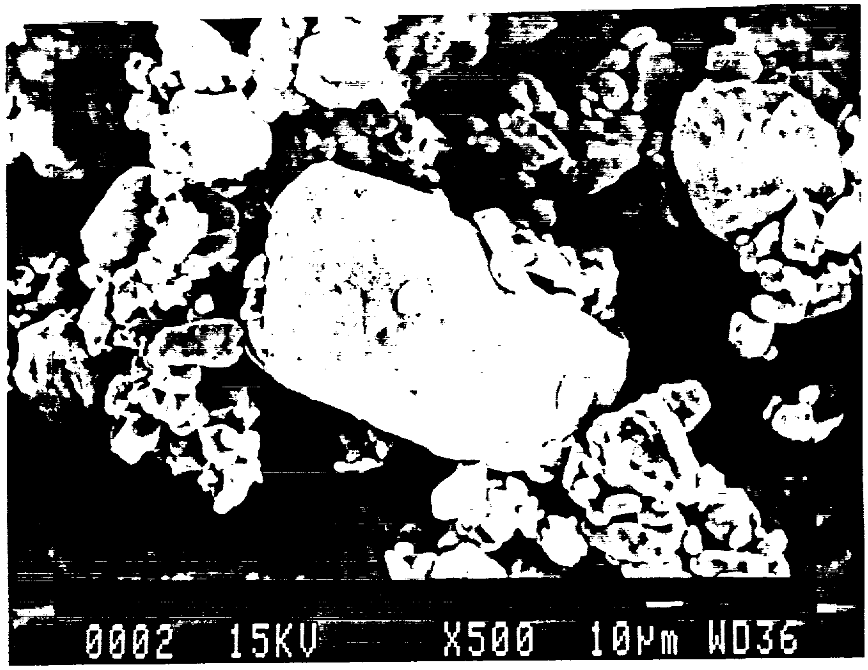

Fig. 17. AP crystals obtained from a source in the United States.

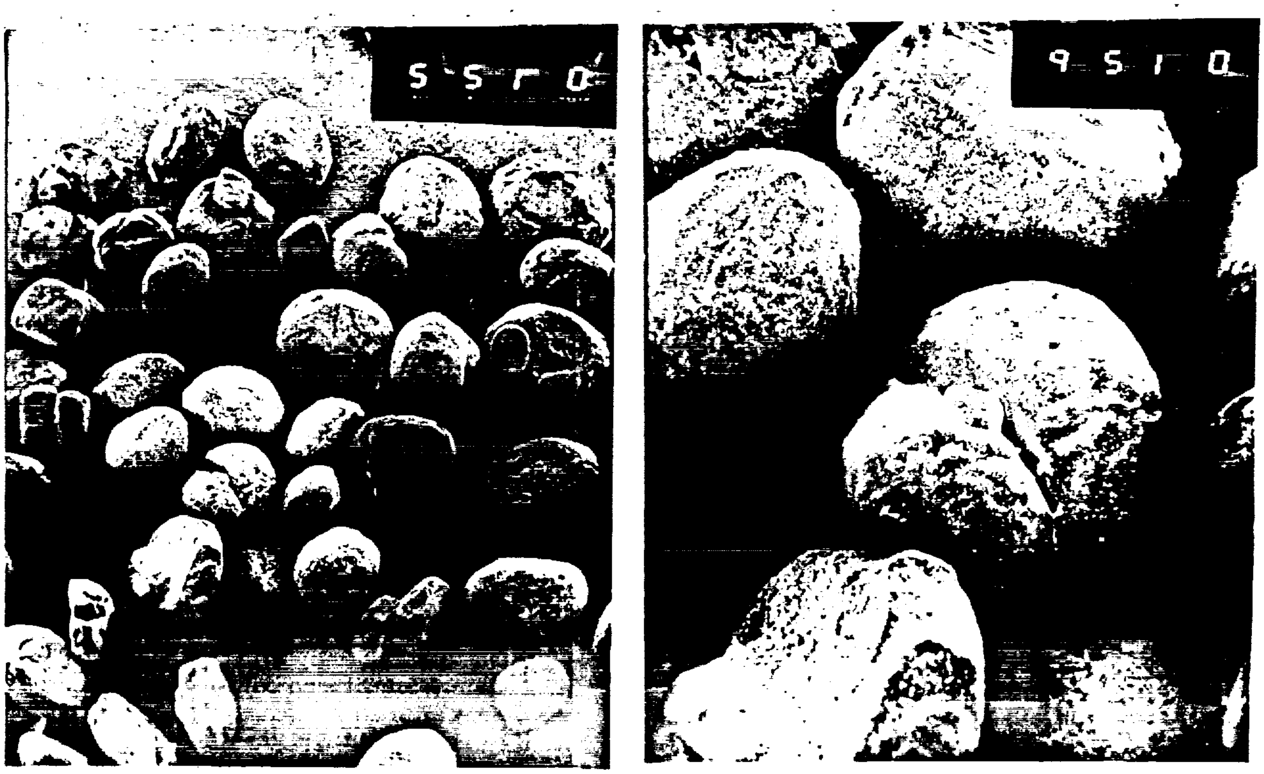

Fig. 18. AP crystals obtained from a source in Japan.

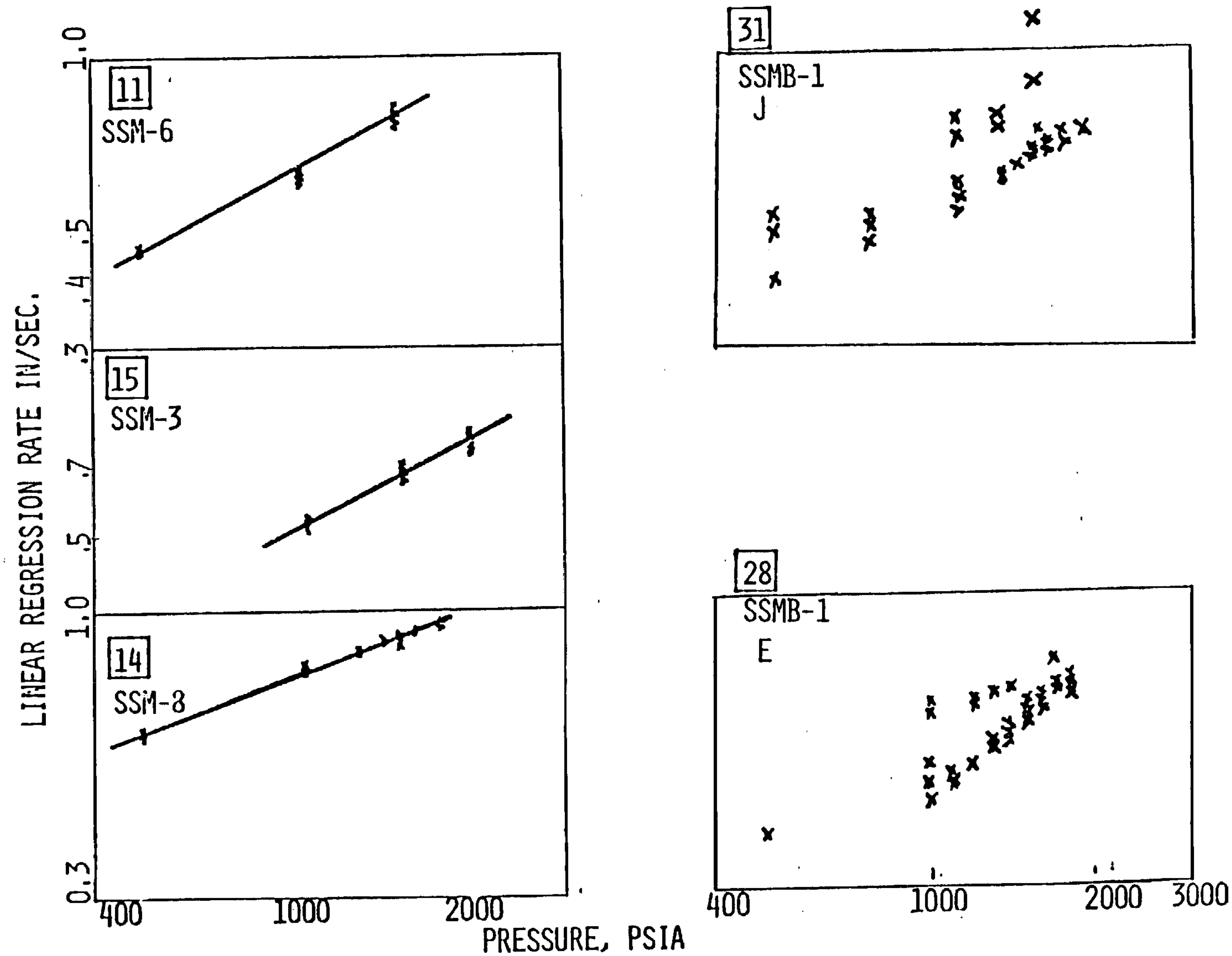

Fig. 19. Time-independent combustion in the Crawford bomb.

propellant that burned in a non-reproducible manner. While these SEM examinations do not solve the problem, they can economically reveal the problem source.

3. Complete Examination of the Particle Size Distribution.--Many ingredients in composite propellants are particles. Examples include coarse AP, fine AP, and aluminum. These particle sizes were designated by the commercially convenient 50% weight average point. This is wholly inadequate for our purposes. Different distributions can have identical 50% weight average points. Shown in Fig. 22 are two such distributions. Their influence on combustion was acutely felt in one program. A solid rocket motor was developed with the first grind and was stable within the pressure range of interest in a double BATES motor. Having exhausted our supply of fine AP, we borrowed some AP of the "same size" from a nearby laboratory to complete the motor tests. The new batch of motors went unstable in firing tests. As is evident in Fig. 22, the second AP had a narrower distribution, with the 100% weight average point at 20 microns, as contrasted with 40 microns for the first AP. A simple computation of natural propellant frequency (mean burn rate divided by the 100% weight average point of fine AP) shows that the frequencies for the two propellants are substantially different. In the first case, the frequency was not close to any of the natural acoustic frequencies of the rocket motor cavity; in the second case, it was. This example from 1973 may seem a little archaic. Today, more complete particle size analyses are indeed routine. Nevertheless, this experience is typical of many other ingredient characterizations that are inadequate to ensure quality and reproducibility in solid rockets.

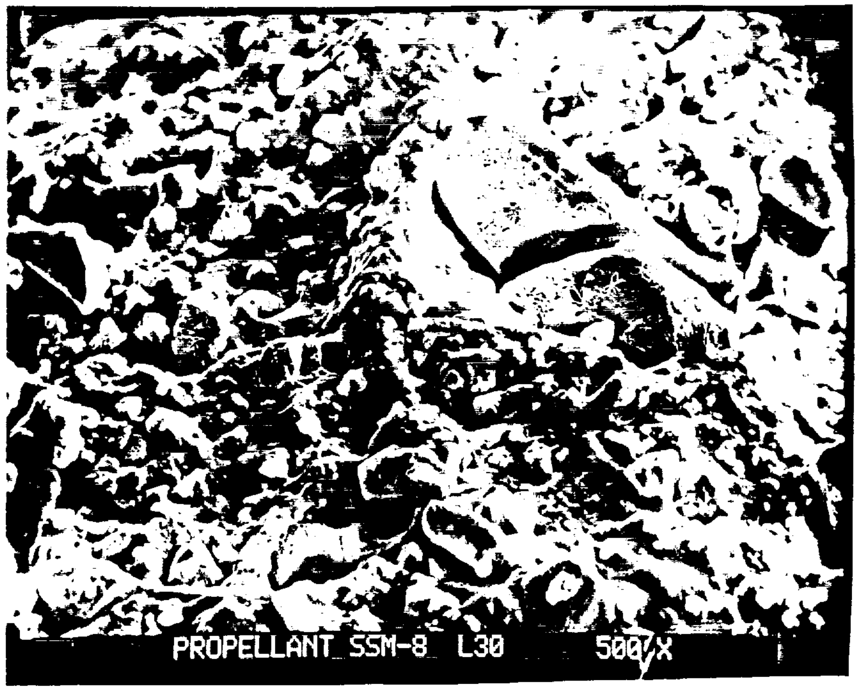

Fig. 20. A propellant whose burn could be reproduced.

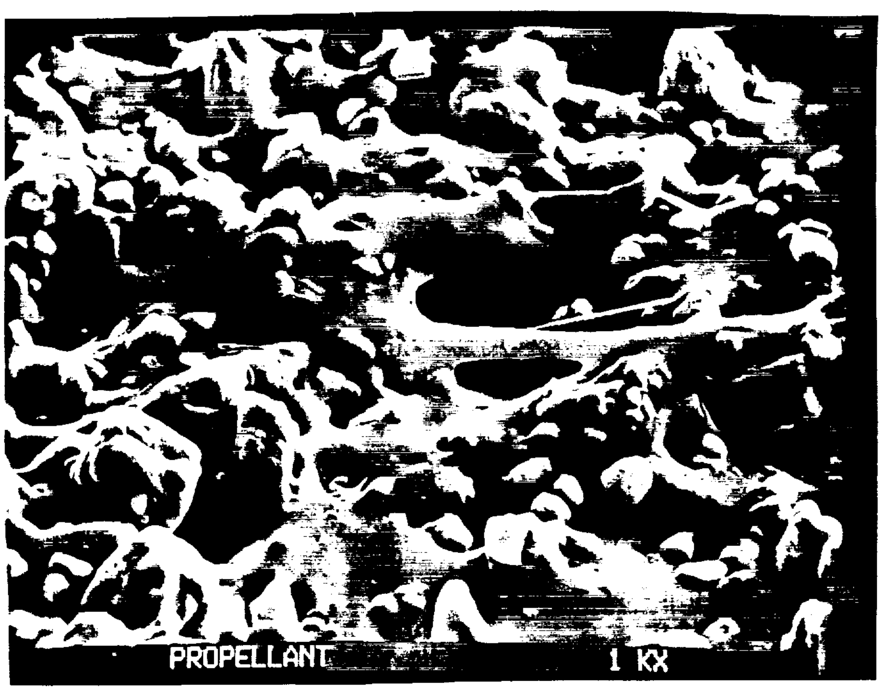

Fig. 21. A propellant that burned in a non-reproducible manner.

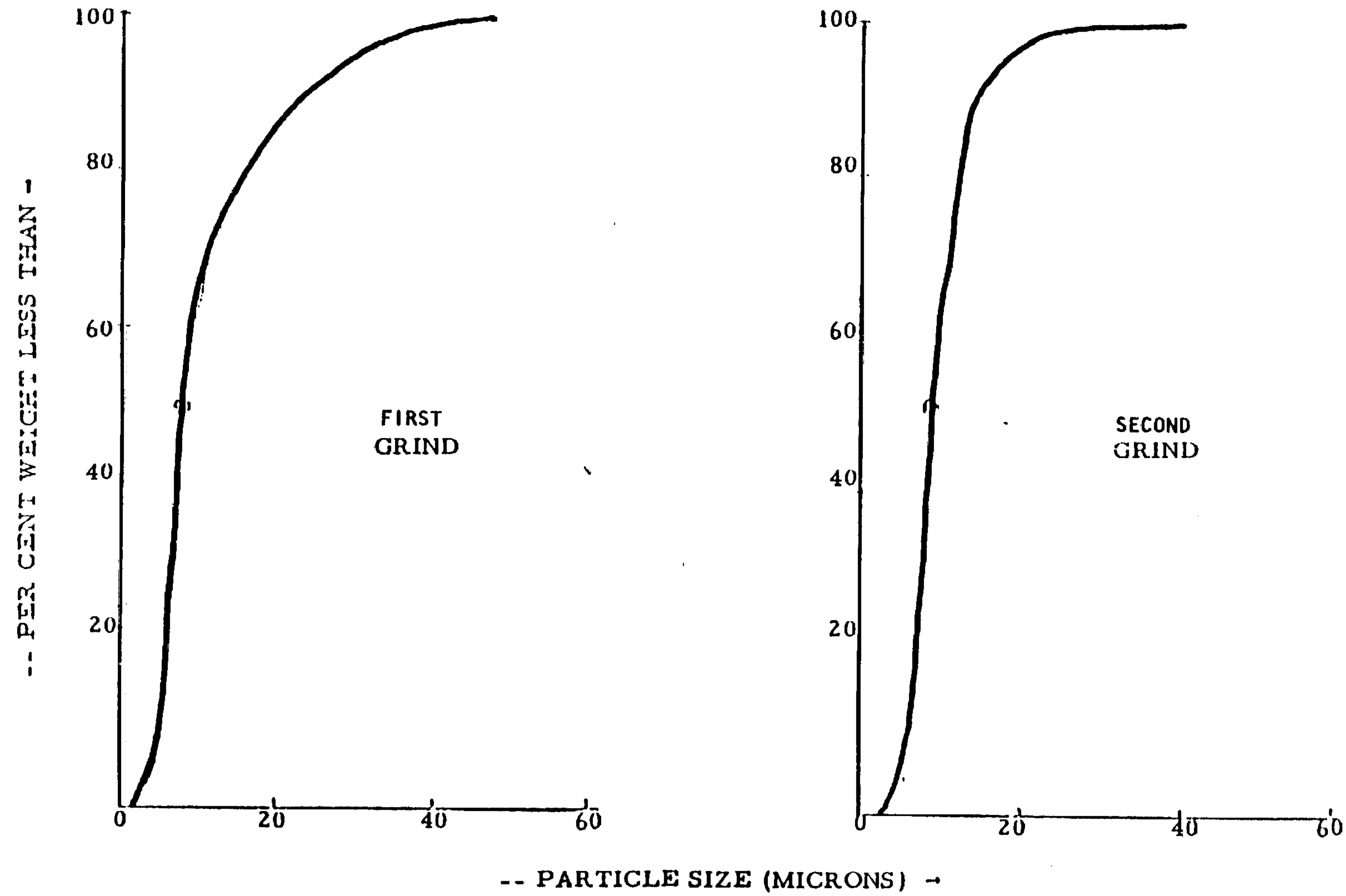

Fig. 22. Differences in the "fine" AP as revealed by micromerograph analyses.