AD-773 433

SOLID STRAND BURN RATE TECHNIQUE FOR PREDICTING FULL-SCALE MOTOR PERFORMANCE

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October 1973

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFRPL-TR-73-49	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD773 433
4. TITLE (and Subtitle) Solid Strand Burn Rate Technique for Predicting Full-Scale Motor Performance		5. TYPE OF REPORT & PERIOD COVERED Final Report - Oct 1972 - Oct 1973
		6. PERFORMING ORG. REPORT NUMBER 305908
7. AUTHOR(s) JAMES L. KOURY		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFRPL/MKMB Edwards AFB CA 93523		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 305908MB
11. CONTROLLING OFFICE NAME AND ADDRESS AFRPL/MKMB		12. REPORT DATE Oct 1973
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; Distribution Unlimited.

18. SUPPLEMENTARY NOTES

Joint Army, Navy, Air Force & NASA Working Group Committee Meeting.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Burn rate
Acoustic Emission System
Titan III - Propellant

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

The degree of success or failure for meeting the space and ballistic mission requirements of rocket launched vehicles depends greatly on the ability to accurately predict propulsion performance.

Solid rocket motor performance predictions are possible by establishing a correlation between full-scale motor performance, and small ballistic test motors, liquid strand burn rate tests and/or solid strand burn rate tests. 42

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The accuracy of these predictions will be maintained if the correlation between motor performance and any of the test techniques remains constant. On two operational motors, a shift in the correlation between liquid strand burn rate (LSBR) and large motors was noticed by SAMSO and the cause of the shift was suspected to be related to some subtle change in the propellant raw material, perhaps the ammonium perchlorate oxidizer. An investigation was initiated to re-establish the correlation between full-scale motor performance and liquid strand burn rate tests and to determine the cause of the shift. The AFRPL approach toward establishing this correlation was to perform solid strand burn rate tests on propellant taken from cartons which were cast during motor manufacture.

This paper describes the results of the AFRPL solid strand burn rate tests on Titan III propellant. During the program an improved monitoring system, to detect the combustion events of solid propellant ignition and burnout, was developed and demonstrated. The paper includes discussion of:

(A) Solid Strand Burn Rate Test Method
(B) Acoustic Emission Detection System
(C) Burn Rate Variability of Solid Strands
(D) Correlation between full-scale motor performance, and small test motors, and liquid and solid strand burn rate tests.

The results of this effort determined the applicability of using the solid strand burn rate technique for predicting full-scale motor performance for current and future Air Force systems. The cost savings associated with using strand burn rate test techniques instead of small motor tests are discussed.

PREFACE

This document describes the results of the Air Force Rocket Propulsion Laboratory solid strand burn rate measurements on Titan III propellants. During the program, an improved monitoring system (Acoustic Emission), improved cutting tool for solid strand preparation and sample selection technique were developed and demonstrated. The program was a mutual effort by Air Force Rocket Propulsion Laboratory (AFRPL) (James L. Koury, Program Manager), and United Technology Center (UTC) (Richard Aldin, Program Manager).

The Air Force portion of this effort was performed under an in-house program 305908MB "Burn Rate Investigation, Titan III Support" in the time period 1 October 1972 through 30 July 1973.

Special recognition should be given to Messrs R. Anderson, F. Rambus, R. Benedict and MSgt L. Franks for their assistance.

This report has been read and approved.

FOR THE COMMANDER

CHARLES R. COOKE
Chief, Solid Rocket Division

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SECTION I
INTRODUCTION

The objective of this program was to perform and evaluate solid strand burn rate measurements on the Titan III propellant taken from cartons which were cast during motor manufacture. The results of this evaluation would determine if the solid strand burn rate technique would be an acceptable approach toward re-establishing the correlation between full-scale motor performance, and small ballistic test motors, and liquid strand burn rate tests.

The effects of strand preparation, sample selection, burn rate variability within the carton, and particle orientation were briefly investigated. During the program, an improved monitoring system was developed and demonstrated.

SECTION II
TECHNICAL DISCUSSION

The preparation and testing of solid propellant strands on UTC-3001 propellant cast in cartons during the production of motors were conducted at AFRPL. The results of the solid strand burn rate (SSBR) tests would be used to determine if a correlation exists between solid strand burn rate, small motor burn rate and liquid strand burn rate (LSBR). A correlation of LSBR with SSBR would not be attempted if the best correlation between SSBR and small motor burn rate yielded a low correlation coefficient $R < .7$ with a standard error of estimate greater than one percent.

SOLID STRAND BURN RATE TEST METHOD

Solid strands were prepared from the propellant cartons as described in Figure 1. The cured strands are prepared at RPL using a new milling machine which was designed and built for this program (Figures 2 and 3). The milling device was so designed that twenty strands can be milled on one cutting. The distance between the grooves represents the thickness of the strand. The cross sectional area of each strand can be controlled to 0.25 in-sq $\pm$ 0.025 which plays an important role toward obtaining reproducible burn rates. The cutting blades were operated remotely and were vacuum cleared after each cutting for safety purposes. A hole was then drilled in each strand three inches from the end of the strand and the igniter wire placed in each strand. The distance between the igniter wire and the end of the strand was controlled by the use of a metal jig. The excess propellant above the igniter wire was removed, leaving approximately 1/8" of propellant above the igniter wire.

Solid Strand burn rate tests were performed on cured strand at RPL combustion facility using the standard ARC strand burner (Figures 4 and 5). It should be noted that water was used as the inhibitor instead of the conventional coating methods used by industry. Earlier in the program, the system monitored the time required for the flame to consume a known

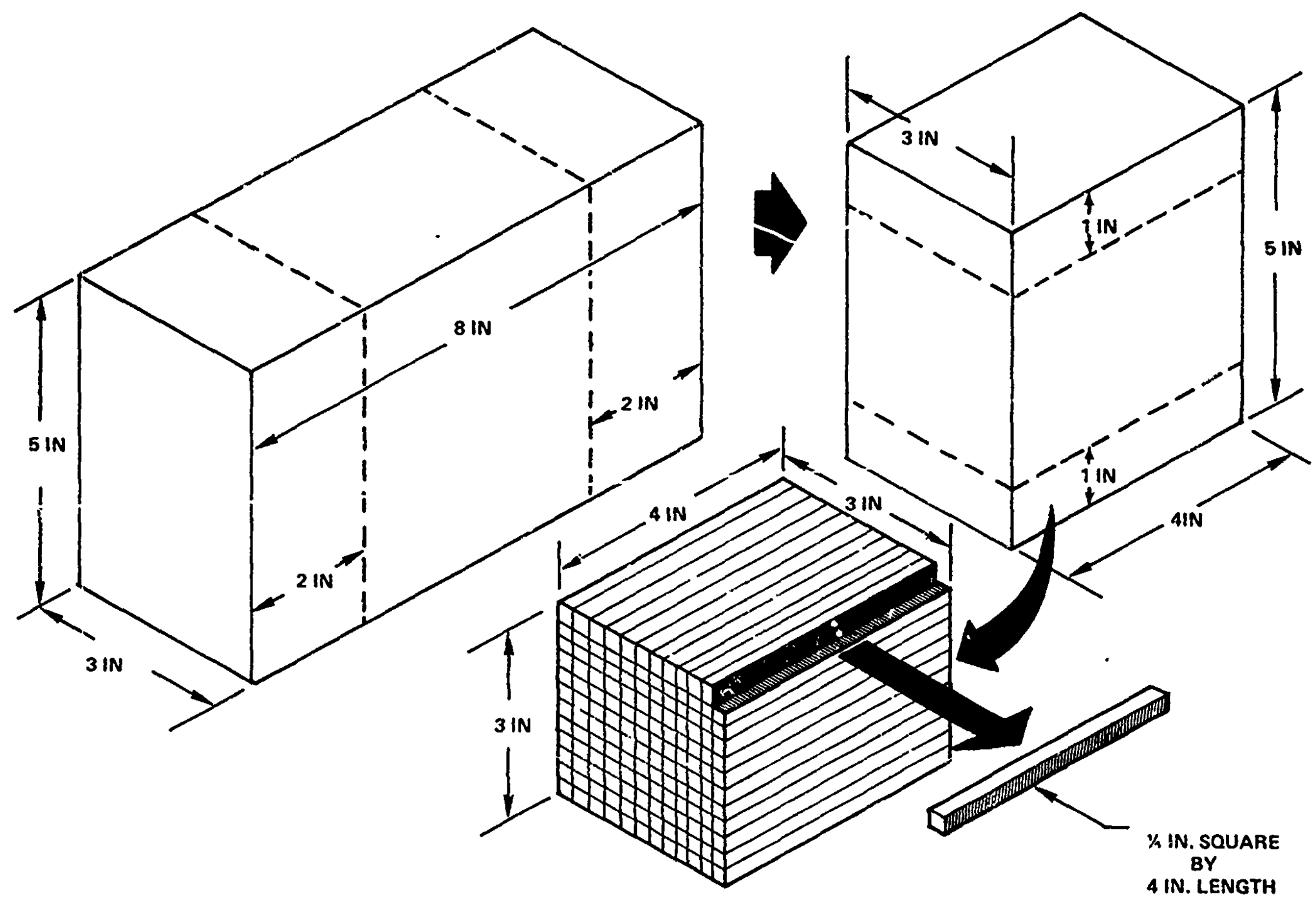


Figure 1. Propellant Carton Dimensions

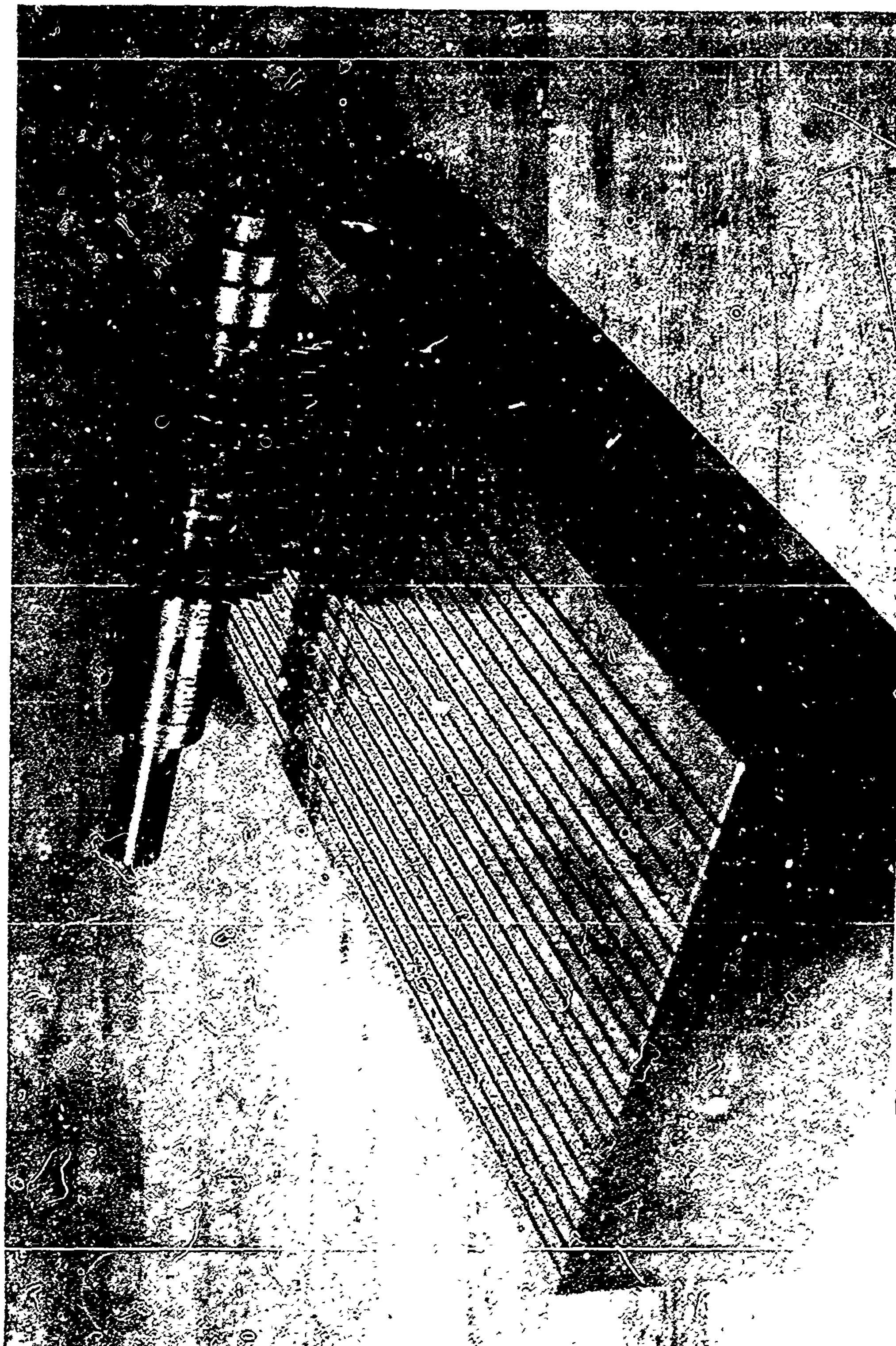


Figure 2. T. S. 1-21 Propellant Cutting Tool

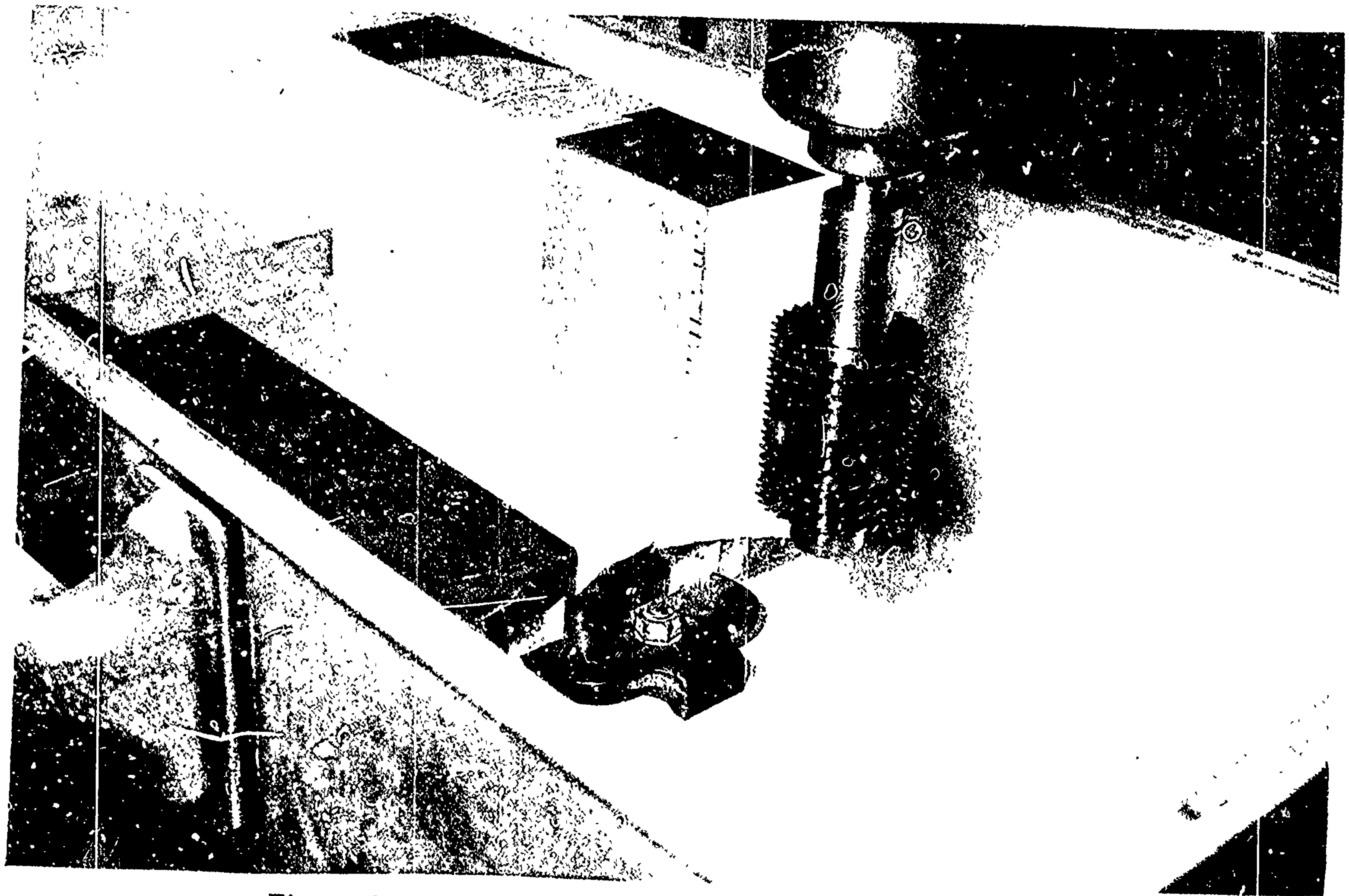


Figure 3. T. S. 1-21 Propellant Cutting Tool

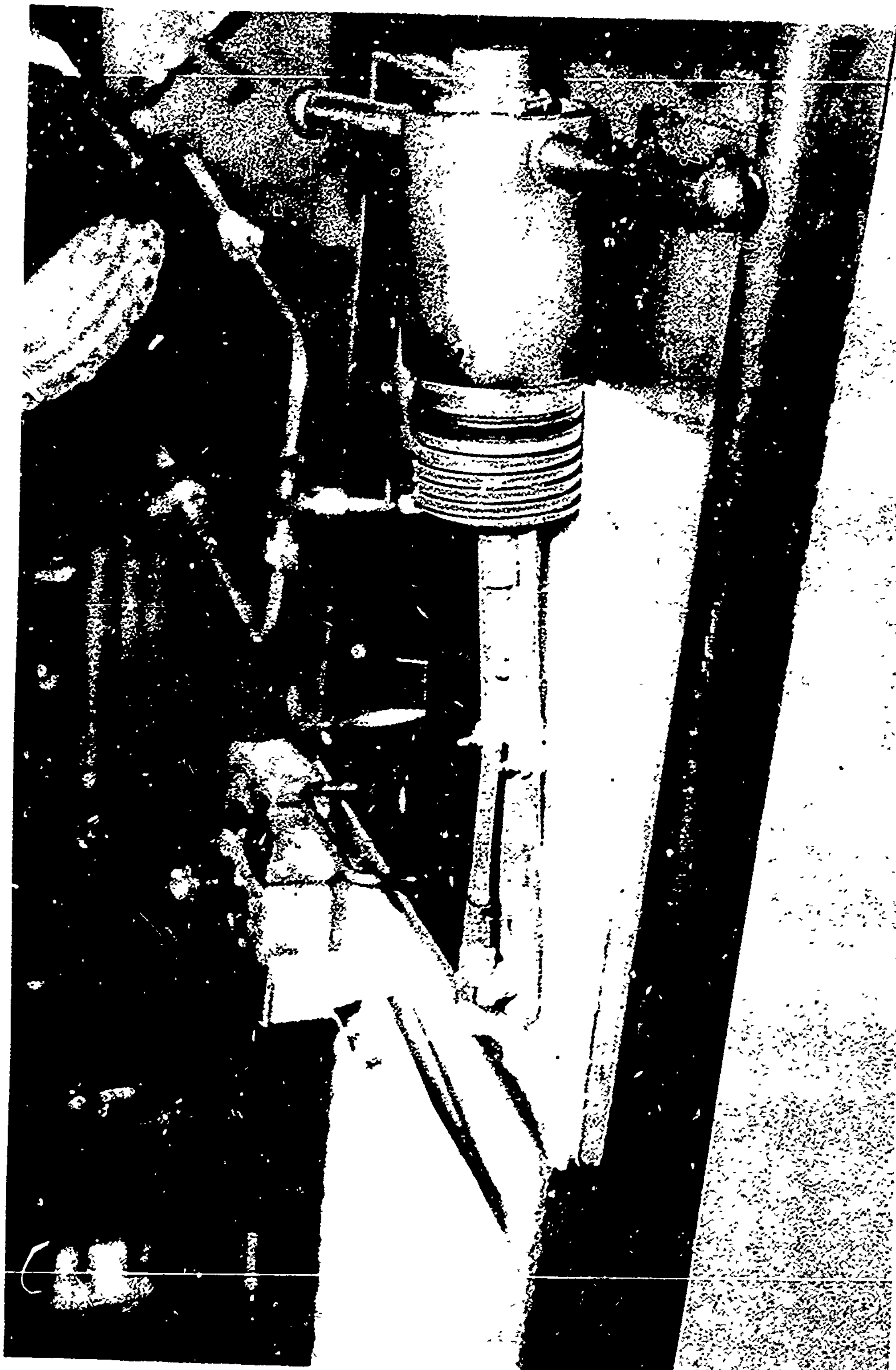
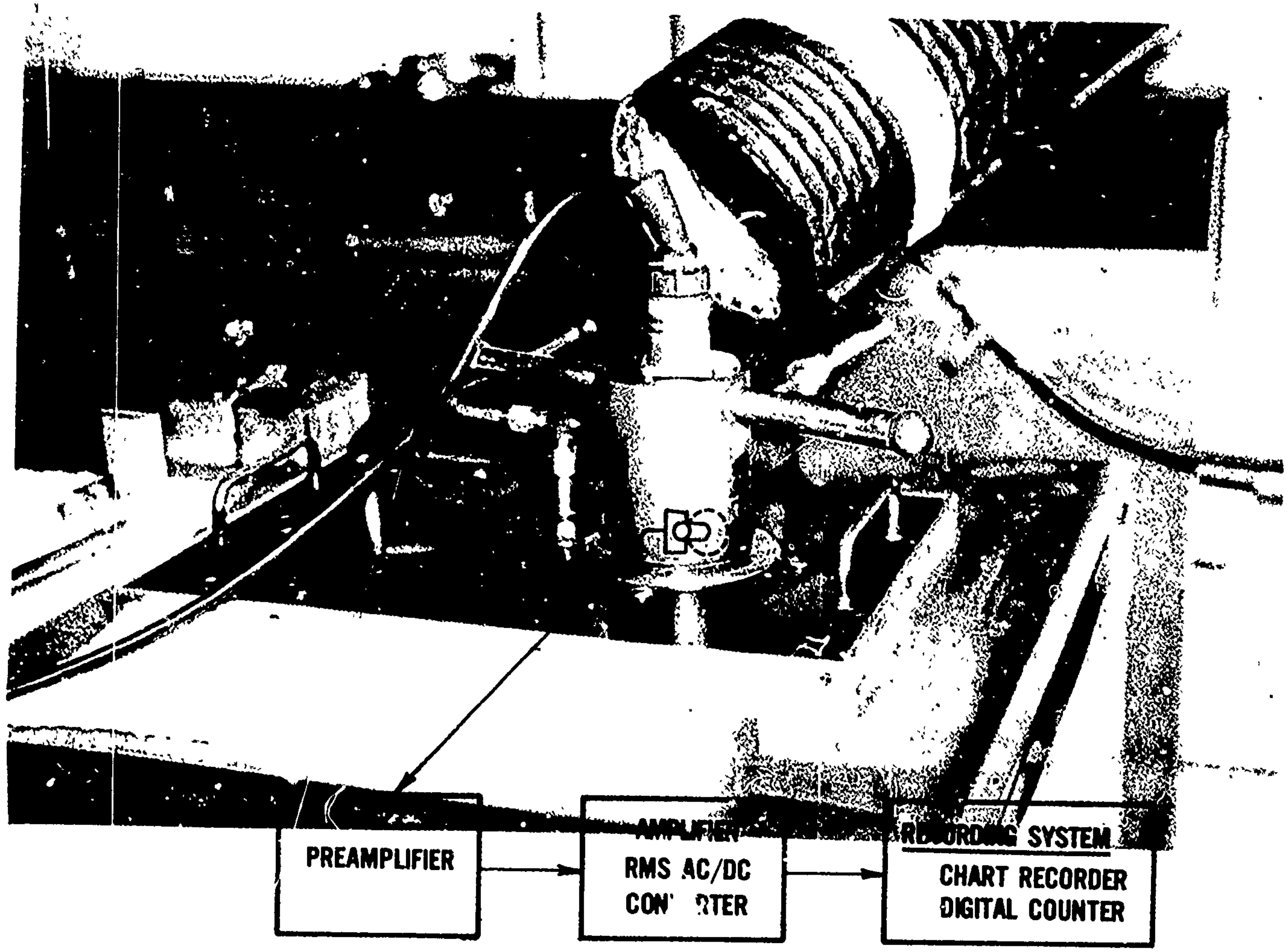


Figure 4. T. S. 1-30 Titan III C



ACOUSTICAL EMISSION SYSTEM

Figure 5. T. S. 1-30 Titan III C

length of the propellant by recording the rate of pressure rise in a closed bomb. Later in the program, AFRPL developed and demonstrated the use of an acoustic emission system to detect the combustion events of solid propellant ignition and burnout.

ACOUSTIC EMISSION DETECTION SYSTEM

The Acoustic Emission System uses a sound sensor mounted externally on the combustion bomb which picks up an acoustic signal, presumably created by the thermal fracture or deflagration of the solid oxidizer as it is exposed to the combustion flame zone at the burning surface. The system monitors the time required for the flame to consume a known length of propellant at a pre-set pressure. The electronic signal output can be recorded and displayed on any one of a number of standard devices (x-y chart recorder, digital counter, etc.).

As assessment of the acoustic emission solid strand burn rate technique was required in order to establish the adequacy of the technique, and to compare with current techniques (Figure 6). The test results showed the following improvements over current techniques:

a. Improves precision and accuracy of measurements through the ability to better identify the occurrence of ignition and burnout.

b. Provides the added feature of incorporating a digital counter with the acoustic emission detection system, which reduces data reduction time and technician error. (Average 100 strands/day).

c. Eliminates complex wiring and sample preparation associated with trip wires as the acoustic emission system only requires physical contact of a sensor to the combustion bomb external surface. (Figure 7).

d. Detects anomalies such as side burning, voids, or sudden changes in burning which is either accidental or pre-programmed to afford accuracy improvements. (Figure 7).

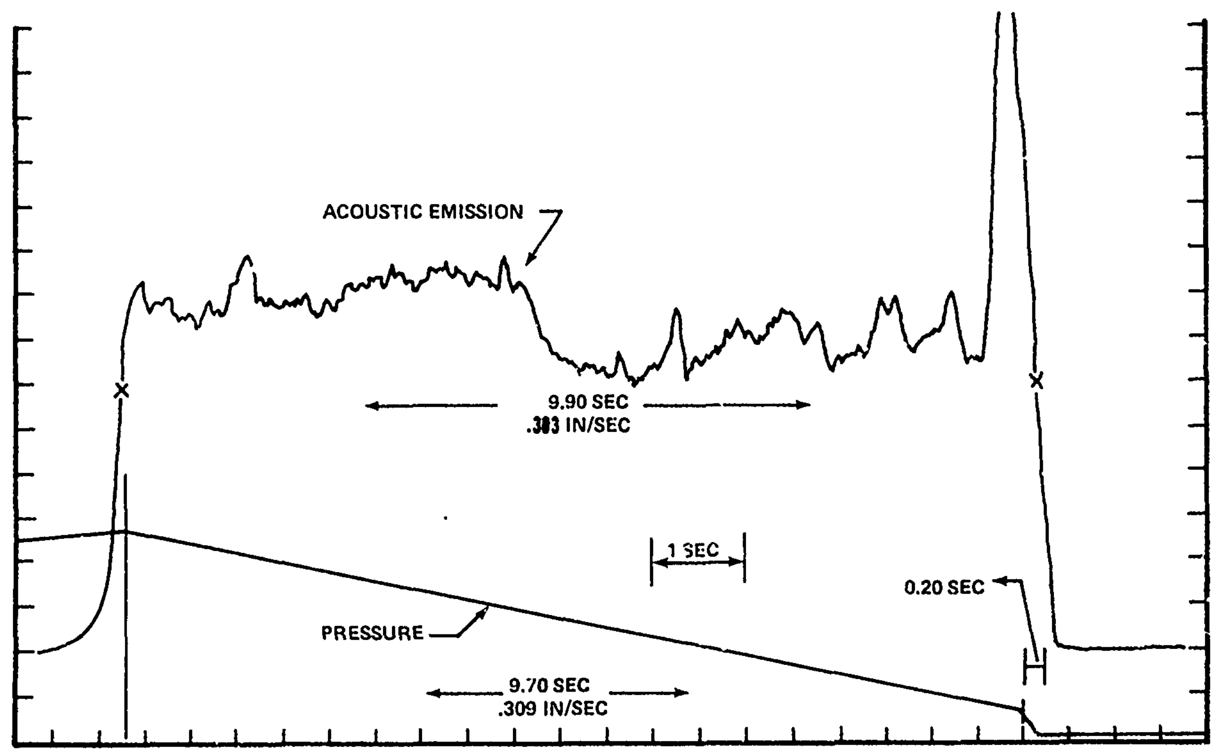


Figure 6. Acoustic Emission Versus Pressure Time

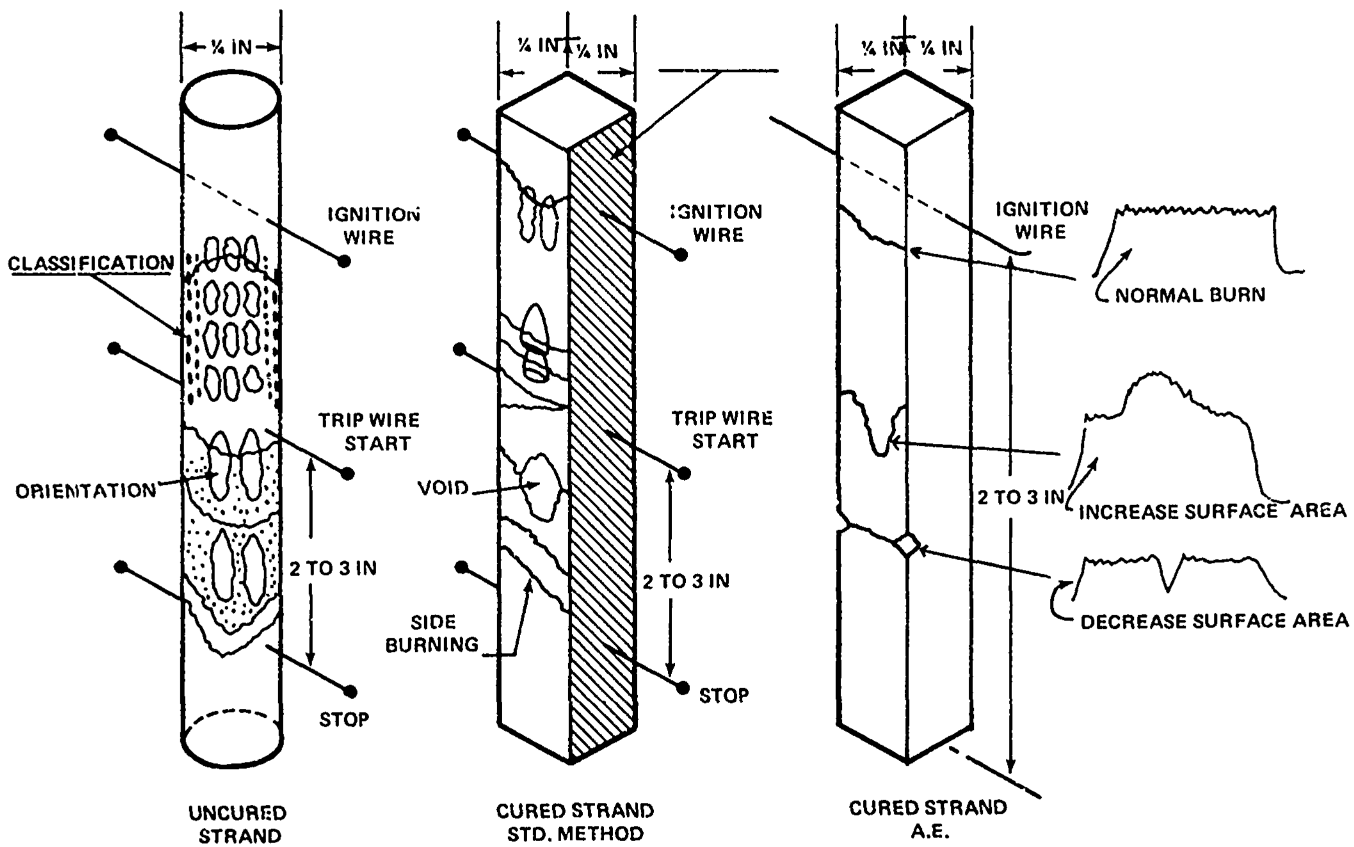


Figure 7. Burn Rate Techniques

BURN RATE VARIABILITY STUDY WITHIN THE CURED CARTON

Orientation of solid particles, the critical factor affecting the propellant surface regression, was evaluated with respect to its effect on burn rate variability within the cartons.

Two UTC-3001 propellant cartons were used to evaluate burn rate variability within the cartons. Cured cartons were bisected and strands were prepared in both horizontal and vertical directions (Figure 8). Each strand was labeled as to its location (e.g., IA as illustrated in Figure 9). Burn rates were measured at 550 psig on both horizontal (H) and vertical (V) strands taken from the top, middle, and bottom and from the edge to the center of the cartons. The burn rate results for each carton show a significant difference (1 percent) between the horizontal and vertical samples as illustrated in Table I. The anisotropic occurrence is likely due to particle orientation. To confirm the theory that particle orientation does occur, photomicrographs were taken which revealed significant orientation of coarse oxidizer (Figure 10).

The data obtained from the variability study showed that propellant strands taken from cartons in the vertical direction yielded a standard error of estimate below one percent, which met the goals set by SAMCO early in the program. It was decided that a minimum of ten strands each would be fired at 550 and 750 psig for each carton of propellant.

SOLID STRAND BURN RATE TEST RESULTS

Solid propellant strands were prepared from five propellant cartons which were cast during motor manufacture. All strands were prepared in vertical position and fired as described in Section II. The improved monitoring system, acoustic emission system, was used to detect the combustion events of propellant ignition and burnout. A digital counter and chart recorder were used to measure the burn time for each strand. A minimum of ten strands each was fired at 550 and 750 psig for each carton of propellant and the data was statistically analyzed for each pressure as

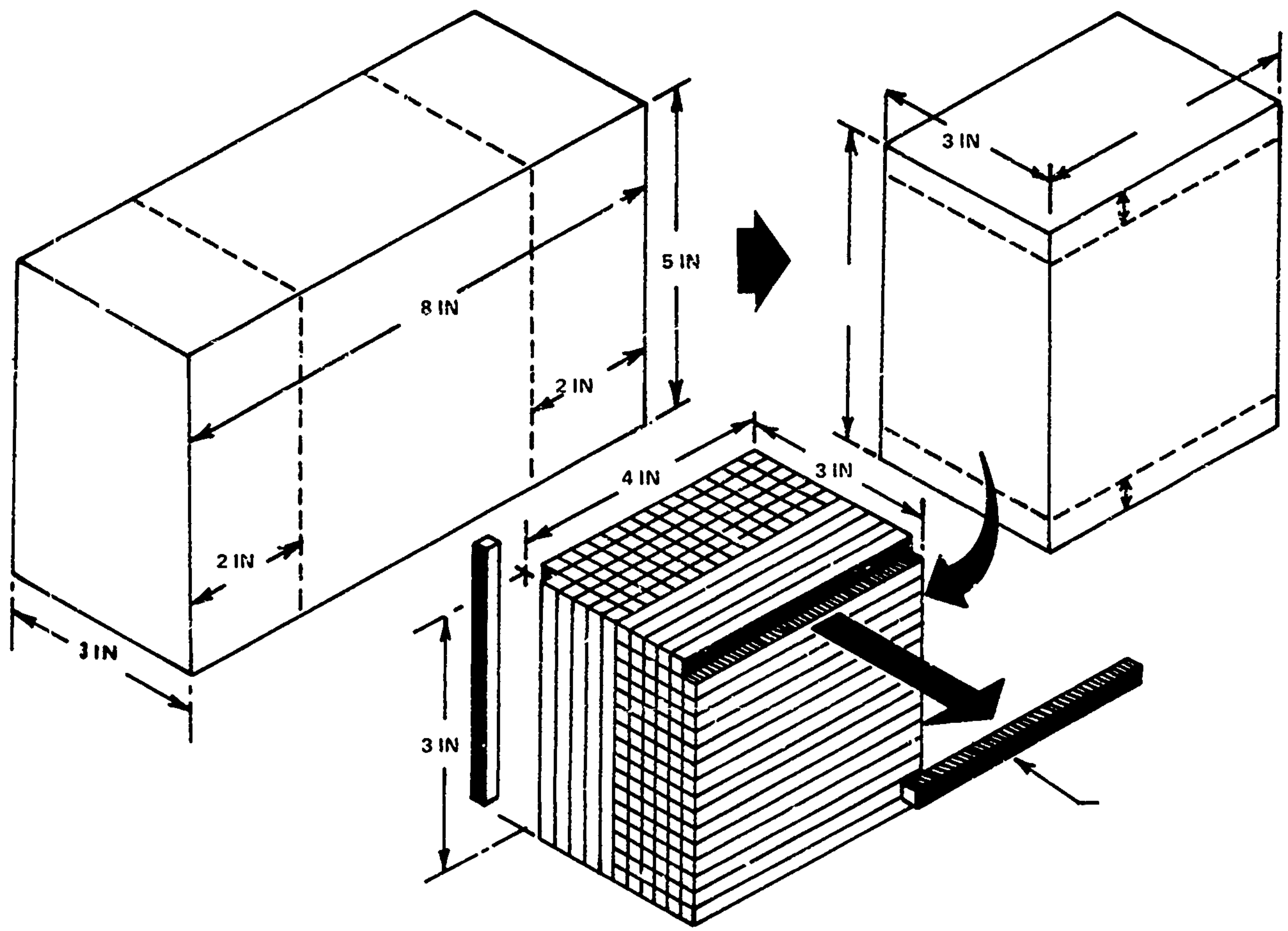


Figure 8. Propellant Carton Dimension (Horizontal Versus Vertical)

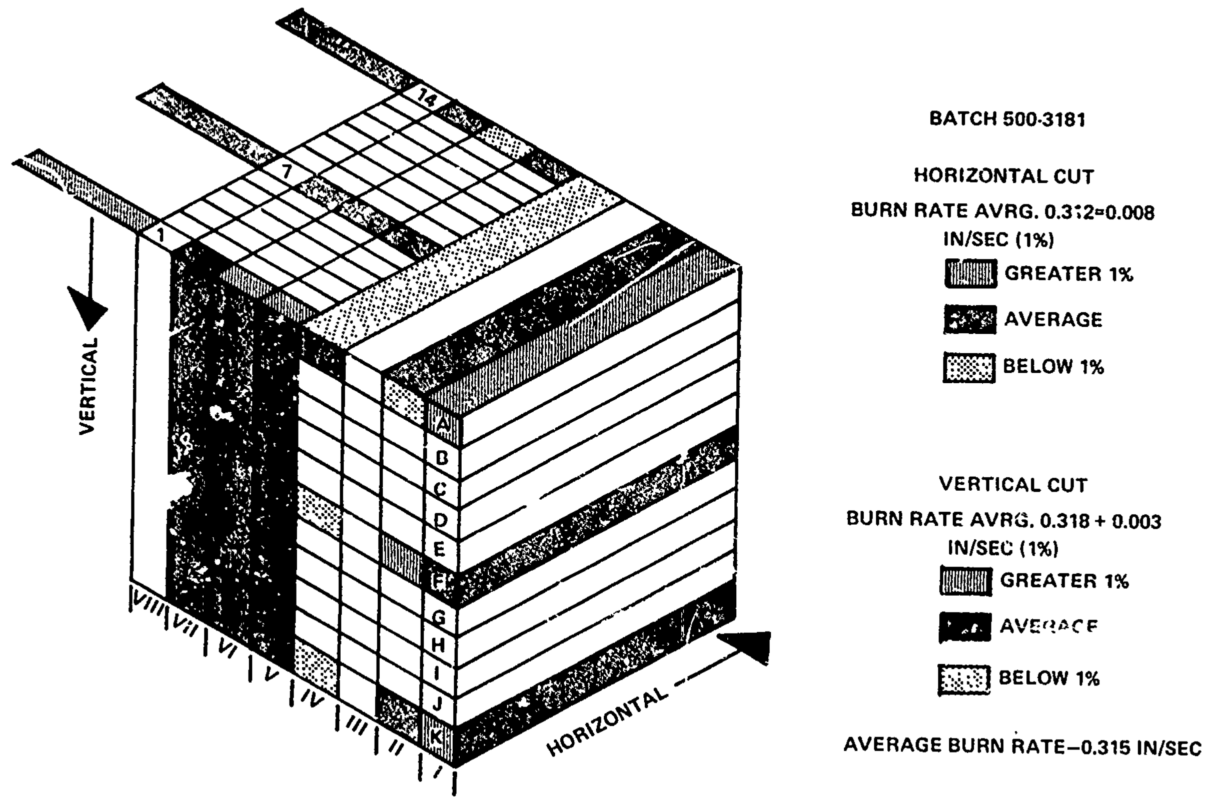


Figure 9. Burn Rate Variability Study Within Cured Carton 500-3181

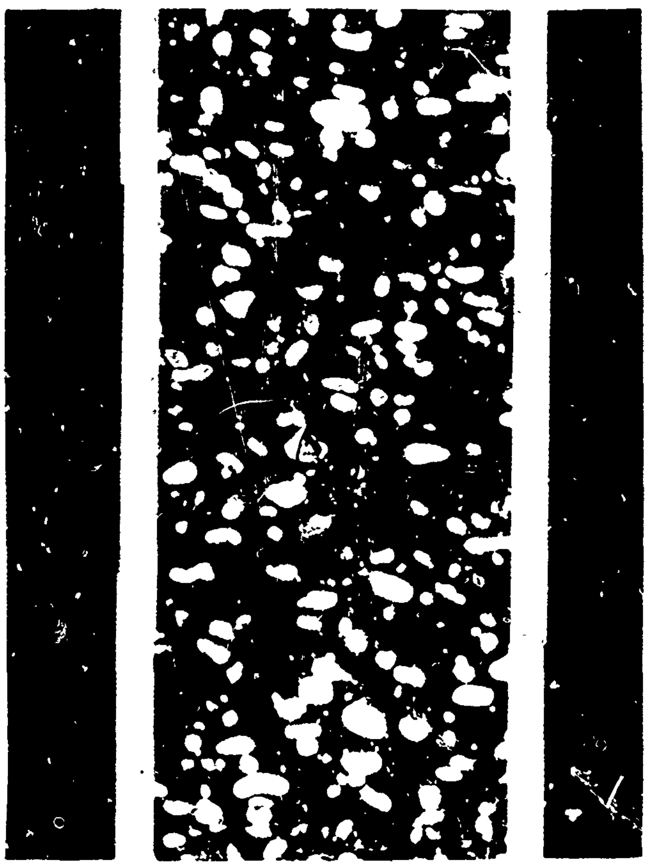


Figure 10. Oxidizer Orientation

TABLE I

SOLID STRAND VARIABILITY STUDY WITHIN THE CURED CARTON HORIZONTAL VS VERTICAL

	Batch 3181 Horizontal	Batch 3181 Vertical	Batch 3182 Horizontal	Batch 3182 Vertical
	.308	.322	.308	.318
	.317	.319	.312	.323
	.311	.319	.319	.322
	.314	.326	.309	.322
	.303	.322	.310	.322
	.308	.320	.308	.318
	.314	.318	.309	.320
	.309	.316	.304	.320
AV	.311 in/sec	.320 in/sec	.309 in/sec	.320 in/sec
SY =	.0048 in/sec	.0028 in/sec	.0050 in/sec	.0020 in/sec

SY = Std error of estimate

illustrated in Table II. The standard error of estimate was less than 0.0022 in/sec. After evaluating the results, a conclusion was reached that the number of samples could be reduced to a minimum of five strands at each pressure for the remaining 139 cartons (as illustrated in Table III).

CORRELATION BETWEEN FULL-SCALE MOTOR PERFORMANCE, SMALL TEST MOTORS AND LIQUID AND SOLID STRAND BURN RATE TESTS

As stated in Section II, a correlation of Liquid Strand Burn Rate with Solid Strand Burn Rate would not be attempted if the correlation between Solid Strand Burn Rate and small ballistic motor (TM-1) burn rates yielded a low correlation coefficient ($R < .7$) with a standard error of estimate greater than one percent. The TM-1 burn rates at 550 psia were compared to the AFRPL solid strand burn rate at 550 psig (illustrated in Table IV), which is described in Reference 1. The correlation coefficients of the least squares regressions were below 0.7 and varied from 0.341 to 0.646; therefore, a correlation between solid and liquid strands was not attempted.

Because the data of AFRPL solid strand burn rate exhibited good precision, UTC decided to attempt a correlation between the full-scale motor web action times and the solid strand burn rates.

The solid strand burn rates associated with each fired 120" motor were averaged. The average solid strand burn rates were compared to the motor web action time, normalized to 80°F. The resultant regression, 24 motor web action times versus average solid strand burn rates, is shown in Figure 11. The correlation coefficient (R) of 0.922 with standard error of estimate (Sy) of 0.53 percent was statistically significant.

Since the ballistic prediction computer programs (UTC) LF12 and LF13 require burn rates as an input, a regression analysis with 120" motor burn rate was developed and is shown in Figure 12. For this regression,

TABLE II

STRAND BURN RATE DATA
VERTICAL

Batch #	2606		2620		1980	
	550psig	750psig	550psig	750psig	550psig	750psig
	.308	.335	.304	.331	.317	.343
	.308	.335	.300	.330	.317	.346
	.304	.331	.300	.331	.317	.347
	.308	.333	.302	.330	.317	.346
	.307	.333	.301	.334	.316	.345
	.307	.335	.303	.334	.316	.345
	.305	.335	.302	.334	.316	.345
	.306	.336	.303	.334	.315	.344
	.309	.336	.305	.334	.314	.343
	.306	.338	.304	.334	.316	.343
AV	.307 in/sec	.334 in/sec	.302 in/sec	.332 in/sec	.316 in/sec	.344 in/sec
Sy =	.0016 in/sec	.0020 in/sec	.0018 in/sec	0.0019 in/sec	0.0010 in/sec	0.0016 in/sec

Sy = std. error of estimate

TABLE III. SOLID STRAND BURN RATE MEASUREMENTS

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
1874	.315	.313	.311	.309	.314	.312	.338	.339	.339	.340	.339	.339
1384	.311	.310	.309	.310	.309	.310	.342	.341	.343	.343	.340	.342
2660	.305	.303	.302	.304	.303	.304	.330	.331	.334	.331	.334	.332
1990	.308	.308	.310	.309	.310	.309	.342	.339	.339	.341	.338	.340
1780	.307	.308	.307	.309	.310	.308	.340	.342	.341	.338	.338	.340
1821	.316	.311	.311	.311	.311	.312	.341	.339	.338	.340	.343	.340
3186	.316	.316	.313	.313	.314	.314	.341	.342	.340	.343	.343	.342
2600	.302	.303	.304	.304	.304	.303	.331	.332	.330	.332	.332	.331
2230	.311	.309	.307	.308	.310	.309	.340	.335	.338	.339	.338	.338
2780	.300	.301	.298	.299	.302	.300	.334	.330	.330	.332	.334	.332
2070	.313	.313	.311	.313	.314	.313	.337	.339	.339	.339	.341	.339
1790	.311	.311	.315	.312	.313	.312	.338	.339	.338	.342	.340	.339
2255	.313	.312	.309	.309	.313	.311	.339	.339	.338	.340	.341	.340
2055	.309	.310	.309	.309	.311	.309	.342	.338	.336	.339	.338	.338
2669	.301	.302	.301	.300	.300	.301	.330	.329	.330	.330	.330	.330
1399	.314	.314	.313	.313	.311	.313	.339	.340	.339	.338	.336	.338
2210	.314	.312	.311	.309	.310	.311	.338	.342	.338	.338	.340	.340
2090	.318	.318	.320	.316	.318	.318	.348	.348	.349	.350	.351	.349
1890	.318	.316	.317	.313	.313	.315	.343	.343	.347	.344	.345	.344
2987	.313	.313	.315	.314	.316	.314	.342	.344	.347	.344	.341	.344

TABLE III. SOLID STRAND BURN RATE MEASUREMENTS (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
2865	.300	.300	.300	.301	.299	.300	.329	.327	.327	.328	.330	.328
2940	.297	.301	.299	.304	.299	.300	.328	.331	.328	.329	.331	.329
3045	.304	.305	.306	.304	.306	.305	.332	.336	.338	.334	.336	.335
1407	.316	.315	.312	.316	.316	.315	.334	.334	.333	.333	.332	.333
3035	.309	.309	.310	.309	.309	.309	.339	.337	.340	.337	.338	.338
2809	.299	.300	.302	.299	.299	.299	.328	.328	.328	.328	.328	.328
3037	.309	.312	.312	.311	.312	.311	.338	.339	.339	.339	.338	.339
2030	.309	.305	.310	.309	.308	.309	.338	.339	.336	.337	.337	.337
2270	.309	.308	.305	.307	.305	.307	.336	.334	.333	.336	.336	.336
3185	.308	.306	.310	.310	.305	.308	.333	.332	.332	.336	.335	.334
1350	.312	.314	.313	.311	.313	.313	.343	.345	.345	.344	.342	.344
2988	.299	.301	.299	.300	.300	.300	.323	.323	.328	.324	.324	.324
2700	.298	.297	.296	.296	.300	.297	.326	.323	.326	.325	.325	.325
2900	.297	.299	.301	.299	.299	.299	.330	.331	.328	.328	.327	.329
2920	.305	.302	.304	.301	.302	.302	.327	.327	.332	.331	.331	.330
2290	.304	.304	.305	.305	.306	.305	.333	.335	.335	.338	.335	.335
1351	.310	.310	.310	.312	.310	.310	.341	.338	.338	.337	.340	.339
1910	.304	.303	.305	.304	.304	.304	.331	.332	.332	.333	.334	.332
1846	.303	.303	.304	.303	.304	.303	.332	.332	.329	.329	.333	.331
1828	.307	.306	.306	.307	.305	.306	.340	.341	.337	.337	.335	.338

TABLE III. SOLID STRAND BURN RATE MEASUREMENTS (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
1702	.300	.297	.296	.295	.297	.297	.322	.322	.325	.325	.325	.324
2680	.300	.300	.299	.301	.300	.300	.330	.326	.326	.328	.329	.328
947	.310	.306	.306	.308	.307	.307	.333	.336	.334	.333	.336	.334
1221	.318	.317	.318	.316	.318	.318	.345	.347	.347	.345	.348	.347
1237	.313	.313	.315	.317	.315	.315	.350	.351	.350	.350	.351	.350
1628	.305	.306	.306	.307	.307	.306	.334	.334	.332	.334	.336	.334
2150	.302	.304	.304	.306	.303	.304	.332	.333	.333	.333	.334	.333
1447	.300	.297	.300	.300	.297	.300	.334	.332	.334	.332	.334	.333
1435	.306	.308	.306	.304	.306	.306	.334	.336	.334	.336	.336	.335
1301	.306	.307	.309	.308	.306	.307	.334	.334	.336	.337	.333	.335
1809	.316	.316	.318	.318	.318	.317	.344	.342	.345	.344	.343	.344
1649	.305	.305	.303	.302	.302	.305	.332	.330	.332	.330	.330	.330
1713	.300	.297	.298	.300	.300	.299	.331	.333	.330	.332	.330	.331
2430	.303	.302	.304	.302	.305	.303	.331	.333	.331	.330	.329	.331
2580	.306	.307	.308	.307	.306	.307	.333	.332	.332	.332	.333	.332
1229	.310	.314	.314	.313	.310	.312	.342	.342	.341	.341	.341	.341
1626	.301	.300	.301	.299	.299	.300	.328	.328	.326	.325	.326	.327
1299	.314	.314	.312	.315	.313	.314	.341	.339	.338	.340	.341	.340
1664	.297	.297	.302	.298	.301	.299	.325	.329	.328	.327	.326	.327
1680	.297	.298	.298	.301	299	.299	.328	.326	.328	.325	.325	.326

TABLE III. SOLID STRAND BURN RATE MEASUREMENTS (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
966	.306	.305	.308	.308	.306	.307	.332	.333	.332	.333	.333	.333
3307	.308	.306	.307	.308	.307	.307	.338	.334	.335	.335	.336	.336
3398	.305	.305	.307	.306	.305	.305	.334	.334	.336	.334	.336	.335
2390	.304	.304	.304	.303	.302	.304	.334	.333	.330	.330	.330	.331
2560	.301	.301	.300	.303	.300	.301	.330	.330	.334	.330	.333	.331
651	.306	.306	.306	.308	.308	.307	.338	.338	.339	.339	.339	.339
2979	.305	.305	.306	.307	.305	.306	.338	.338	.339	.339	.336	.338
3270	.305	.306	.305	.305	.306	.305	.337	.335	.335	.335	.334	.335
3390	.307	.309	.308	.307	.306	.307	.333	.334	.334	.335	.333	.334
1777	.312	.313	.312	.312	.311	.312	.343	.343	.342	.340	.340	.342
2330	.305	.306	.304	.305	.304	.305	.335	.332	.332	.335	.332	.333
2405	.299	.300	.301	.299	.300	.300	.331	.332	.330	.330	.332	.331
2440	.301	.299	.299	.300	.302	.300	.330	.332	.331	.332	.329	.331
2500	.301	.300	.298	.300	.301	.300	.333	.334	.333	.333	.334	.333
2520	.302	.301	.300	.301	.300	.301	.329	.329	.327	.331	.330	.329
2450	.305	.304	.303	.303	.304	.304	.333	.333	.332	.332	.331	.332
1641	.299	.299	.299	.300	.299	.299	.325	.327	.324	.324	.324	.325
930	.301	.304	.303	.303	.304	.303	.335	.334	.337	.336	.334	.335
1439	.303	.305	.304	.302	.304	.304	.332	.334	.334	.331	.332	.333
1206	.306	.307	.307	.306	.306	.306	.336	.336	.335	.334	.335	.335

TABLE III. SOLID STRAND BURN RATE MEASUREMENTS (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
2960	.300	.299	.298	.297	.296	.298	.326	.327	.326	.326	.326	.326
1690	.296	.296	.297	.296	.295	.296	.325	.326	.327	.328	.326	.326
2740	.300	.299	.301	.301	.298	.300	.325	.324	.324	.324	.324	.324
2870	.294	.292	.295	.294	.294	.294	.323	.320	.322	.320	.323	.322
2967	.296	.294	.295	.292	.292	.294	.319	.322	.320	.318	.318	.319
3355	.306	.309	.306	.308	.307	.307	.334	.337	.334	.336	.335	.335
3498	.309	.309	.310	.309	.310	.309	.339	.338	.336	.338	.337	.338
1651	.298	.299	.299	.297	.301	.299	.326	.329	.326	.328	.326	.327
2365	.306	.306	.308	.304	.304	.306	.332	.333	.334	.332	.331	.332
2768	.299	.297	.297	.297	.298	.297	.325	.326	.327	.327	.324	.326
3251	.306	.307	.304	.305	.305	.305	.333	.332	.332	.332	.332	.332
2794	.298	.297	.301	.301	.299	.299	.325	.326	.324	.325	.324	.325
1753	.301	.301	.299	.300	.302	.301	.334	.333	.333	.333	.332	.333
2340	.303	.305	.305	.304	.305	.304	.334	.331	.332	.330	.300	.332
3230	.308	.309	.308	.310	.309	.309	.336	.335	.336	.335	.333	.335
670	.301	.299	.298	.297	.299	.299	.333	.330	.331	.330	.330	.330
938	.302	.301	.299	.299	.299	.300	.327	.330	.328	.328	.329	.329
2491	.303	.302	.302	.300	.303	.302	.332	.333	.332	.330	.330	.332
2880	.298	.297	.297	.298	.300	.298	.326	.325	.324	.325	.325	.325
2855	.304	.300	.301	.302	.301	.301	.330	.330	.330	.331	.329	.330

TABLE III. SOLID STRAND BURN RATE MEASUREMENT (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
3000	.295	.298	.296	.297	.298	.297	.323	.322	.323	.324	.322	.323
2595	.300	.300	.300	.300	.299	.300	.325	.325	.325	.326	.326	.325
1416	.303	.302	.301	.303	.302	.302	.331	.331	.332	.333	.330	.331
2565	.302	.302	.302	.302	.302	.302	.332	.329	.329	.332	.329	.330
3184	.306	.305	.303	.303	.302	.304	.331	.332	.331	.330	.330	.330
1612	.297	.295	.296	.298	.298	.297	.325	.325	.326	.329	.328	.327
2110	.304	.304	.304	.302	.304	.304	.332	.332	.334	.333	.330	.333
3147	.311	.310	.311	.310	.309	.310	.337	.339	.337	.339	.337	.338
3491	.306	.306	.307	.306	.307	.306	.339	.339	.339	.341	342	.340
1282	.304	.303	.305	.303	.303	.304	.334	.332	.333	.336	.333	.334
1720	.299	.299	.299	.298	.299	.299	.324	.324	.325	.325	.326	.325
3518	.302	.301	.302	.303	.302	.302	.332	.330	.330	.330	.331	.331
3532	.299	.299	.298	.299	.298	.299	.329	.329	.329	.328	.329	.329
2470	.299	.302	.302	.300	.299	.300	.329	.329	.330	.329	.331	.330
3339	.305	.307	.306	.306	.305	.306	.333	.334	.332	.333	.333	.333
2190	.307	.309	.307	.309	.308	.308	.331	.330	.332	.332	.333	.332
2485	.300	.301	.299	.300	.302	.301	.330	.328	.329	.330	.328	.329
3363	.313	.313	.311	.312	.310	.312	.338	.339	.339	.337	.340	.339
2550	.307	.306	.307	.306	.305	.306	.334	.332	.332	.333	.332	.333
3161	.310	.308	.310	.309	.309	.309	.335	.335	.336	.337	.336	.336

TABLE III. SOLID STRAND BURN RATE MEASUREMENT (CONT'D)

Batch Number	Burn Rates at 550 Psig In/Sec					AVE	Burn Rates at 750 Psig In/Sec					AVE
2540	.303	.303	.304	.305	.306	.304	.333	.334	.334	.334	.334	.334
3104	.306	.306	.306	.308	.306	.306	.339	.338	.338	.338	.338	.338
3203	.308	.310	.307	.308	.309	.308	.339	.337	.338	.338	.338	.338
2130	.303	.304	.304	.302	.302	.303	.330	.331	.329	.329	.332	.330
3499	.311	.312	.313	.312	.314	.312	.339	.338	.340	.339	.341	.339
2971	.306	.305	.305	.304	.304	.305	.337	.339	.337	.336	.339	.338
1244	.319	.315	.316	.316	.317	.317	.346	.345	.347	.346	.346	.346
2830	.303	.302	.304	.302	.301	.303	.330	.329	.330	.328	.331	.330
3031	.308	.309	.308	.308	.307	.308	.336	.338	.334	.334	.334	.334
2760	.302	.303	302	.302	.302	.302	.330	.328	.329	.330	.329	.329
3086	.302	.301	.302	.303	.304	.302	.331	.330	.328	.329	.328	.329
911	.302	.301	.300	.302	.301	.301	.330	.330	.331	.332	.329	.330
2950	.302	.300	.298	.301	.298	.300	.332	.331	.331	.328	.329	.330
982	.304	.305	.304	.306	.307	.305	.338	.338	.336	.338	.338	.338
1415	.299	.300	.301	.299	.301	.300	.336	.337	.337	.338	.338	.337
2820	.299	.301	.301	.300	.302	.300	.330	.332	.330	.330	.330	.330
2972	.293	.293	.293	.293	.292	.293	.319	.318	.318	.318	.318	.318
2840	.296	.295	.296	.294	.294	.295	.323	.322	.322	.322	.321	.322
1455	.299	.301	.299	.298	.299	.299	.334	.332	.331	.332	.333	.332
2727	.301	.300	.299	.299	.299	.300	.322	.322	.322	.324	.323	.323

TABLE IV

LEAST SQUARES FITS OF TM-1 BURN RATE AT 550 PSIA VERSUS SSBR AT 550 PSIG

Group No.	No. of Data Points	R	Sy, In/Sec	Slope (TMBR/CSBR)
All Data	53	.543	.005	1.75
Group 3	13	.341	.004	2.29
Groups 4, 6, and 7	35	.569	.005	1.67
Group 8	5	.646	.004	1.77
Regression of all data using propellant formulation variables, SSBR and TM-1 burn rate at 550 PSI	53	.662		*

$$* \quad r_{TM\text{-}1\ 550} = e^{-.58774} SSBR^{.42627} \% Fe_2O_3^{.037087}$$

Groups 3 through 8 listed above refer to those motors which were manufactured during a specific time period with different processing variables and are discussed in detail in Reference 1.

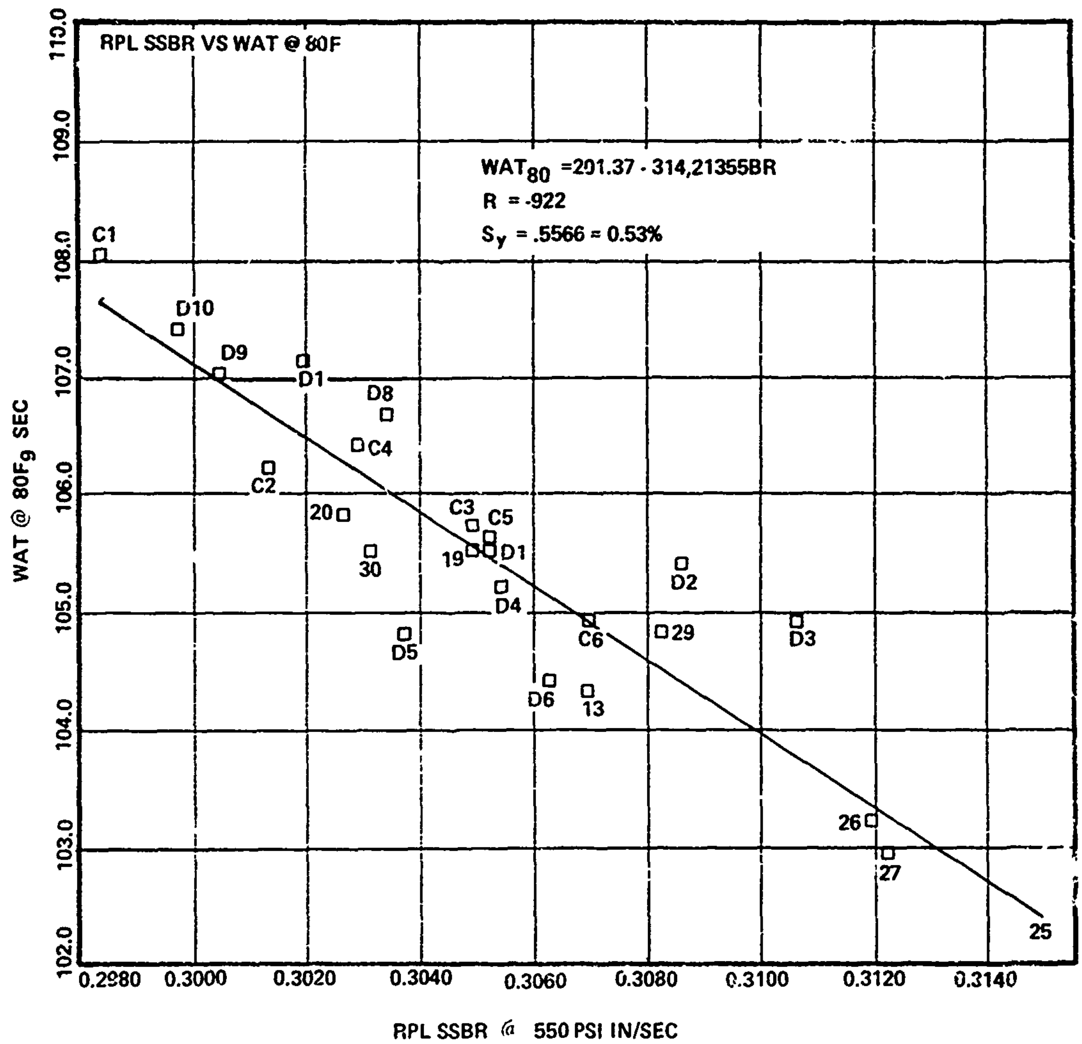


Figure 11. AFRPL Solid Strand Burn Rate (SSBR) Versus Full-Scale Motor Web Action Time (WAT)

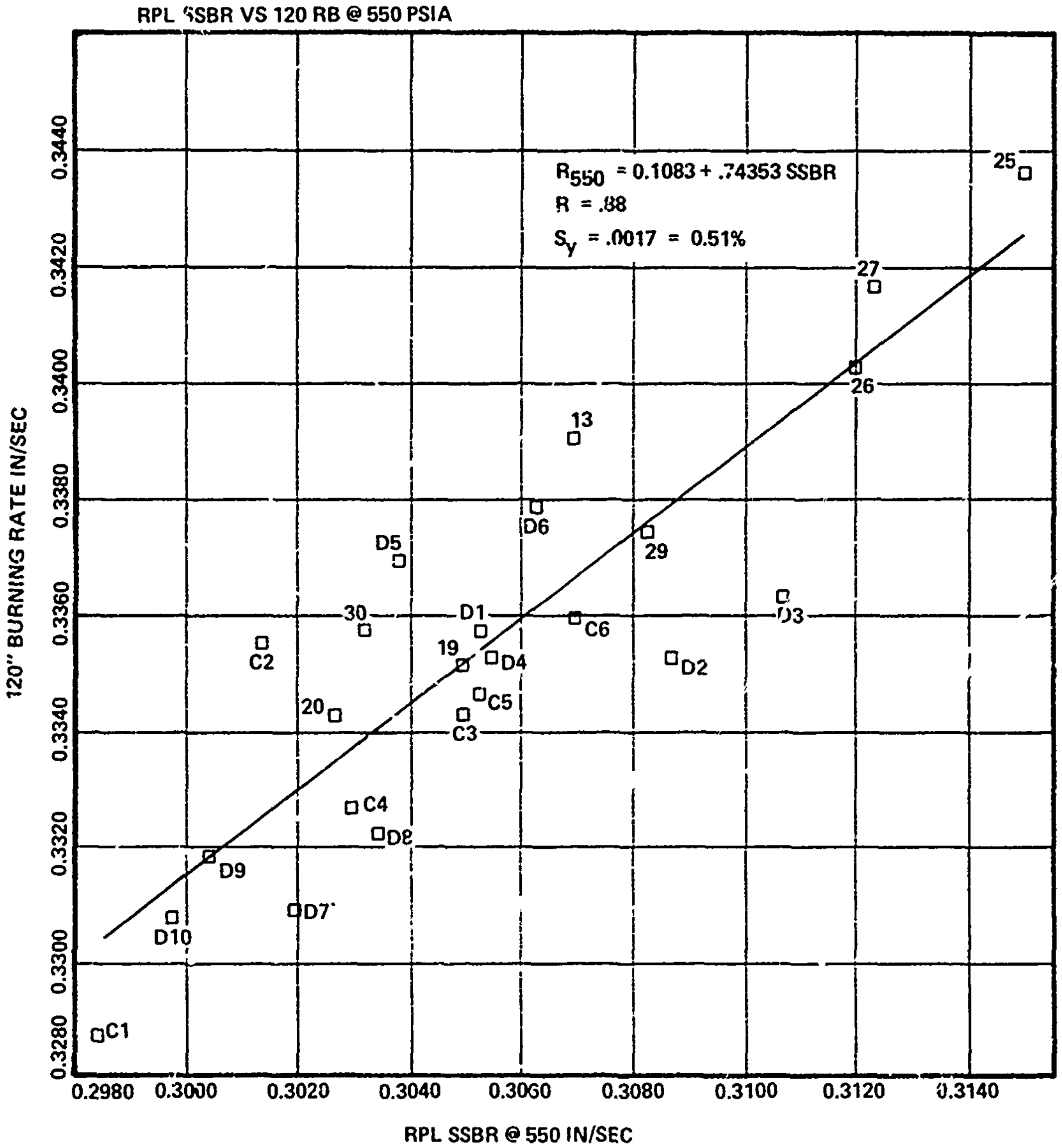


Figure 12. AFRPL Solid Strand Burn Rate Versus Full-Scale Motor Burn Rate @ 550 Psia

the web action times were converted to 120" motor average burn rates at 550 psia (80°F) using the formula:

$$r_{550} = \frac{35.2}{t_b} \frac{(550)^n}{P}$$

where: 35.2 - average web thickness, inches

t_b - 80°F web action time, seconds

P - measured average chamber pressure, psia

n - burn rate exponent, 0.2415

This regression, where R = 0.884 and Sy = 0.51 percent, is also statistically significant.

PERFORMANCE PREDICTIONS

Based on the statistically significant correlation between solid strand burn rate data and actual motor performance, a comparison of measured performance and solid strand/LF13 computer program performance predictions of all flown 120" full-scale motors was conducted and the results are presented in Table V and shown graphically for one motor in Figure 13. The AFRPL solid strand burn rate/UTC LF13 prediction of web action time was within one percent of measured for all motors except SRMs 13 and 14 which deviated 1.76 and 1.40 percent, respectively. This excellent agreement between solid strand predictions and measured flight data demonstrated the capability of the solid strand burn rate technique for predicting full-scale motor performance.

Based on the success of the solid strand burn rate performance prediction technique in correlating measured flight data, the performances of remainder of the full-scale motors were predicted. The predicted performances for each motor were submitted with the solid rocket motors acceptance documentation.

The cost savings associated with using solid strand burn rate test techniques instead of small ballistic motor tests are large. The Titan

TABLE V

COMPARISON OF MEASURED AND PREDICTION 60°F WEB ACTION TIMES, FLOWN MOTORS

Motor	Measured Web Action Time, Sec	Predicted Web Action Time, Sec (CSBR/LF13 Prediction)	Deviation Between Predicted and Measured, %
D1	108.3	108.9	+0.55
D2	108.2	108.1	-0.09
D3	107.7	107.6	-0.09
D4	108.0	108.9	+0.83
D5	107.6	109.5	+1.76
D6	107.2	108.7	+1.40
D8	109.5	109.6	+0.09
D9	109.8	110.3	+0.46
D10	110.2	110.7	+0.45
C1	110.8	110.8	0.00
C2	109.0	110.0	+0.92
C3	108.5	109.1	+0.55
C4	109.6	109.6	0.00
C5	108.4	108.9	+0.46
C6	107.7	108.6	+0.84

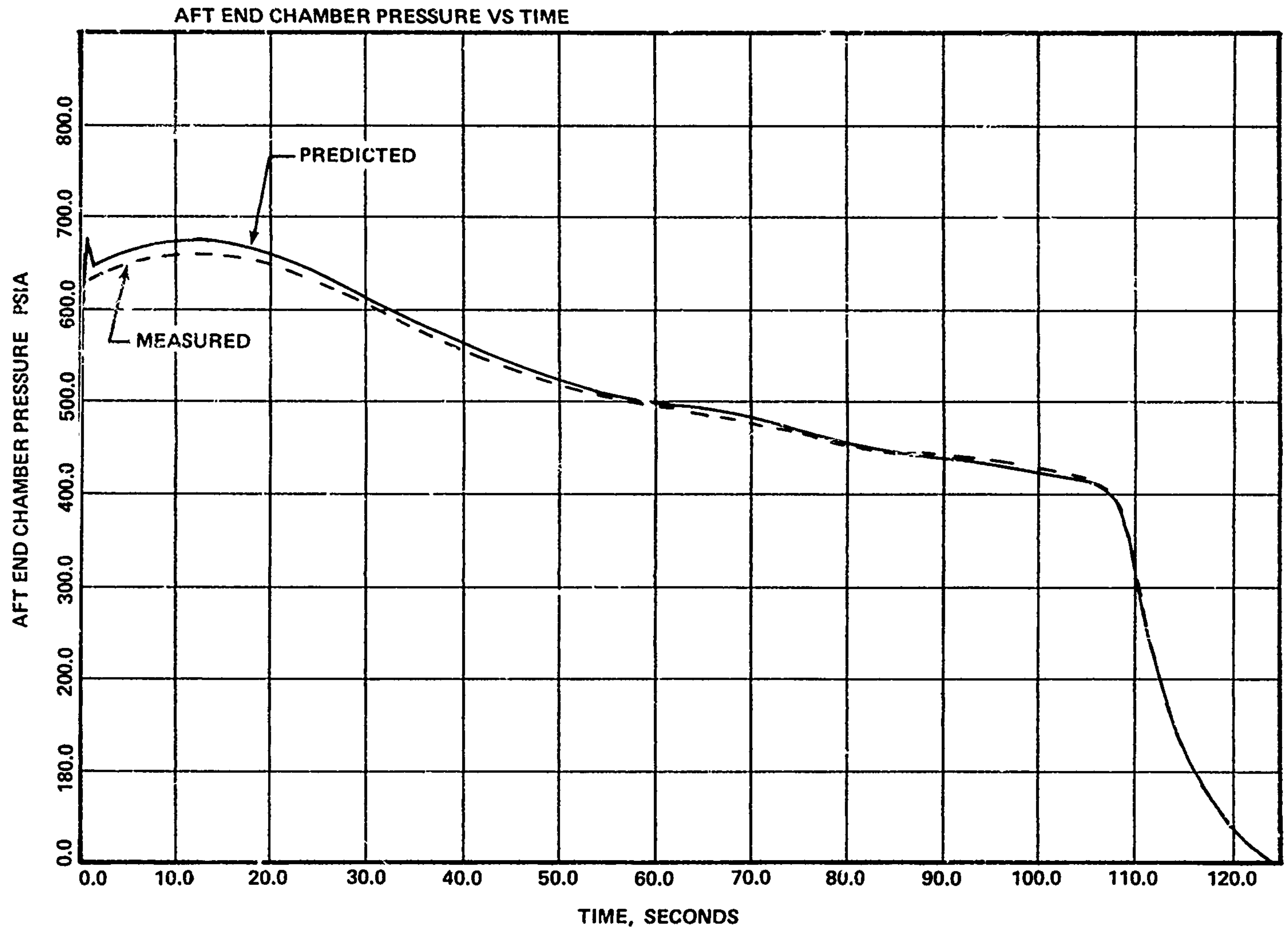


Figure 13. RPL Solid Strand/LF13 Predicted and Measured Chamber Pressure Versus Time

program uses four to six small ballistic motors at $1,500/each for two full-scale motors. By using the solid strand burn rate technique in lieu of the small ballistic motors, an estimated $60,000 to $90,000 would be saved during the next procurement. The savings are expected to increase even more as future motor procurements are made.

SECTION III
SUMMARY OF RESULTS

The reproducibility of solid strand burn rate tests on cured strands is greatly dependent on sample preparation, sample selection, and technique used in determining combustion ignition and burnout.

The evaluation between the acoustic emission technique and other techniques for determining burn rates showed that the acoustic emission technique would increase precision and accuracy.

The orientation of solid particles was a significant contributor to the burn rate variability study within the cured cartons.

The burn rates between strands taken in the horizontal and vertical directions were significantly different. A correlation between solid rocket motor performance and solid strand burn rate measurements was established.

The results of this effort have demonstrated the applicability of using the solid strand burn rate technique for predicting full-scale motor performance for current and future Air Force systems.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this program, it is recommended that the solid strand burn rate techniques be used by government and industry for predicting large motor performance for such motors as Minuteman, Poseidon, C-4, and Space Shuttle.

Other applications in which the acoustic emission technique may be employed, such as determining accurate burn time for motors, should be investigated.

This program has shown that an effective sampling plan is very important if a correlation between full-scale motors and solid strand burn rate is to be established. AFRPL has demonstrated a sampling plan which did insure reproducibility burn rates within one percent.

The anisotropic occurrence due to particle orientation found in the variability study could have affected the results of the liquid strand and, as a result, may affect the correlation between liquid strands, SSBR, and the large motors.

The solid strand sample preparation used in this program has demonstrated the ability to control the cross-sectional area of the strands along with reducing sample preparation time as compared with the conventional methods.

REFERENCES

Report

United Technology Center - Report No. 4310 73-51-1 October 1973, Unclassified, D. L. Aldin

Drawings

Drawings of the propellant cutting to' are available from AFRPL/MKMB, Edwards CA 93523, Attn: Mr. James L. Koury

Acoustic Emission System

Test set and specification for the Acoustic Emission System may be obtained from AFRPL/MKMB (Mr James L. Koury), Edwards CA 93523