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SPACE SHUTTLE MAIN ENGINE RADIO FREQUENCY EMISSIONS

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November 1988

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CONTENTS

SUMMARY iv

INTRODUCTION 1

Background 1
Objectives 1

EXPERIMENTAL METHODS 2

Approach 2
Apparatus 2
Experiment Description 5
SSME Description 6
Test Stand/Installation 6

RESULTS 7

CONCLUSIONS 13

RECOMMENDATIONS 14

APPENDIX--COMPONENTS AND SETTINGS FOR THE SPECTRUM ANALYZER USED IN THE LOCAL VIDEO RECORDING AND REMOTE SITE MONITORING SYSTEMS 15

FIGURES

1. Antenna Location, RFE Measurement Systems 3

2. RFE Measurement Systems 4

3. Engine 0211, Test 901-582, Thrust Profile 5

4. Comparison of Spectral Waveforms Before and After Test Firing as Measured on August 29, 1988 8

5. Six Sequential Video Displays of Plume Emission Spectral Signatures Before, During, and After SSME Test Firing 9

TABLE

RFE from the SSME Exhaust Plume, Expressed in Terms of Spectral Line Amplitude (in microvolts) from 25 to 43 MHz 12

SUMMARY

Several approaches to develop a diagnostics system for monitoring the operational health of the Space Shuttle Main Engine (SSME) are being evaluated. The ultimate goal is to provide protection for the SSME as well as to improve ground and flight test techniques. One scenario with potential is to measure Radio Frequency Emissions (RFE), if present, in the exhaust plume and correlate the data to engine health. The work reported herein is the first step in evaluating this approach.

An RFE detection system was designed, the equipment leased, and the components integrated and checked out to conduct a quick-look investigation of RFE in the SSME exhaust plume. The system was installed on the A-1 Test Stand at Stennis Space Center, and data were successfully acquired during SSME firings from May 3 to September 15, 1988. The experiments indicated that emitted radiation in the RF spectrum (20-470 MHz) definitely exists in the SSME exhaust plume, and is of such magnitude that it can be distinguished from background noise during the firing. Although additional efforts are necessary to assess the merit of this approach as a health monitoring technique; the potential is significant, and additional studies are recommended.

SPACE SHUTTLE MAIN ENGINE RADIO FREQUENCY EMISSIONS

INTRODUCTION

Background

Widespread efforts are currently underway to develop an engine diagnostics system to monitor the Space Shuttle Main Engine (SSME) (and subsequent engines) during operation in order to detect component degradation. Theoretically, the development of such a system, combined with a feedback control system to shut down the engine, can be utilized to avoid catastrophic engine failure. Several approaches are being evaluated to accomplish this goal, and those with the most potential will be pursued to a greater extent. One scenario with apparent potential is to measure the emitted radiation in the radio frequency (RF) spectrum in the SSME exhaust plume and to correlate the data to engine health. Since the plume is a cool plasma with ions accelerating at various rates, the characteristics of these products of combustion quite possibly are related to the normal or abnormal status of engine operation. Although it is generally known that electromagnetic energy is indicated in the plume as noise or electromagnetic interference (EMI), no known studies have been previously conducted or measurements taken in the RF spectrum to support this approach.

The work reported herein was conducted at the Stennis Space Center (SSC) under TWR No. CB-NEMI, using Center Director Discretionary Funding (CDDF), at the request of the Technical Operations Division of the Center Operations Office of NASA. The results of the test were obtained by Sverdrup Technology, Inc., SSC Group, Technical Support Services Contractor at the SSC, Tektronix, and Rhode & Schwarz.

The data presented were acquired at the A-1 Test Stand during the period of May 3 to September 15, 1988. The NASA Technical Monitor was D.J. Chenevert and the Sverdrup Project Manager was L.R. Smith. Key personnel in accomplishing the work were Dr. S.T. Wu (NASA) and E.L. Valenti, A.W. Rester, and J.C. Lau (Sverdrup).

Objectives

The objectives of the efforts reported herein were to perform a quick-look baseline experiment to confirm that RF signatures exist and to document the measurement of the emissions in the SSME exhaust plume. The long-range objective is to establish a relationship between RF signatures and engine health.

EXPERIMENTAL METHODS

Approach

To accomplish the quick-look baseline experiment, an industry survey was conducted to determine the most suitable, off-the-shelf hardware currently available to measure radio frequency emissions (RFE). From the results of the survey, the desired components were selected and either purchased or leased depending on cost and anticipated future use. Then the system was assembled, checked out, installed on the A-1 Test Stand at Stennis Space Center, and operated during Space Shuttle Main Engine (SSME) static test firings. The data acquired were analyzed and evaluated to determine the existence of RFE and also to begin formulating a perspective of the potential use of RFE as an engine health monitoring technique.

Apparatus

Basically, three components or subsystems were required to perform the experiment:

1. An RFE field-strength receiver (antenna)

2. An electromagnetic (EM) wave spectrum analyzer

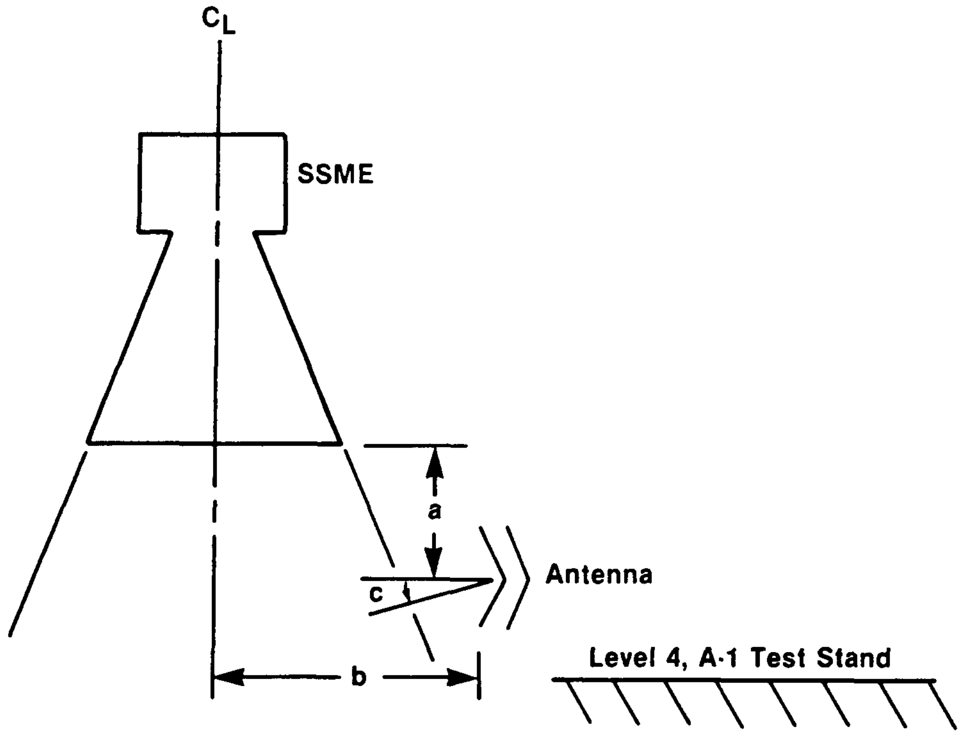
3. Associated computer and recording systems to process and store the data.

Since no known previous studies on RFE in the SSME exhaust plume were available for reference, it was necessary to select a system to cover and fast-sweep a wide frequency range in the spectrum, i.e., from essentially 0 to 1000 MHz in real time. Two instrumentation systems were used.

- A regular VHF/UHF TV antenna (already on hand and covering an approximate range of 20-800 MHz) was used in all four of the experiments discussed herein.

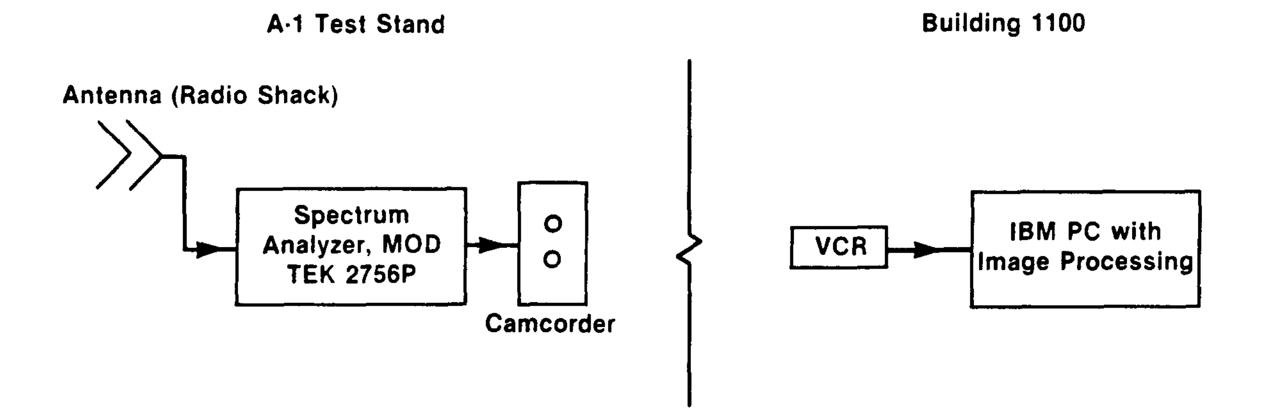
- A calibrated, log periodic antenna (covering an approximate range of 200-1000 MHz) was also purchased, installed, and used for the latter two experiments as part of a second, independent detection system.

The initial system, referred to as the Local Video Recording System, was contained totally at the A-1 Test Stand, and was set up, turned on, and left running before personnel were evacuated for the SSME firings. The second, or Remote Site Monitoring System, utilized a telephone interconnect and additional computer systems to allow monitoring and adjustment of frequency settings (on the spectrum analyzer) from a protected area (Building 4301) during the actual static firings. A separate spectrum analyzer was coupled to each antenna and its respective computer system to provide system independence. Schematics of the two system configurations are shown in Figures 1 and 2, with the respective listing of equipment, model numbers, and other pertinent information listed in the Appendix.

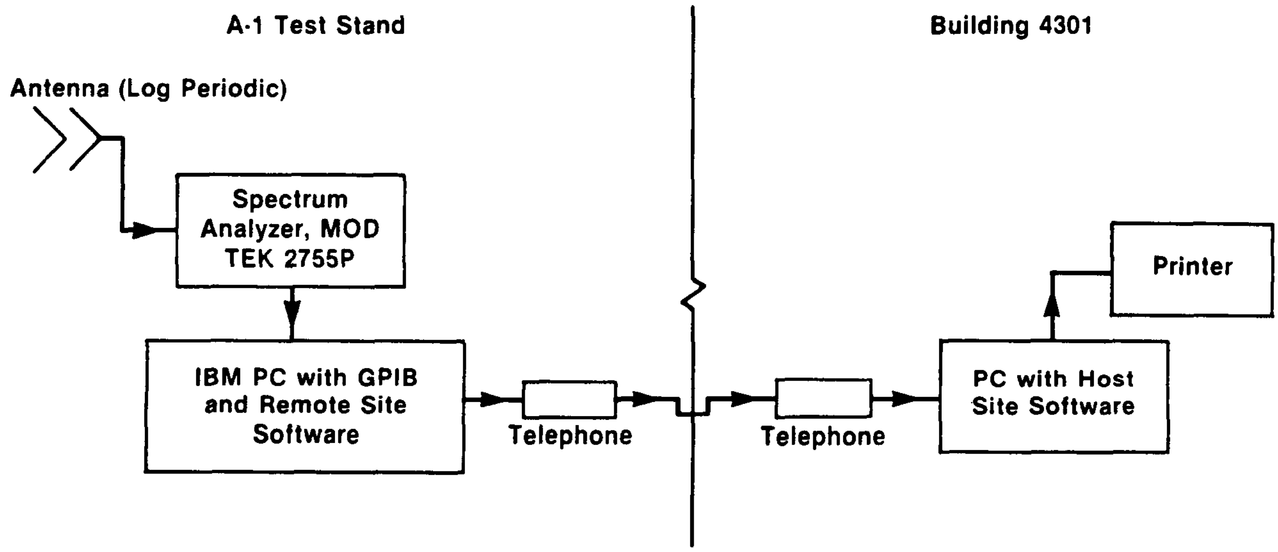


	Monitoring System	
Antenna Location	Local Video	Remote Site
a = Distance from nozzle exit to center of antenna (ft)	0.0	2.5
b = Distance from nozzle center line to antenna (ft)	24.5	26.0
c = Antenna viewing angle—degrees from horizontal	15.0	0.0

Figure 1. Anntenna Location, RFE Measurement Systems



a. Local Video Recording System



b. Remote Site Monitoring System

Figure 2. RFE Measurement Systems

Experiment Description

The experiments were conducted during the period May 3 to September 15, 1988. Several baseline measurements were obtained during SSME static firings from May 3 to August 29, 1988, during which the system was checked out and personnel became familiar with the equipment. However, the primary test, which was investigated with a full-up system following resolution of early problems, was conducted on September 15, 1988 (Test No. 901-582). The duration of this firing was 50 sec and it occurred at approximately 7:00 p.m. The data from this experiment are presented in the Conclusion along with data from the last baseline experiment. The SSME Run Schedule/Thrust Profile is shown in Figure 3 for the September 15 test.

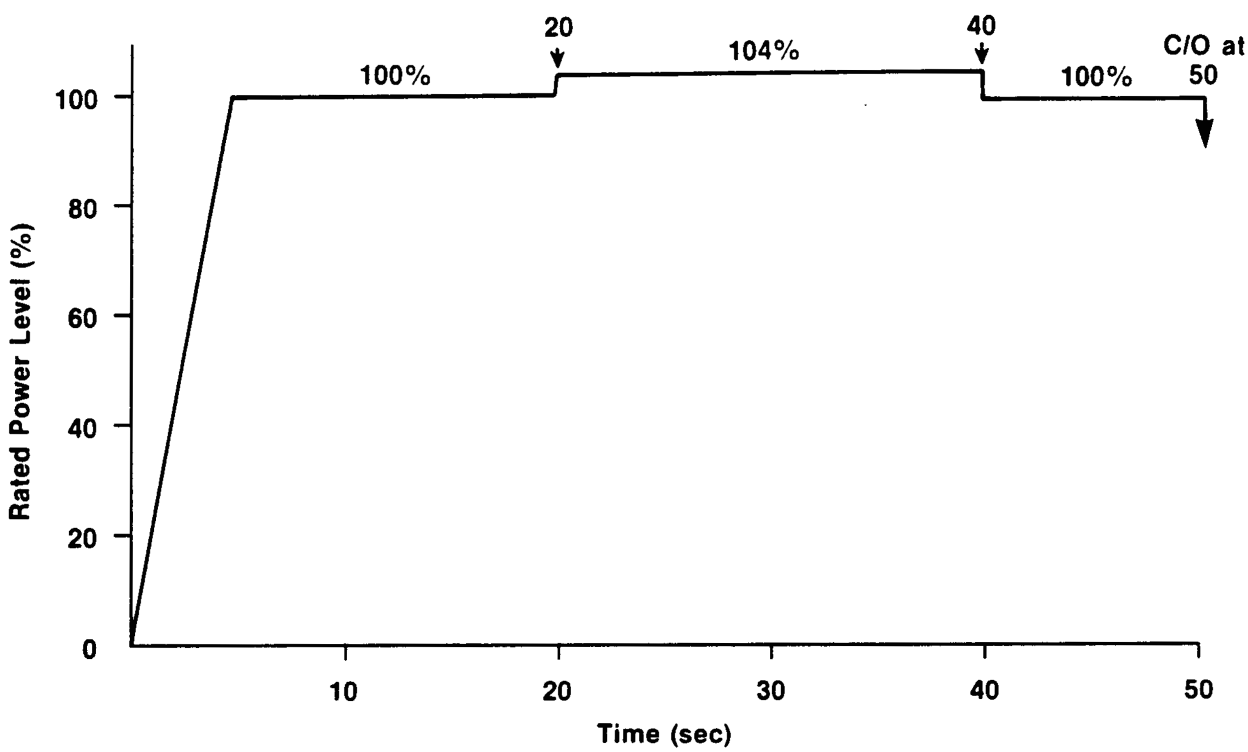


Figure 3. Engine 0211, Test 901-582, Thrust Profile

The RFE propagated in the exhaust plume were received by the antenna and transmitted to the spectrum analyzer where the signals were converted to a function of frequency and voltage. The output was then recorded on the camcorder (for the Local Video Recording System) and after the firing was processed on an IBM PC located in Building 1100, or transmitted through the telephone interconnect and processed in near real time on the IBM PC in Building 4301 (for the Remote Site Monitoring System). The data were then analyzed and evaluated to determine the presence of EM energy and whether or not it could be distinguished from background noise.

SSME Description

The SSME is a liquid propellant (LOX/LH_2), pump-fed, regeneratively cooled rocket engine that develops 393,000 lb of thrust (104% of rated power level) at sea level conditions. The SSME has a nozzle area ratio of 77 and, with an oxidizer/fuel ratio of 6 (a total mass flowrate of 1081 lbm/sec), operates at 3126-psia combustion chamber pressure and 3000 °F chamber temperature. SSME S/N 0211 was undergoing production testing at the A-1 Test Stand when the experiments discussed herein were conducted.

Test Stand/Installation

The A-1 Test Stand was designed and built to accomplish static testing of the Saturn V, S-IC engine at ambient conditions. Following the end of the Apollo Program, the test was modified to accomplish similar testing of the SSME engine. The RFE Detection System was installed on the fourth level of the A-1 Stand, and the RF antennas were positioned near the SSME exhaust nozzle to receive the emitted radio waves.

RESULTS

Several baseline RFE measurements (using max-hold, and later remotely controlled sweep-frequency techniques) were conducted from May 3, 1988 to August 29, 1988. In addition to establishing a baseline, these initial operations provided the necessary checkout period required to identify inherent problems with the equipment and techniques used, and also allowed the personnel to become familiar with the systems operation. These early tests are discussed below:

1. May 3, 1988--(760-sec SSME test firing). Using the max-hold technique with the Tektronix 2756P Spectrum Analyzer, and by comparing the recorded spectral waveforms before, during, and after the test firing; it was found that the exhaust plume did radiate EM energy in several spectral regions: 20 to 100, 140 to 160, 400 to 420, and 460 to 470 MHz. The maximum amplitude differences were more than 20 dBm from the regular noise level. However, since the max-hold technique was used, no real-time amplitude variations on the dynamics of spectral signatures were recorded.

2. July 20 and 21, 1988--Rhode & Schwarz, designers and manufacturers of EMI and RFI instrumentation, were contacted for the purpose of using their spectrum analyzer FSA in place of the Tektronix 2756P to conduct a demonstration measurement of RFE from the SSME exhaust plume during test firings on July 20 and 21. The results were similar to those obtained from the previous measurements, which utilized the Tektronix Model 2756P Spectrum Analyzer. The two sets of measurements confirmed that electromagnetic energy is radiated in several spectral regions of the SSME exhaust plume.

3. August 29, 1988--(1040-sec SSME test firing). Two Tektronix spectrum analyzers were used to measure RFE: Model 2755P with max-hold, remote-site control techniques, and Model 2756P with run-time display of spectral waveforms using a video camcorder to record real-time amplitude variations or the dynamics of spectral signatures from the scope. The video recording failed due to low battery power, but the offsite system did record a very prominent RF radiation in the spectral range of 20 to 40 MHz (as shown in Figure 4).

Following the baseline experiments, data were then acquired that yielded the following results:

1. September 15, 1988--(50-sec SSME test firing). The encouraging results obtained on August 29 indicated the need for additional measurements with spectral bandwidth set at 4 to 44 MHz. To resolve the problem previously encountered, an AC adapter was used to power the camcorder. The tape recorded the dynamics of spectral signatures from the scope, and the recorder images were sequentially "frame-grabbed." The RFE from the SSME exhaust plume expressed in terms of spectral line amplitude variations, in microvolts, from 25 to 43 MHz are shown in the table. There are significant amplitude variations both in 29 to 31 MHz and 34 to 38 MHz spectral bands. Figure 5 also illustrates these variations.

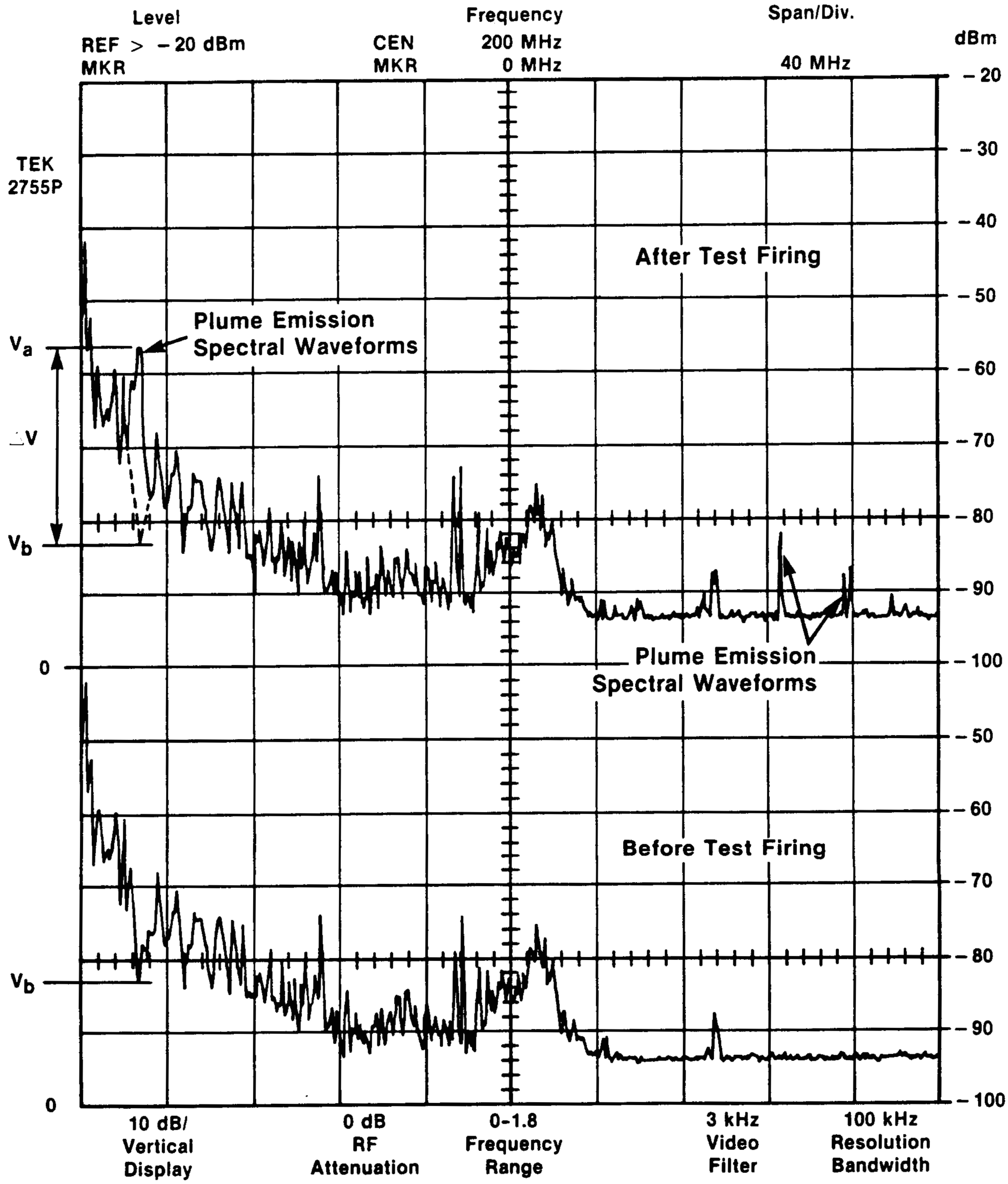


Figure 4. Comparison of Spectral Waveforms Before and After Test Firing as Measured on August 29, 1988

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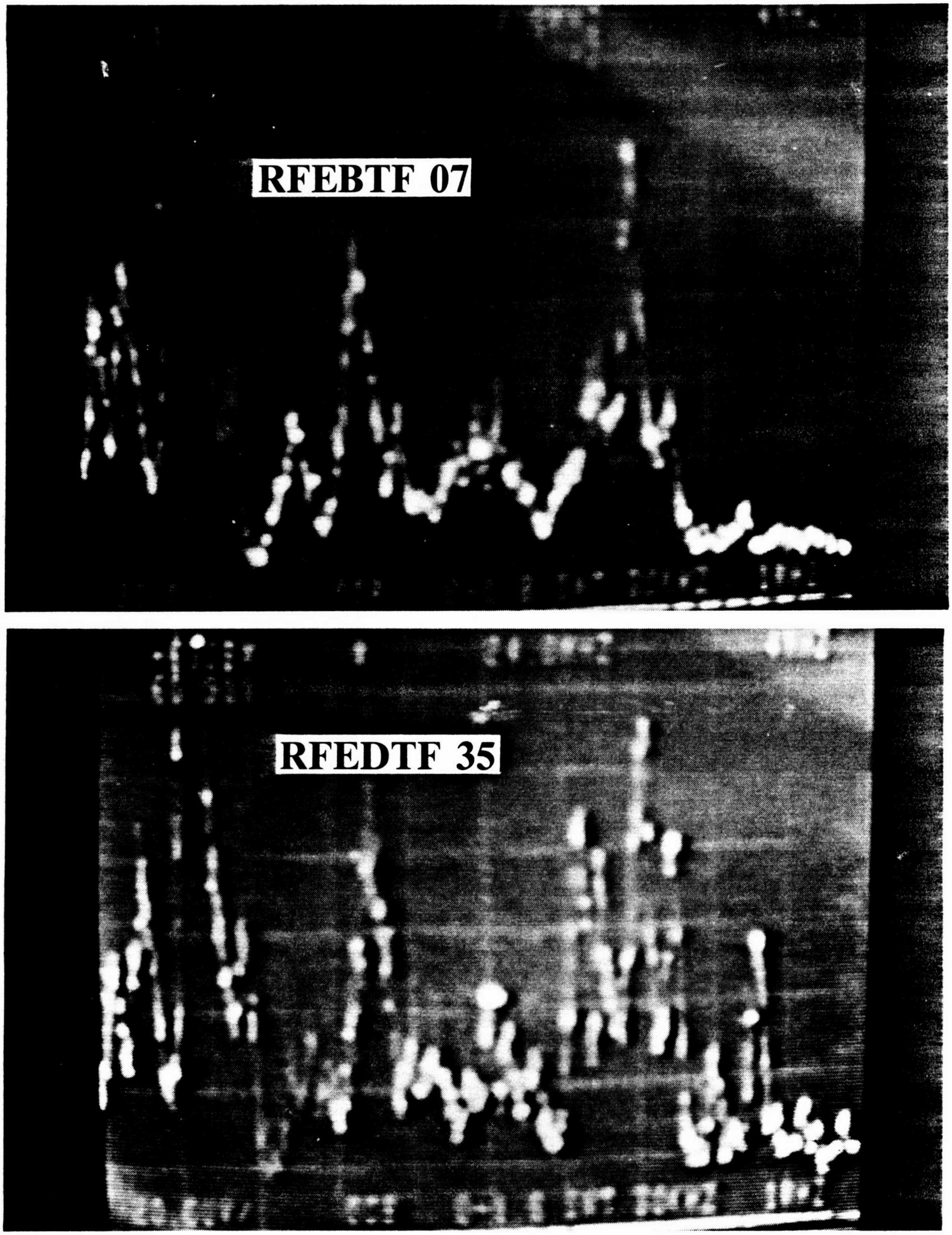

Figure 5. Six Sequential Video Displays of Plume Emission Spectral Signatures Before, During, and After SSME Test Firing

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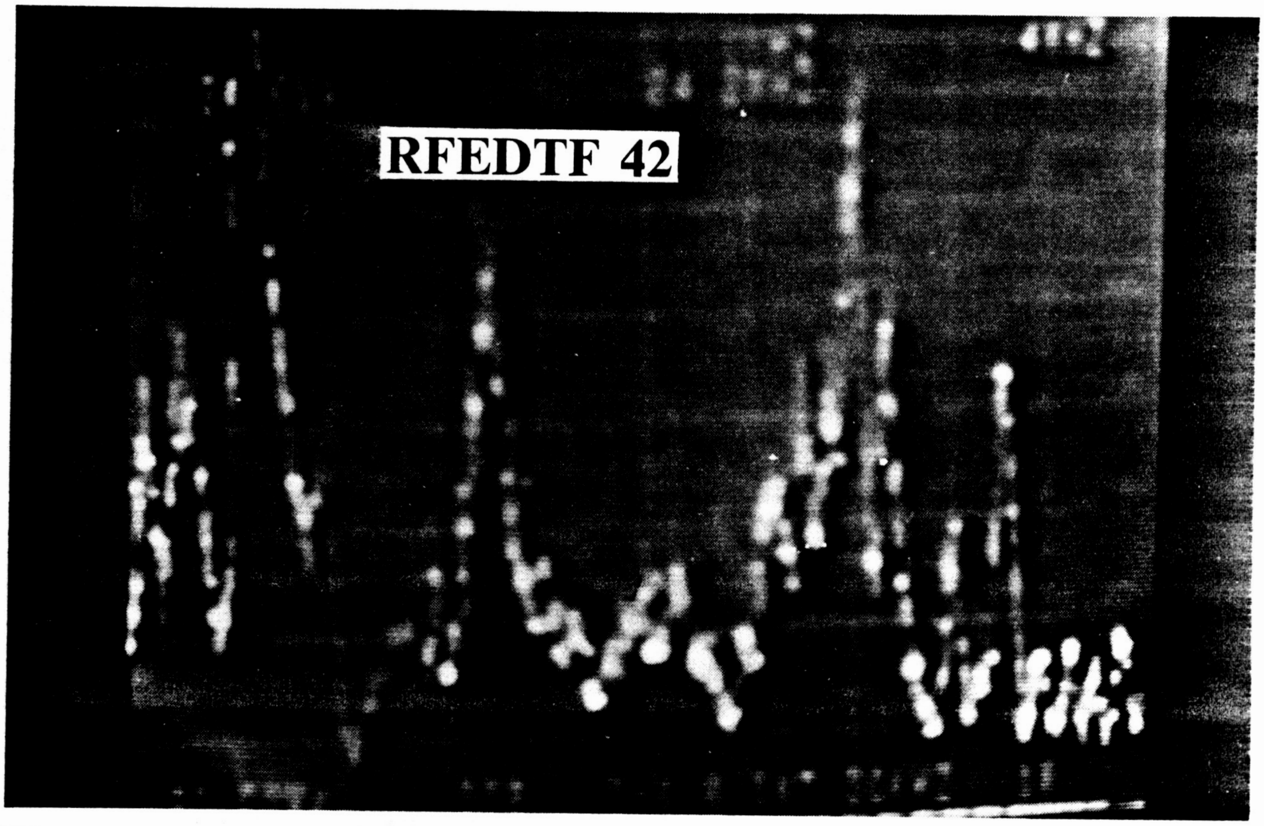

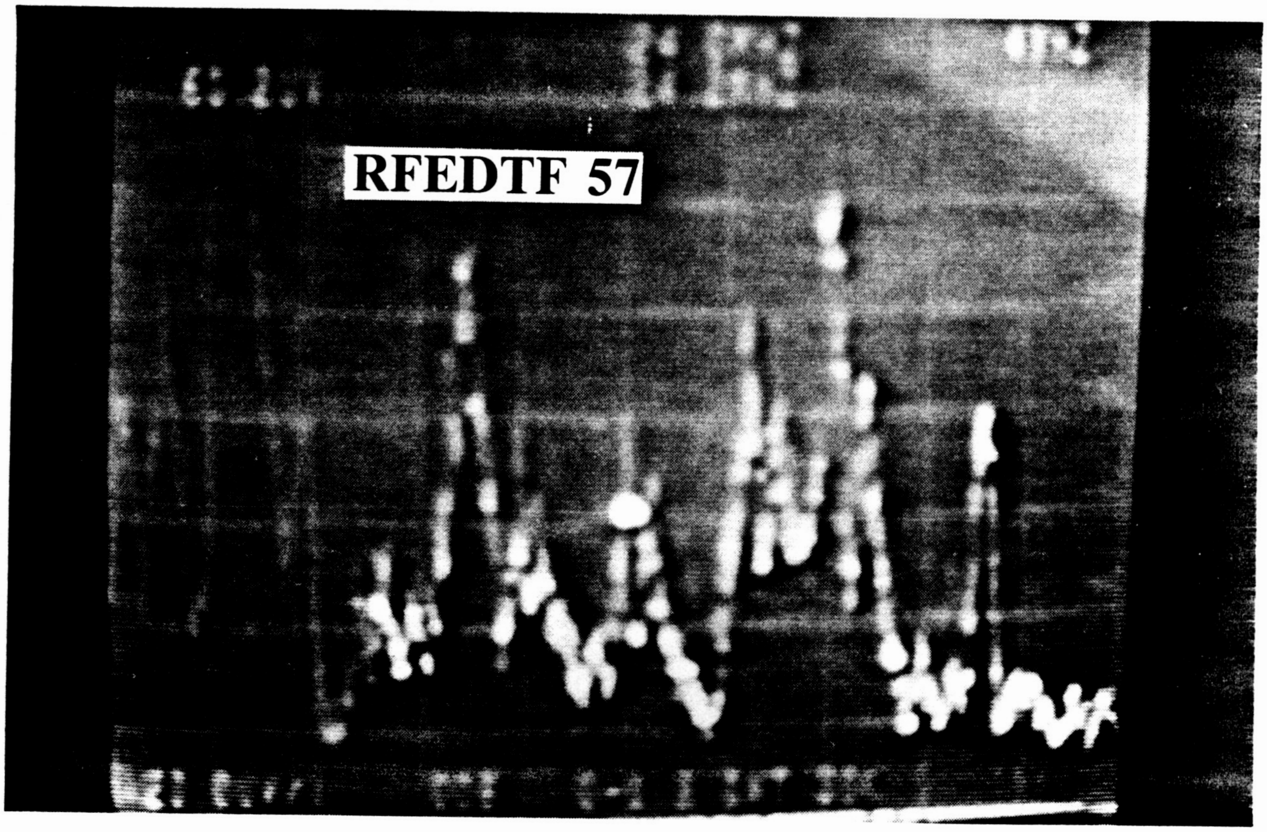

Figure 5. Six Sequential Video Displays of Plume Emission Spectral Signatures Before, During, and After SSME Test Firing (Continued)

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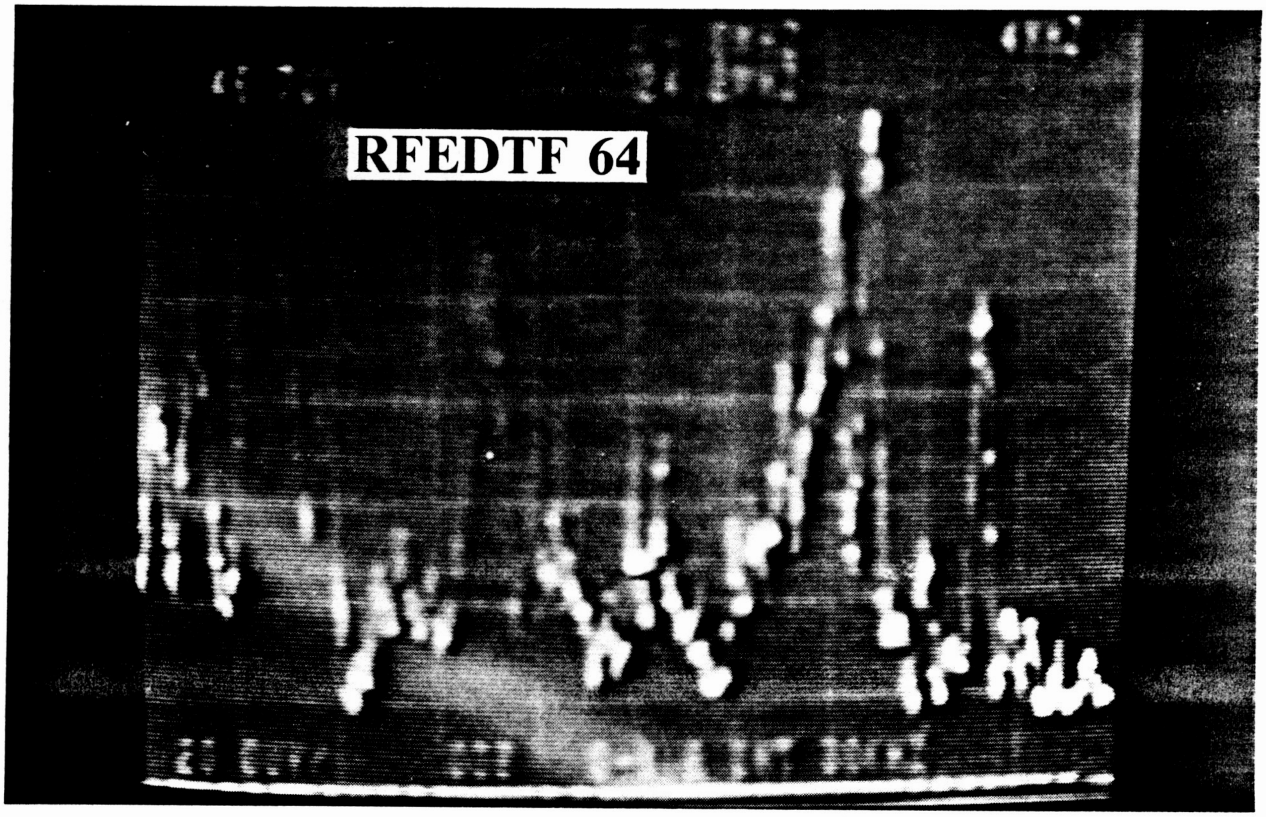

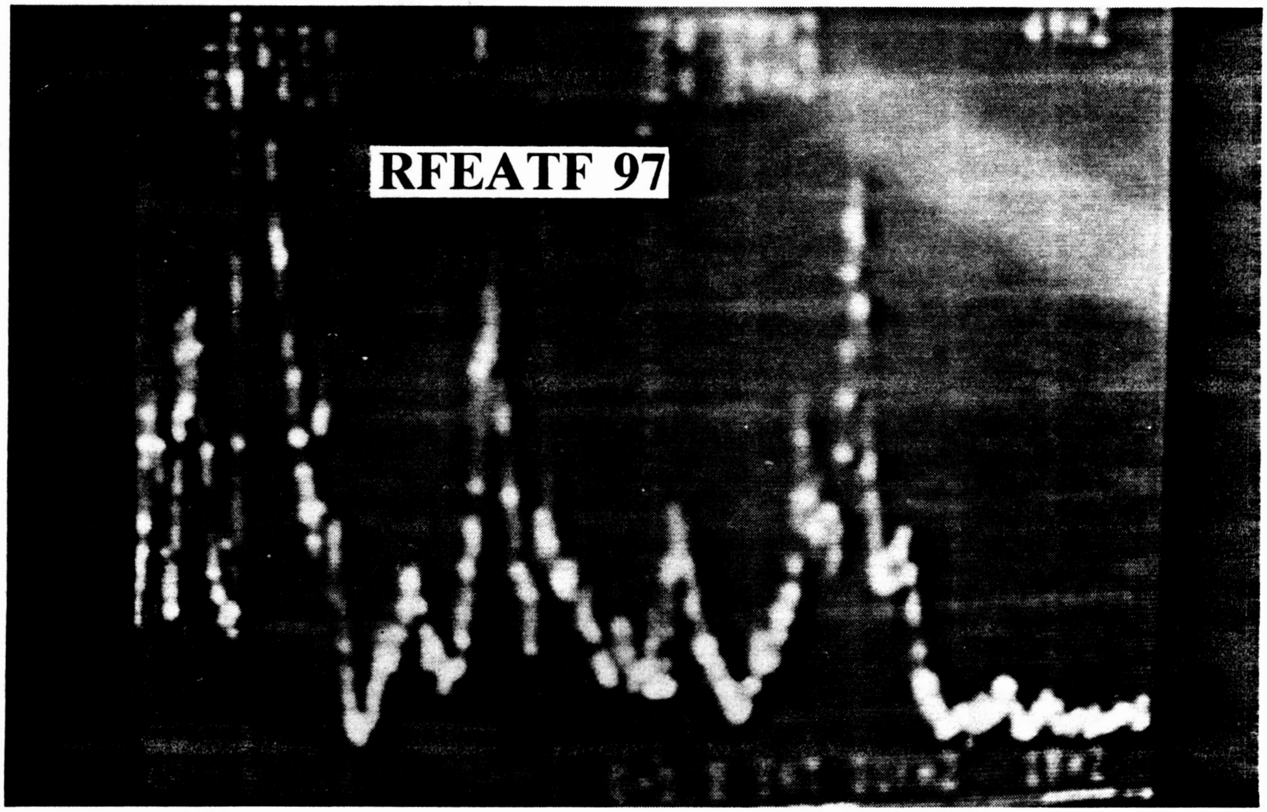

Figure 5. Six Sequential Video Displays of Plume Emission Spectral Signatures Before, During, and After SSME Test Firing (Continued)

Table. RFE from the SSME Exhaust Plume, Expressed in Terms of Spectral Line Amplitude (in microvolts) from 25 to 43 MHz.

	Frequency (MHz)											
Data File ID*	25	29	30	31	32	34	36	38	40	41	42	43
Baseline before test												
RFEBTF 07	61	--	70	--	120	56	--	26	--	--	--	--
Data during test												
RFEDTF 32	60	--	90	<u>95</u>	131	118	41	72	32	30	31	28
RFEDTF 35	60	<u>110</u>	100	--	130	102	48	75	30	31	25	26
RFEDTF 42	50	70	91	93	141	102	<u>60</u>	91	32	33	20	37
RFEDTF 53	60	<u>110</u>	--	--	124	120	40	80	32	29	30	29
RFEDTF 57	65	100	100	--	120	86	35	80	28	26	25	25
RFEDTF 60	60	70	70	90	131	<u>145</u>	55	90	36	37	28	25
RFEDTF 64	70	60	<u>115</u>	--	120	132	50	<u>100</u>	35	33	30	29
RFEDTF 68	68	86	79	87	122	140	56	95	--	40	--	32
Baseline after test												
RFEATF 97	61	--	80	--	122	55	--	24	--	--	--	--

*Data File ID Code:

RFE = Radio Frequency Emissions
ATF = After Test Firing
BTF = Before Test Firing
DTF = During Test Firing
07, 32, etc. = Video frame numbers

CONCLUSIONS

Measurements of RFE from the SSME exhaust plume using a spectrum analyzer system identified several spectral bands of electromagnetic radiation. The use of a video camcorder to record the run-time spectral waveform captured the dynamics of the emission spectral signatures. These preliminary results indicate that future efforts should definitely be pursued as a potential means of engine health monitoring or anomaly condition detection. The approach taken was innovative and the results were significant. To maintain a low-cost initiative, the main measurement system (spectrum analyzer and computer systems) was leased. Since the A-1 Test Stand was inaccessible during the test firing, a remote-site interface system was implemented using a host computer and a remote-site control computer. To capture the real-time emission spectral signature variation, a video camcorder was used to record the real-time emission spectral waveforms.

The following conclusions were developed:

1. The small data sets obtained to date are qualitative, but not conclusive.

2. The efforts should be continued in order to acquire additional data using the same techniques.

RECOMMENDATIONS

To further these study efforts, the following items are recommended:

1. Obtain the same measurements at SSC's Diagnostic Test Facility (DTF) investigating different spectral regions, i.e., from 100 KHz to 50 MHz. The DTF thruster should emit electromagnetic energy in much lower frequency regions because of temperature, pressure, firing duration, and thrust.

2. The spectrum analyzer system was leased for six months (through January 1989). To acquire additional data, a one-year extension of this lease is recommended.

3. In addition to the lease extension, the current measurement system should be upgraded to include:

   a. A new antenna with calibrated operating frequency ranging from 10 to 200 MHz.

   b. Modification of the programmable part of the spectrum analyzer to be capable of storing the spectral waveform data to computer random access memory, cache, or expand memory in real time. (This will replace the use of a camcorder to record the real-time spectral waveforms, and the digitally stored spectral data are much better for the study of plume emission spectral signatures.)

   c. Direct measurement of radiation field strength, using RFI receivers (manufactured by Rhode & Schwarz, Electro-Metrics, and others). Direct measurement is recommended for future investigation, since the technique provides better accuracy and faster data acquisition when emission spectral bands are located.

APPENDIX

COMPONENTS AND SETTINGS FOR THE SPECTRUM ANALYZER USED IN THE LOCAL VIDEO RECORDING AND REMOTE SITE MONITORING SYSTEMS

APPENDIX

COMPONENTS AND SETTINGS FOR THE SPECTRUM ANALYZER
USED IN THE
LOCAL VIDEO RECORDING AND REMOTE SITE MONITORING SYSTEMS

Components of the Local Video Recording System

Component	Description
Log periodic antenna	Electro-Metrics Model No. LPA-30
Antenna cable	rg-59/u; 75 ft
Spectrum analyzer	Tektronix model no. 2756p
TV camcorder	Panasonic model no. PV 330
VCR	Realistic HQ PLL model no. 41
PC with image processing card and software	IBM PC/AT; Targa/AT&T-24

Settings for the Spectrum Analyzer Used in the Local Video Recording System

Parameter	Setting	Parameter	Setting
Center frequency	24 MHz	Linear vertical display	ON
Span division	4 MHz	Auto resolution bandwidth	ON
Reference level	(-) 63 dBm	Video filter wide	ON
Vertical display	20 V/div	Marker threshold auto	ON
RF attenuation	0 dB	Grating illumination	ON
Frequency range	0-1.8	Readout	ON
Reference oscillator	INT	Digital storage view A	ON
Video filter	30 kHz	Triggering free run	ON
Resolution bandwidth	1 MHz	Time/division	AUTO

Components of the Remote Site Monitoring System

Component	Description
VHF/UHF antenna	Radio Shack model no. VU-75
Antenna cable	RG-59-U; 75 ft
Spectrum analyzer	Tektronix model no. 2755P
PC with GPIB Card and Remote-Site Software	IBM PC/AT; IBM GPIB card; Tektronix model No. S26RM01 V.1.00 RSM (remote site) program disk, and V.1.30 RSM (remote site) system disk; Norton-Lambert Close-up (customer), Tektronix Version, V1.10
Telephone/Modem System	Intecom Corp. model no. IBX; ITE 12B DOB1A (operated at 9600 baud)
PC with Host-Site Software	IBM PC/AT; Tektronix model no. S26RM01 V.1.00 RSM host-site disk; Norton-Lambert Close-up (support), Tektronix Version, V1.10
Printer	Epson FX 286E

Settings for the Spectrum Analyzer Used in the Remote Site Monitoring System

Parameter	Setting	Parameter	Setting
Center frequency	200, 400, 600, 800 MHz	10 dB/Div. vertical display	ON
Pan division	40 MHz	Auto resolution bandwidth	ON
Reference level	(-) 23 dBm	Video filter wide	ON
Vertical display	10 dB	Marker threshold auto	ON
RF attenuation	10 dB	Grating illumination	ON
Frequency range	0-1.8	readout	on
Reference oscillator	INT	Digital storage view a	on
Video filter	30 kHz	Triggering free run	ON
Resolution bandwidth	1 MHz	Time/division	AUTO

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15. Supplementary Notes

NASA Technical Monitor - D. J. Chenevert
NASA Investigator - Dr. S. Wu

16. Abstract

Several approaches to develop a diagnostics system for monitoring the operational health of the Space Shuttle Main Engine (SSME) are being evaluated. The ultimate goal is providing protection for the SSME as well as improving ground and flight test techniques. One scenario with some potential is measuring radio frequency (RF) emissions (if present) in the exhaust plume and correlating the data to engine health. The work reported herein was the first step in evaluating this approach. An RF emissions detection system was therefore designed, the equipment leased, and the components integrated and checked out to conduct a quick-look investigation of RF emissions in the SSME exhaust plume. The system was installed on the A-1 Test Stand at Stennis Space Center, MS, and data were successfully acquired during SSME firings from May 3 to September 15, 1988. The experiments indicated that emitted radiation in the RF (20-470 MHz) spectrum definitely exists in the SSME exhaust plume, and is of such magnitude that it can be distinguished during the firing from background noise. Although additional efforts are necessary to assess the merit of this approach as a health monitoring technique, the potential is significant, and additional studies are recommended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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