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Space Shuttle Main Engine Health Monitoring with Exhaust Plume Emission Spectroscopy

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The spectral data from some recent engine test firings at the A-1 test stand are presented and discussed. On Jan. 25, 1996, test 901-853, a planned 754-s test on block II development engine 0523, was cut by the plume observer at approximately 553 s due to abnormal streaking and flashing in the plume. Also, increased vibration levels and degrading turbine performance were observed. The alternate turbopump high-pressure fuel turbopump experienced major turbine damage during the test. Space Shuttle main engine exhaust plume emission spectral data obtained by various instrumentation are described for test 901-853 and tests 901-851 and 901-852 in which the same four turbopumps were utilized on engine 0523. Spectral data show extreme sensitivity of this technology in detecting abnormal wear of metallic components. The optical multichannel analyzer systems observed emission lines of Ni, Cr, Fe, Co, Al, Mn, Cu, Ag, and Pd during several major plume events during test 901-853. It is the largest number of metallic elements observed at one time in the plume at the Stennis Space Center ever since the exhaust plume emission spectroscopy technology was first implemented at the A-1 test stand in 1989. Most of the emission events in test 901-853 are highly localized in the plume as evidenced by high-speed and low-speed video cameras. This nonuniformity introduces additional complications for the mass quantification algorithms. These algorithms have previously shown to be extremely accurate when the assumption of uniform distribution of plume contaminants holds. These quantification problems, somewhat unique to test 901-853 or other tests involving substantial degradation of one or more major line replaceable units such that the plume events are highly localized, are further discussed.

Introduction

PLUME diagnostics technology, in particular exhaust plume emission spectroscopy technology, for Space Shuttle main engine (SSME) ground testing health monitoring at the Stennis Space Center (SSC) has matured from development stages to full fledged system application. Early development of this technology for rocket engines is well documented in Ref. 1. SSME exhaust plume spectral data have been routinely acquired at test stands since 1989 (Ref. 2). Most of the data acquisition, data reduction, and data analysis functions and procedures have been automated. The centerpiece of our automated data analysis system is the engine diagnostics console (EDC).[3,4] The EDC quantifies the effluent material(s) in the plume, under the assumption of uniform distribution of plume contaminants, by utilizing the results obtained from a line-by-line spectral simulation computer program.[5–7] Our spectral data analysis procedures, including material(s) identification and quantification routines, have been sufficiently validated based on independent post-test measurements of the engine components.[4,7] Because of this, the engine test personnel at SSC depend on the plume spectral data for critical information regarding the health of any engine tested at the A-1 test stand.

The spectral data from a series of recent test firings leading up to an incident on engine 0523, test 901-853, on Jan. 25, 1996, are presented. This series of three tests—901-851, 901-852, and 901-853—for block II development engine 0523 were carried out on the A-1 test stand on Jan. 19, Jan. 24, and Jan. 25, 1996, respectively. All three tests were conducted with high-pressure oxidizer turbopump (HPOTP) unit 8208, low-pressure oxidizer turbopump (LPOTP) unit 92502, high-pressure fuel turbopump (HPFTP) unit 8306, and low-pressure fuel turbopump (LPFTP) unit 2316R1. The designation R indicates rebuild. HPOTP 8208 is a Pratt and Whitney alternate turbopump (AT) HPOTP with 12 test firings before test 901-851. All 12 tests utilized engine 0523. HPFTP 8306 is also a Pratt and Whitney AT development unit with no accumulated testing time before test 901-851.

Test 901-851 ran to a programmed duration of 520 s with 335.3 s at 104% rated power level (RPL) and 51.5 s at 109% RPL. All of the primary and secondary objectives were attained, and engine operation was satisfactory with acceptable engine performance parameters. Emissions due to copper and silver occurred throughout the test, and emission lines of Ni, Fe, Cr, Cu, and Al were observed during a plume event lasting 4 s beginning at engine start (E/S) + 395.5 s.

Test 901-852 also ran to a programmed duration of 520 s. The planned test profile consisted of 150.3 s at 104% RPL and 199.5 s at 109% RPL. Again, all of the primary and secondary objectives were met, and the engine performance parameters were within acceptable ranges. Some minor anomalies were noted, including a dip in HPFTP efficiency at the start of 109% RPL operation (255–270 s). Fairly strong emissions of Cu and Ag were observed during a plume event peaking at E/S + 262.5 s.

Test 901-853, a 754-s planned duration test, was cut off at E/S + 553.9 s by the plume observer due to abnormal streaking and flashing in the plume. Very intense plume emissions were also observed by the SSC plume diagnostics team on their near-real-time instrumentation displays. Extremely strong emissions occurred at 130, 276, 283, 404, 551, and 553 s from engine start. The information was reported to the plume observer during the test, who also visually observed the strongest of these events. All of these plume events consisted of emission lines due to Ni, Cr, Fe, Co, Al, Mn, Cu, and Ag. In addition, Pd was observed during all of the preceding events except 276- and 283-s events. This is the largest number of metallic elements observed at one time in the plume at SSC. Detailed spectral data for these three test firings (901-851–901-853) are presented. Spectral data are analyzed and quantification problems are discussed.

Spectroscopic Instrumentation

Currently, each test firing at the A-1 test stand is monitored primarily by three optical multichannel analyzer (OMA) systems, one

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high-speed polychromator, and four video imaging systems. One OMA system monitors the spectral region from 303 to 429 nm. Another OMA system currently monitors the spectral region from 319 to 415 nm. It incorporates a newer and more sensitive detector and currently serves as a backup to the first OMA system. Once a sufficient database has been established, the newer OMA system will replace the first system. The 320–429 nm region covers the primary atomic emission lines of most of the significant SSME metallics.[8] A third OMA system monitors the spectral region from 503 to 757 nm, which covers emission lines for the oxides of titanium and yttrium. Both Ti and Y have weak atomic emission lines, but their oxides have strong bands in the aforementioned region. Two OMA systems have a temporal resolution of 0.5 s; the newer OMA system has a temporal resolution of 0.2 s. The high-speed polychromator monitors emission lines of individual elements with a temporal resolution of 1.0 ms. The four video systems on the A-1 test stand provide visible region imaging of the exhaust plume and the nozzle, near infrared imaging of the nozzle, and long wavelength infrared imaging of the HPFTP. These systems are described in greater detail in Ref. 9.

As noted in Ref. 2, the observed spectral dispersion per element in the spectrometer photodiode array detector for OMA systems is slightly nonuniform. Three factors influence the uniformity of wavelength intervals in dispersive spectroscopic systems. First, dispersive instruments are not perfect instruments that provide a truly linear dispersion of an input signal. As with any optical system, dispersive systems are subject to wavelength-dependent aberration, manufacturing imperfections in the optical components, and the wavelength-dependant efficiency of grating elements. Therefore, spectrometer systems are optimized at one wavelength. Second, the relative mechanical geometry and efficiency from element to element in a detector array are not uniform and can vary ± a few percent in a quality detector causing a nonuniformity in the photoresponse and fill factor across the detector. Third, and most important, is the simple fact that the quantum mechanical nature of optical radiation does not adhere to the same limits as mechanical fabrication does. As a result, detection systems are only an attempt to measure an infinitely variable signal at discrete spatially separated points (typically 1024).

A method of accounting for these nonuniformities must be included in instrument calibration. To compensate for these nonuniformities a wavelength correction curve is generated for an instrument that allows the assignment of correct spatial values for points on the detector array. The method used at SSC uses a cubic spline routine to generate a correction curve at several points on the detector. It should be mentioned that this is a very normal and standard method of wavelength calibration for all sorts of spectroscopic instruments and techniques. Further details of the wavelength and spectral radiance calibration are available in Refs. 2 and 9.

For high temporal resolution of plume emission events, a high-speed polychromator system (HSPCS) is utilized. The HSPCS also provides precise time stamps for observed plume anomalies. The HSPCS is a 16-channel instrument designed to provide a detection system with fast temporal response to plume anomalies involving any of the seven elements Cr, Mn, Co, Fe, Ni, Ag, and Cu and two OH spectral branch main heads[10] in the 306.4-nm band system. The instrument currently used at SSC is a redesign of the optical plume anomaly detector (OPAD) system[2] developed and fabricated by Sverdrup Technology at the Arnold Engineering Development Center, Arnold Air Force Base, Tennessee. Main improvements in the HSPCS system are the doubling of temporal resolution compared with the old OPAD system, the much higher signal-to-noise ratio, and the completely new data acquisition and control software. These improvements were achieved through a major redesign and overhaul of electronic and software components. Complete details of the HSPCS are available, along with wavelength calibration procedures, in Ref. 9.

Spectral Data Analysis

During a typical engine firing, three OMA systems collect and archive thousands of spectral scans. Therefore, it is essential that data reduction and data analysis procedures are automated as much as possible. The centerpiece of this automation process is the EDC.[3,4,9,11] The EDC is a tool that automates the process of alloy identification. Most critical SSME components consist of alloys with similar groups of elemental constituents.[12] Therefore, simply identifying elements in the plume does not adequately pinpoint degraded hardware. Because of the specialized environmental properties of SSME alloys,[12] each alloy usually occurs only in a limited number of components. Alloy identification therefore narrows the search for degraded engine components when metallics appear in the exhaust plume. Data from additional engine sensors and rules based on past experience can narrow the list further. The EDC includes an expert system that incorporates data from additional engine sensors, rules based on past experience, and input from human experts. The EDC has been developed at SSC over several years with constant improvements in diagnostics capability and upgrading of various software components.[3,4,9,11]

Table 1 Wavelengths of the atomic lines used by the EDC

Element	Wavelength, nm
Ni	361.94
Fe	371.99
Cr	425.43
Co	387.31
Mn	403.08
Cu	327.40
Ag	338.29
Al	396.15
Ca	422.67
Pd	363.47

The central components of the EDC are radiance lookup tables for quantifying elemental plume contaminants. The EDC currently can quantify 10 elements in the SSME exhaust plume. These elements are Ni, Fe, Cr, Co, Mn, Cu, Ag, Al, Ca, and Pd. The quantification procedure for the first five of these elements has been validated by utilizing spectral data from test firings where the amount of a particular elemental material in the plume is known.[4,7] Therefore, greater confidence is placed in quantification results for Ni, Fe, Cr, Co, and Mn. The EDC quantifies elements in the plume by computing the radiance of one atomic emission line for each element and comparing the computed radiance to values in lookup tables. Table 1 gives the wavelengths (in nanometers) of the atomic lines that the EDC uses.

The lookup tables contain the radiance values of atomic emission lines at many different concentration levels in the plume. For all elements except Mn in the EDC, the range of plume concentration contained in the lookup tables is 0.0–1.5 ppm. For Mn, this range is 0.0–0.15 ppm because Mn is an extremely strong emitter and therefore detectable at less that 1.0 ppb and because Mn is a very minor constituent of SSME alloys.[12] Elemental lookup tables are constructed by utilizing a line-by-line (LBL) spectral simulation code.[6,7]

Line-by-Line Code

The radiance lookup tables are generated by running the LBL code at several concentrations for each SSME element at several power levels of interest. The SSME is commonly test fired at 90, 96, 100, 104, and 109% RPL. The LBL code, originally developed at NASA Ames Research Center[5,13] and available through the NASA Computer Software Management and Information Center, Athens, Georgia, was acquired by SSC in 1989. The program assumes a Voigt line profile and allows the computed spectral intensity to be printed or plotted as a function of wavelength over any arbitrary wavelength interval, or the computed spectrum can be convoluted with an entrance slit function and an instrument sensitivity to simulate a scanned spectrum. It allows the simulation of a spectrum for either optically thin (no self-absorption) or optically thick (self-absorption) conditions. It has been modified by us for application to SSC exhaust plume spectral data analysis.[6,7] By adapting this code for SSC applications, resource requirements were minimized for the code development and implementation.[14,15]

The original LBL code[5,13] computes the instrument output signal (spectral radiance) at a uniform wavelength interval. However, as explained earlier, the observed spectral dispersion per element in the spectrometer/photodiode array detector setup for OMA systems

is slightly nonuniform. For tests 901-851–901-853, the wavelength calibration remained the same, and the spectral range was 302.571–428.822 nm for all three tests. At the lower end of this range, the spectral dispersion per element is 0.124 or 0.125 nm, and at the upper end of the spectral range, it is 0.121 or 0.122 nm. We modified the LBL code so that the wavelength values in the code for instrument output signal computations are obtained by using a cubic spline fit that is identical to the OMA wavelength calibration curvefit.[6,15] It required considerable ingenuity to introduce the nonuniform spectral interval for output computations without affecting other functions and parameters in the program.[6,15] Obviously, we have an excellent match between the experimental and theoretical output wavelength matrices, and there is no need to resort to convoluted modeling procedures.[16,17]

Another important feature of our LBL calculations is incorporation of multiple layers for radiance computation wherein each layer is specified by a different thermochemical and thermodynamic environment. This methodology is a vast improvement over the calculations based on a single layer of uniformly mixed gas of constant properties,[18] not to mention that it is based on a more realistic depiction of flowfield properties of the plume.[19] The line of sight through the SSME Mach diamond goes through varying temperature and pressure regimes with a pathlength of roughly 144 cm (Ref. 7). In a multiple-layer scheme of radiance computations, the true spectrum radiating from a gas layer is used as the incident radiation for a new gas layer along the line of sight. The true spectrum consists of spontaneous emission, induced emission, and absorption. Each layer is specified by a different thermochemical and thermodynamic environment. In principle, one can have any number of layers in the computational scheme. But the size of the input file, as well as the CPU time, increases in direct proportion to the number of layers. For SSME Mach diamond line of sight, a three-layer model provides a satisfactory description for all flowfield parameters with good convergence for spectral radiance computations.

Radiance lookup tables in the EDC are based on this three-layer computation scheme.[7,18] Overall, radiance vs metallic elemental concentration results show a significant variation with respect to the power level values. Therefore, lookup tables have been generated for several different RPL values at which the SSME is normally tested. Occasionally power levels occur that fall between the standard levels, e.g., during thrust ramps. The EDC now incorporates an interpolation function that automatically generates new lookup tables for any nonstandard power level. Note that there are no adjustable parameters in our radiance computations for generating lookup tables. Indeed, the flowfield properties (temperature, pressure, etc.) and combustion species distribution in the plume do not change measurably at any given operating power level under normal operating conditions.

The EDC uses elemental concentration levels to identify the alloy combinations that are present in the plume. Most SSME alloys in the plume are quantified on the basis of elemental masses of Ni, Fe, Cr, Co, and Mn in the plume. The EDC quantifies the alloy(s) that have elemental proportions that most closely match those of an unknown contaminant by using a least-squares optimization algorithm. The details of the EDC alloy identification and quantification procedures are given in Refs. 3, 4, and 9.

The last step in the data analysis process is to identify possible hardware sources for the observed plume contaminants. The selection of hardware components is primarily based on the SSME materials database[12] and its unpublished updates. It is also based on current test data from other sensors on the engine and experience gained from hundreds of tests at the A-1 test stand. The EDC identifies hardware components by using NEXPERT object, an expert system shell developed by Neuron Data, Inc., Palo Alto, California. Further details are available in Ref. 9.

The EDC has been validated by successful application to the plume spectral data obtained from A-1 engine firings over the last three years covering more than 100 tests. EDC alloy identification and quantifications have been independently confirmed by means of post-test engine and/or pumps inspections and exact amount of material loss determinations.[4,7,9] Preliminary analysis reports of the plume spectral data are distributed to the engine testing personnel within one–three days of the engine firing. This report includes the significant elemental and alloy quantifications, if any. However, it should be noted that the detailed posttest engine or pump inspection reports from engine personnel are available only after an engine and/or its pumps have been removed from the testing cycle and thoroughly inspected. This could be several weeks from the time when plume event(s) may have first occurred. Herein lies part of the value of plume diagnostics for engine health monitoring: the ability to obtain quantitative data in a manner much more expedient than hardware teardowns. As plume diagnostics has matured, it has been very gratifying to obtain corroboration of our alloy identifications and/or quantification results on numerous occasions whenever significant plume emissions have occurred.

Spectroscopic Data

The focus of this work is the test series 901-851–901-853 wherein block II SSME development engine 0523 was tested. Some of the primary test objectives were evaluation of engine 0523, which has a large throat main combustion chamber (LTMCC), evaluation of HPFTP/AT 8306 and HOPTP/AT 8208, evaluation of LPOTP 92502, a block II certification unit, and LPFTP 2316R1, evaluation of the main injector, and evaluation of LTMCC heat load and condition.

Test 901-851 was conducted on Jan. 19, 1996, for a programmed duration of 520 s. Cu and Ag emission lines were observed sporadically by the high-resolution OMA system throughout the test; the likely source of these events is NARloy-Z alloy.[8,12] Ni, Fe, Cr, Cu, and Al were observed in the plume starting at E/S + 395.5 s. This event lasted 4 s, and the peak intensities for all elements occurred at E/S + 396 s. The thrust profile for this test firing indicates that the engine was throttled up to 109% RPL from 104% RPL at E/S + 395 s. Figure 1 is a plot of the plume difference spectrum (spectrum at E/S + 396 s subtracted by spectrum at E/S + 405.5 s) for this event. Spectral range in Fig. 1 is 320–429 nm. Most significant transitions[8] for all five elements mentioned earlier are identified in Fig. 1. Al is a weak emitter, yet it can be clearly identified in Fig. 1. The EDC did not converge to a single alloy, which may be due to the fact that there was some water vapor recirculation problem that attenuates and distorts emission signals. Also, it is likely that a multiple alloy event occurred because both Cu and Al were observed in the plume and none of the SSME materials[12] or HPFTP/AT alloys[20] contain Cu and Al in significant amounts together. Overall emission levels for Ni, Fe, and Cr are low to moderate. It is not unusual to observe low-level metallic plume emissions after a large-magnitude engine throttle. However, emission during test 901-851 are somewhat stronger than typical for an engine throttle and include more elements than normal, and the event lasts longer than usual.

Test 901-852 was conducted on Jan. 23, 1996, for a programmed duration of 520 s. It was predominantly a clean test except for one plume event that reached maximum intensity at E/S + 262.5 s. The elemental makeup of the event suggests NARloy-Z as the likely alloy. Emission levels for this plume event are higher than similar events in test 901-851. Emission of NARloy-Z typically indicates MCC wear, which is presumed to produce localized regions of metallic constituents along the plume boundary. In such cases, the observed emission intensity is affected by the position of the wear area relative to the instrument's field of view. One of the necessary requirements for quantification of the plume spectral data by any LBL code is that the constituents must be uniformly distributed in each layer along the line of sight. The spectral instruments on the A-1 test stand use relatively small fields of view, i.e., 1.5–2 in. When a plume contaminant is uniformly distributed throughout the plume, then data collected within a narrow field of view can be extrapolated out to the rest of the plume. The extrapolation then gives an estimate of material loss throughout the plume as a whole. If localized plume events are occurring outside the field of view, then our spectral data do not tell us enough to quantify material passing throughout the entire plume. Experience has shown that most typical SSME hardware degradation modes result in uniform distribution of contaminants.[4,7] However, localized plume events have also been observed.[1] As a general rule, degradation modes that

occur very far downstream in the propellant flow path are the ones that result in localized contaminants. Unfortunately for the goal of material quantification, plume emission during the hardware failure of test 901-853 was extremely nonuniformly distributed, as we shall see later in this section.

Test 901-853 was conducted on Jan. 25, 1996, with a planned duration of 754 s, but the test was terminated by the plume observer at E/S + 553.9 s due to excessive exhaust plume emissions. Increased vibration levels and turbine performance degradations were also observed during the test. The OMA systems observed emission lines of Ni, Cr, Fe, Co, Al, Mn, Cu, Ag, and Pd. This is the largest number of metallic elements ever observed at one time in the plume at SSC. Very significant emissions occurred at 130, 276, 283, 404, 551, and 553 s from E/S. A plot of time traces of plume emission for Ni, Fe, Cr, Al, and Co are shown in Fig. 2. The spectral data in Fig. 2 are from the high-resolution OMA system. The data for Ni, Fe, Cr, Al, and Co were obtained from their lines at 361.94, 371.99, 425.43, 396.15, and 387.31 nm, respectively. From E/S + 404 s onward, the emission activity was considerably increased and nearly continuous. From E/S + 551 s to the engine cutoff at E/S + 553.9 s, the spectral radiance levels for all the elements were the highest ever observed since the plume diagnostics program was started on a permanent basis on the A-1 test stand in 1989. Emission strength can be seen in Fig. 3, wherein spectral radiance for Cr transition at 425.43 nm is plotted vs time. The maximum peak value at E/S + 551.5 s reached 124.9 μW/cm^2 · sr · nm, and it went as high as 352.7 μW/cm^2 · sr · nm at E/S + 553.5 s before the engine cutoff, which is not shown so that low-level events can be visualized better. Such extremely high levels of emission indicate severe distress of the engine. Even at E/S + 130 s, the emission levels were quite

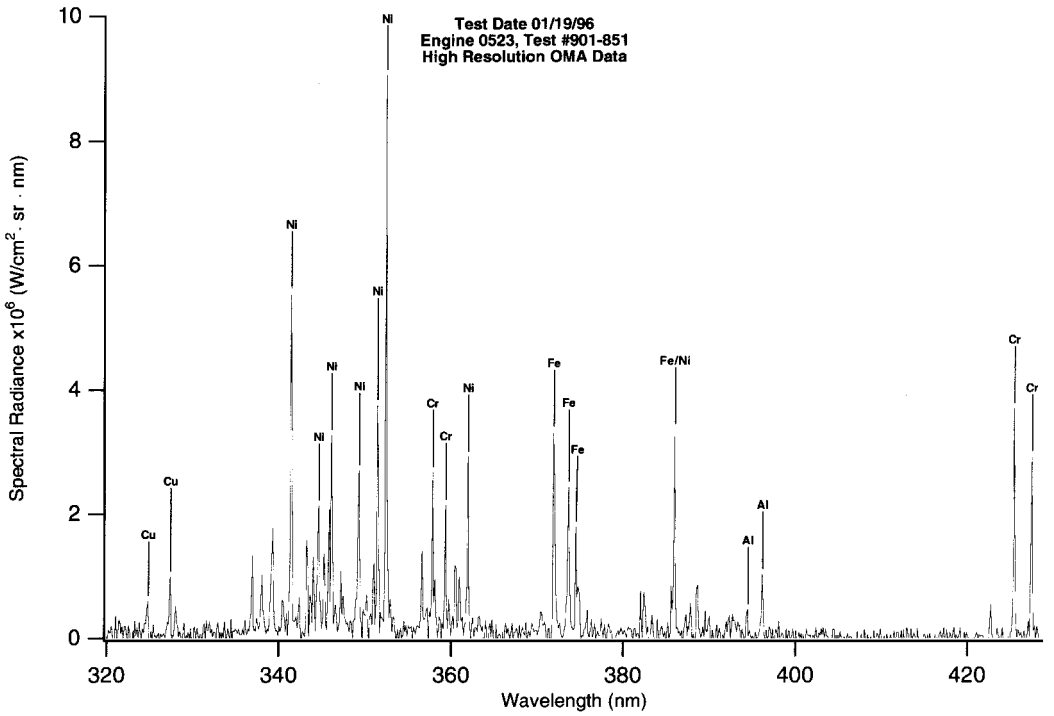

Fig. 1 SSME difference spectrum (E/S + 396 s minus E/S + 405.5 s), 320–429 nm.

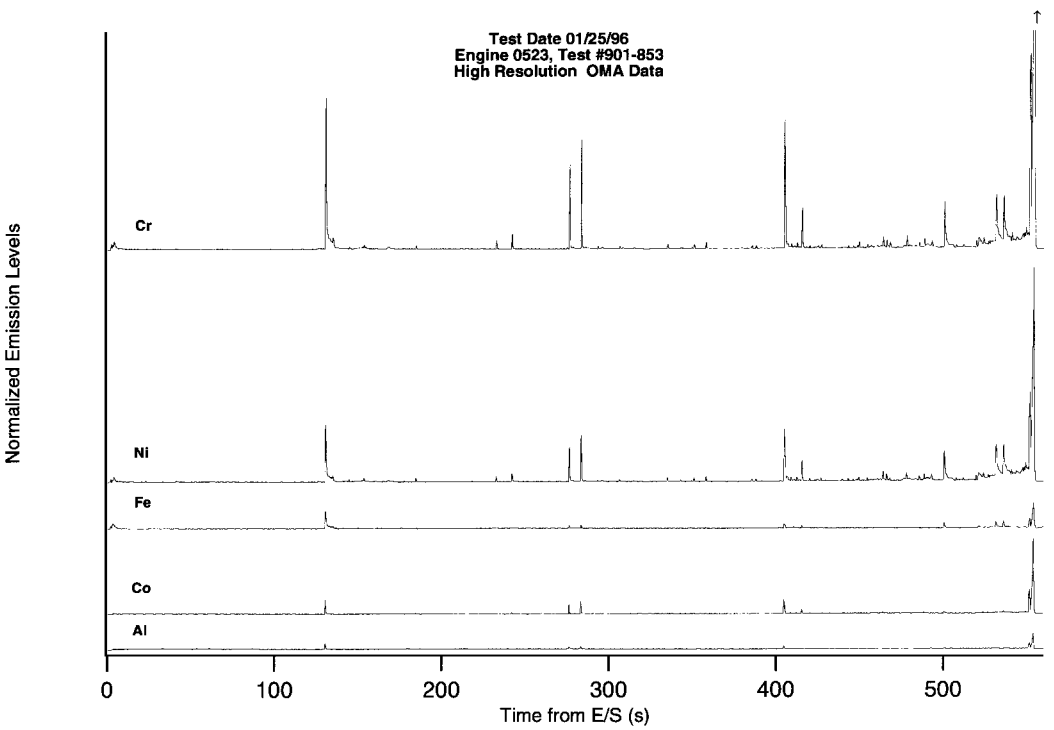

Fig. 2 Time history of Cr, Ni, Fe, Co, and Al emissions, test 901-853.

high, as seen in Fig. 4. Figure 4 is a difference spectrum, wherein the spectrum from a previous scan (at E/S + 119.5 s) during this test has been subtracted out to eliminate most of the OH interference. Ni, Fe, and Co have many transitions in the spectral range of 320–429 nm, not all of which have been labeled in Fig. 4. Chromium HSPCS data at 1-ms resolution for this plume event are shown in Fig. 5. High temporal resolution is evident in this figure. Figure 5 encompasses only 0.5 s of spectral data, i.e., from E/S + 130.20 to E/S + 130.70 s. Figure 5 also indicates that the plume event occurred due to a very sharp and quick ingestion of some material. The main event lasted only 0.1 s.

No single alloy can account for all of the emissions observed at the 130-s event or for that matter any subsequent plume events. No single SSME alloy[12] or HPOTP/AT or HPFTP/AT alloy[20] contains all of the elemental constituents observed in the main plume events. Palladium is unique to AMS 4786, a brazing material used on honeycomb turbine seals in the HPFTP/AT and HPOTP/AT. The only previous appearance of palladium in an SSME plume on the A-1 test stand occurred during two tests with HPOTP/AT honeycomb seal degradation. Because Pd is not a strong emitter and comprises only 8% by weight of AMS 4786, any appearance in the plume is potentially significant. Emission of Al is also noteworthy because it has rarely been observed during SSME testing. As mentioned earlier, Al was also observed in test 901-851.

Tables 2–4 give the time lines for the major plume events of tests 901-851 through 901-853, respectively. All times in these tables are expressed relative to engine start. The engine start Inter-Range Instrumentation Group (IRIG) times that were used to construct

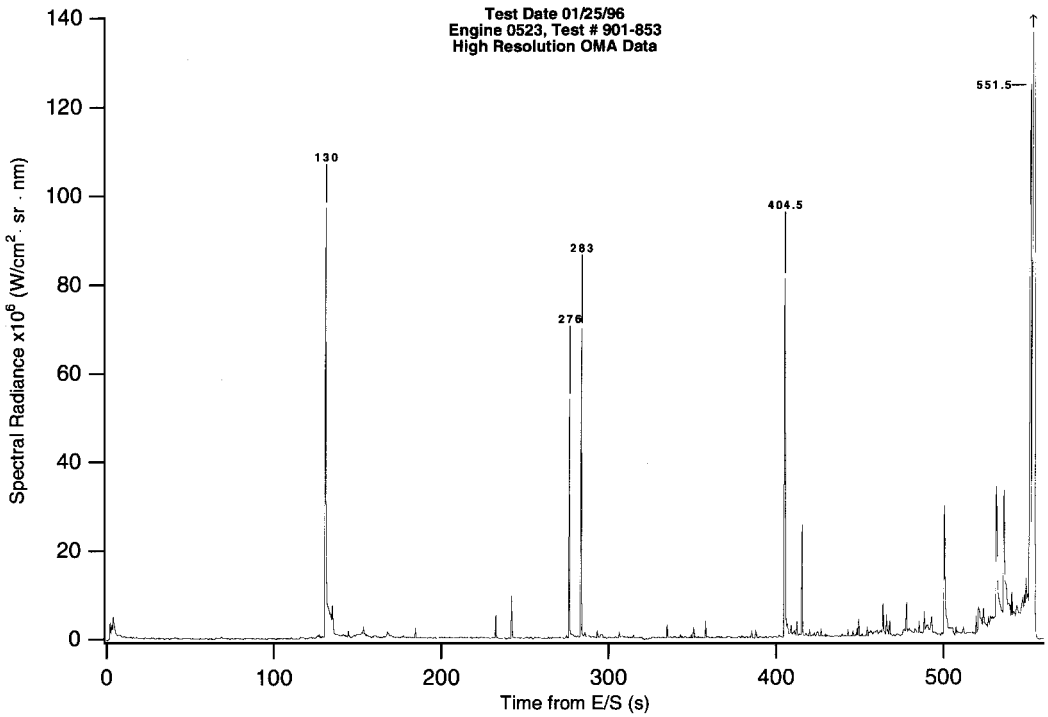

Fig. 3 Spectral radiance vs time for Cr line at 425.43 nm.

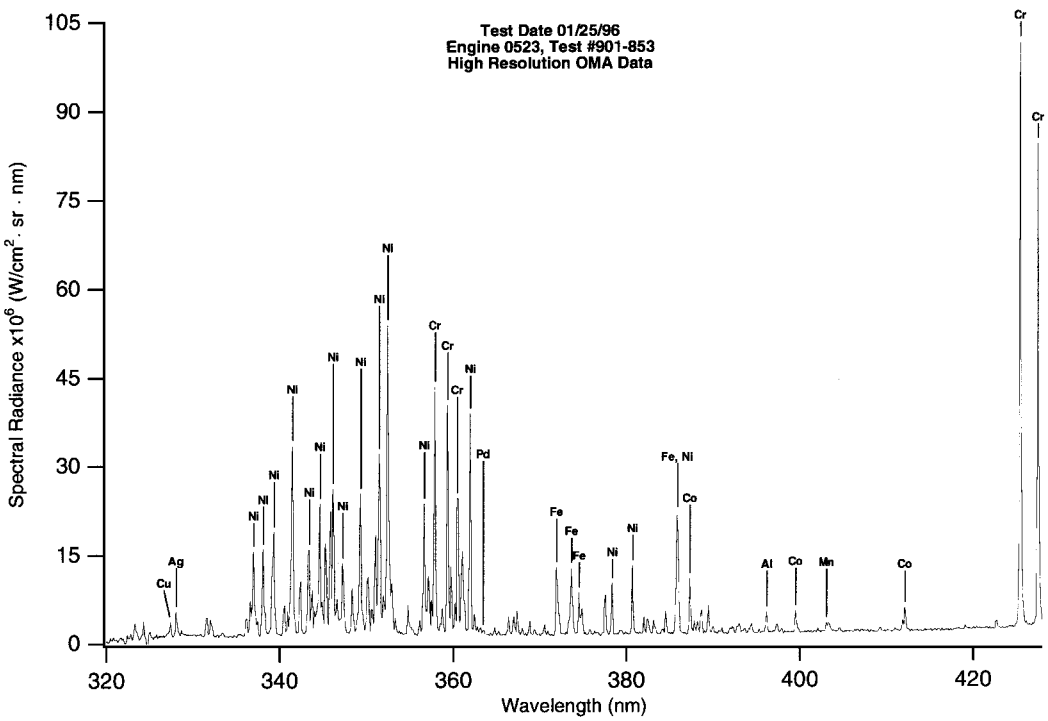

Fig. 4 SSME difference spectrum (E/S + 130 s minus E/S + 119.5 s), 320–429 nm.

Table 2 Metallic emissions observed during the A-1 test 901-851

Approximate event time, s	Start time[a], s	Peak time, s	Stop time, s	Confirmed elemental constituents
61.5	60.860	61.360	62.360	Ni, Cr, Al
122.5	121.860	122.360	122.860	Ni, Cr
181.0	179.860	180.360	181.360	Ag, Cu
370.0	369.360	369.360	369.860	Ag, Cu, Ni, Cr
385.0	382.860	384.360	386.360	Ni, Cr
396.0	394.860	395.360	398.360	Ni, Cr, Fe, Al, Co, Mn, Cu
411.5	407.860	410.860	428.360	Ag, Cu
		426.860		(Sporadic throughout event)
433.5	432.860	433.360	433.860	Cr, Fe

[a]Engine start time: 019:17:51:38.980.

Table 3 Metallic emissions observed during the A-1 test 901-852

Approximate event time, s	Start time[a], s	Peak time, s	Stop time, s	Confirmed elemental constituents
262.5	256.503	262.003	264.503	Ag, Cu
268.5	267.003	268.003	274.503	Ag, Cu
389.0	379.503	388.503	391.503	Ni, Cr, Ag (sporadic)
395.5	395.003	395.503	396.003	Ni, Cr

[a]Engine start time: 023:23:15:20.740.

Table 4 Metallic emissions observed during the A-1 test 901-853

Approximate event time, s	Start time[a], s	Peak time, s	Stop time, s	Confirmed elemental constituents
127.0	126.148	127.143	127.643	Cr, Ni
130.0	130.311	130.343	130.398	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag, Pd
276.0	276.357	276.378	276.445	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag
283.0	283.413	283.460	283.516	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag
404.0	404.724	404.766	404.845	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag, Pd
415.0	415.461	415.510	415.580	Cr, Ni, Fe, Co, Cu
500.0	500.366	500.421	501.069	Cr, Ni, Fe, Co, Mn, Pd
531.0	531.362	531.380	531.592	Cr, Ni, Fe, Co, Al, Mn, Pd
551.0	551.522	551.558	551.628	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag, Pd
551.0	551.809	551.855	551.919	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag, Pd
553.0	552.963	553.534	Shutdown	Cr, Ni, Fe, Co, Al, Mn, Cu, Ag, Pd

[a]Engine start time: 025:22:29:44.200.

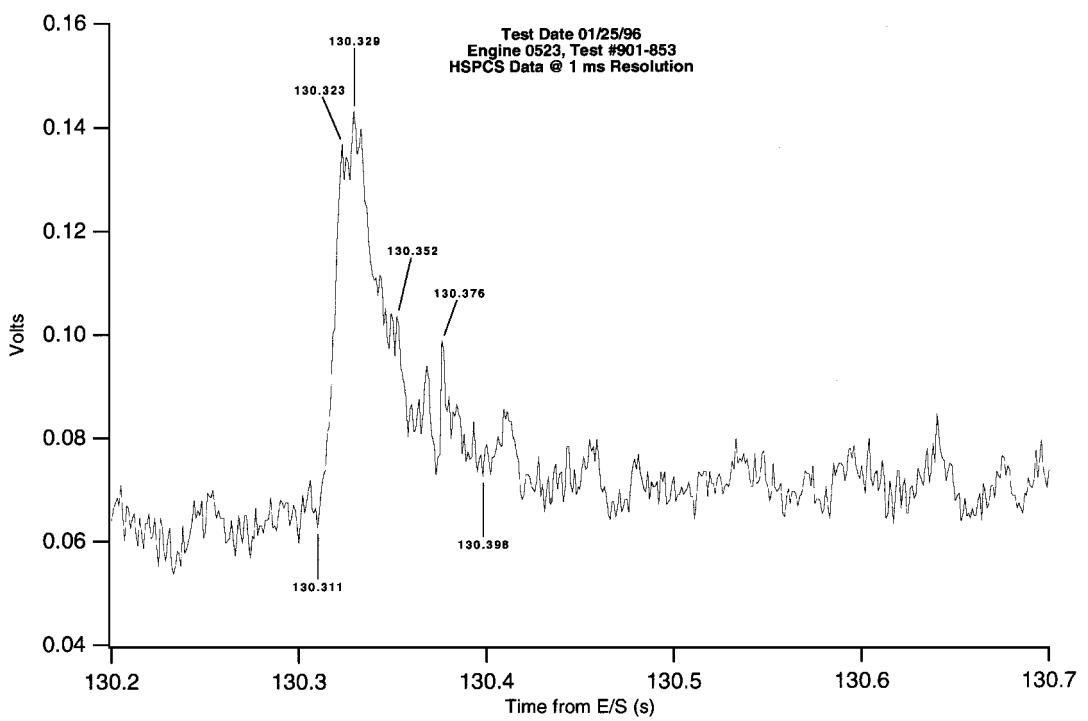

Fig. 5 High-speed spectral data from Cr channel (425.43 nm) of the SSC HSPCS.

Table 5 Comparison of emission levels of palladium plume events observed during the A-1 test 901-853

Approximate event time, s	Scan start time[a], s	Scan stop time, s	Percentage of total Pd
130.0	130.143	130.643	1.09
404.0	404.643	405.640	1.37
500.0	500.143	501.643	5.21
504.0	503.643	504.143	0.64
515.5	515.143	515.640	0.60
520.0	520.643	Shutdown	91.08

[a]Engine start time: 025:22:29:44.200.

each table are indicated therein. Tables 2 and 3 are based on spectral data from the high-resolution OMA system, which has a temporal resolution of 0.5 s. Each half-second interval is referenced to IRIG time, so that the endpoints can be quoted with a millisecond of precision. Table 4 is partially based on HSPCS data, which has a temporal resolution of 1.0 ms. For test 901-853, high-speed data were obtained from chromium, nickel, iron, and cobalt. During the first major plume event at E/S + 130 s, the aforementioned four elements begin emitting within 1 ms of one another. The difference in relative emission strength of the elements can easily account for a 1-ms difference between the times two different signals rise above the noise floor. Therefore, we cannot conclude from the high-speed data which element appeared in the plume first. Degradation of honeycomb seal material, i.e., Hastelloy X, could account for all of the elements recorded by the high-speed polychromator. In such a case, all elements would appear in the plume simultaneously. In Table 4, for the sake of completeness, the plume events at 127, 415, 500, and 531 s have also been included, although these are relatively weaker emissions. Table 5 gives a separate time line for palladium emission, based on high-resolution OMA data. The time line in Table 5 can be interpreted as a direct measure of honeycomb braze degradation.

Results and Discussion

This incident was completely and thoroughly investigated by a NASA board of investigation. Posttest inspection of the engine and data analysis revealed extensive damage to the HPFTP/AT. Upon pump teardown, severe damage to the turbine was revealed. The most severe damage occurred in the first-stage turbine, where numerous blades exhibited significant airfoil loss, and all but one of the blade outer gas seal (BOGS) segments had released material. Extensive damage to second-stage turbine components was highlighted by fractures through retainer hooks from eight vanes, moderate-to-heavy airfoil losses from several blades, and partially fractured ship laps from the BOGS. Spectroscopic data played a very key role in the board's investigation and findings. For example, the plume spectral data were utilized in eliminating many branches of the fault tree and thus eliminating those HPFTP/AT components from further consideration. Also, the spectral data, in particular the HSPCS data, were used in developing the failure events time line. Finally, the board's determination of the most likely scenario for the test 901-853 incident was quite heavily supported by the plume spectral data. The investigation team concluded that the anomaly at 130 s was most probably a first-stage blade airfoil failure resulting from a progressive failure of both the first-stage BOGS and the second-stage vanes of the HPFTP/AT. Involvement of the second-stage vanes in the 130-s event was confirmed by the presence of palladium in the plume. Palladium is a constituent of the honeycomb braze on the second-stage vanes.

The board concluded that the first-stage blades and BOGS continued to degrade following the initial event at E/S + 130 s. Second-stage blades and BOGS degradation was a result of first-stage debris traveling downstream. The turbine continued to degrade until an engine cutoff was initiated at E/S + 553 s.

The unique circumstances of hardware degradation during test 901-853 make it extremely difficult to establish absolute quantities for mass loss based on spectral data. The technique currently used for mass quantification at SSC relies on the assumption of axially uniform distribution of plume contaminants. Previous cases of SSME hardware degradation have shown that, when the assumption holds, mass quantification based on spectral data is extremely accurate.[4,7] The ability to correctly quantify chromium, nickel, iron, and cobalt

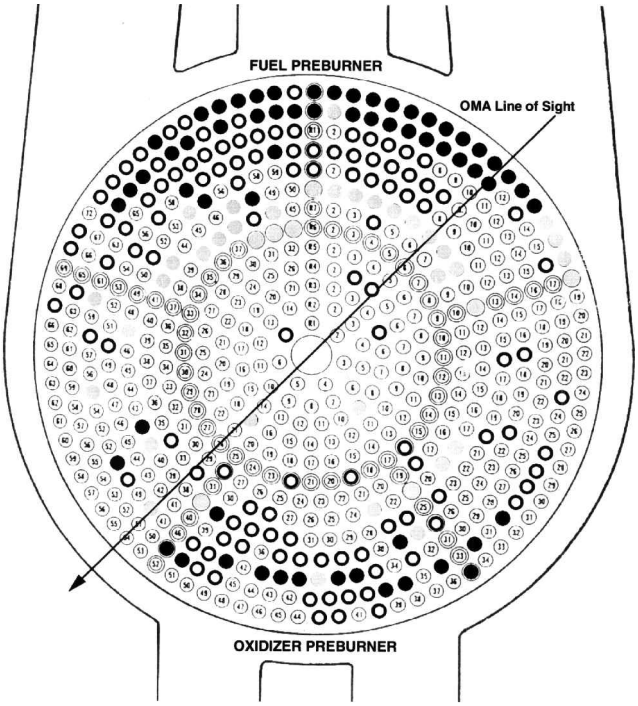

Fig. 6 Main injector damaged slagged posts: Dark annular circumference indicates gouged posts, solid light shading indicates slagged posts, and solid dark coloring indicates gouged and slagged posts.

in the SSME plume has been demonstrated. Unfortunately, for test 901-853 the assumption of uniform contaminant distribution does not apply. High- and low-speed videotapes clearly show highly localized streaking on the plume boundary that falls outside the narrow field of view, i.e., about 2 in. in diameter, of OMA-1 and the high-speed polychromator. Nonuniform contaminant distribution is not a surprising result, given the degradation mode of test 901-853. Most of the contaminants that originate in the turbine end of HPFTP/AT result from impact damage (which would be expected to produce relatively large contamination particles) and are likely to be entrained in the perimeter of the injector. Physical examination of damage to the main injector following the test correlates exactly with the video observations. Figure 6 is based on the examination of each and every injector post conducted by Rocketdyne. The solid light shading shows where metal fragments were retrieved from these injector posts. The dark color annular circumference shows injector posts that sustained damage (gouged markings). Those injector posts that sustained damage and in which slag material was also found have been indicated by solid dark coloring in Fig. 6. The OMA line of sight is shown in Fig. 6. As indicated, the line of sight does not pass through the zones where the vast majority of the fragments are being entrained. Inspections of the nozzle after the test also showed nonuniform patterns of contamination along the hot wall surface. In view of the preceding considerations, emission observed at the core of the Mach diamond, such as by OMA-1, represents only a fraction of the mass that actually passed through the plume. Nonetheless, radiometric signal levels for test 901-853 are the highest observed in an SSME plume since test 901-666, where the loss of a turbine blade was experienced in the Rocketdyne HPFTP.

Metallic contamination (approximately 120 fragments) was found in the hot gas cavity of the main injector with debris trapped in the fuel sleeve and secondary face plate retainers. The weight of the fragments ranged from 0.01 to 0.37 g. Figure 7 shows some of these fragments. Obviously, numerous fragments of similar sizes did get into the plume, and the larger of these fragments resulted in localized plume events as observed by the video cameras.

On the basis of these observations, it is clear that most of the plume contaminants passed through zones not captured within our narrow field of view, i.e., 1.5–2 in., for OMA systems. Therefore, any mass quantifications performed by the EDC would heavily underestimate the actual amount of the material through the plume. Furthermore, any results could not be trusted because the central assumption of a

Fig. 7a Most of the 70+ metallic fragments retrieved from secondary faceplate.

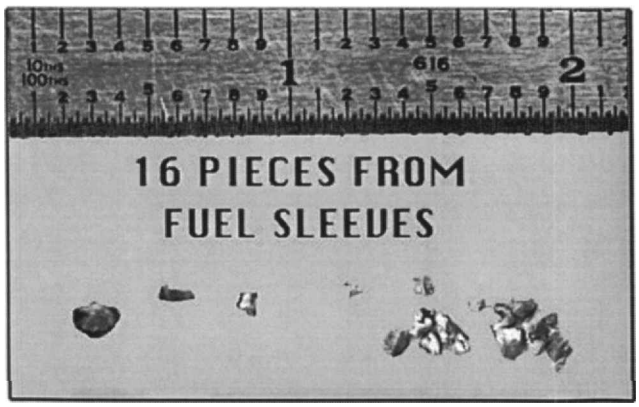

Fig. 7b Sixteen metallic fragments retrieved from fuel sleeves.

uniform distribution for the LBL computations was violated. Most of the streaks during test 901-853 were on the boundary layer. This fact is corroborated by video data and maps of hardware damage. Because the LBL code (even more so, a single-layer Spectra6 code mentioned in Ref. 16) assumes emission is dominated by the high-temperature Mach diamond, that effect should also produce very significant underestimate of mass loss. Therefore, any valid method of material quantification that is applied to spectral data from test 901-853 should heavily underestimate the actual material quantity in the plume. As such, any quantification results are not meaningful[16] and are not given here.

Conclusion

Exhaust plume emission spectroscopy has proven to be invaluable in the SSME testing program at SSC. Plume spectral data were made an integral part of the final report of the NASA board of investigation, which thoroughly investigated the events leading up to the engine cutoff during test 901-853. Plume spectral data provided very essential clues in this puzzle. Because of this recent success and other fruitful results from the SSC plume diagnostics program, it has achieved wide recognition and acceptance in the rocket engine testing community in a short period of time. Plume diagnostics is very much an integral part of the engine testing program at SSC. In many situations, plume spectral emission data have been instrumental in helping identify the source of a problem from precursor events in the SSME exhaust plume.

The Pratt and Whitney high-pressure fuel turbopump has been successfully tested at SSC in a large number of continuing series of test firings after some design modifications were made to the pump as recommended by the board of investigation.

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