ROCKET ENGINE PLUME DIAGNOSTICS AT STENNIS SPACE CENTER*

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ABSTRACT

The Stennis Space Center has been at the forefront of development and application of exhaust plume spectroscopy to rocket engine health monitoring since 1989. Various spectroscopic techniques, such as emission, absorption, FTIR, LIF, and CARS, have been considered for application at the engine test stands. By far the most successful technology has been exhaust plume emission spectroscopy. In particular, its application to the Space Shuttle Main Engine (SSME) ground test health monitoring has been invaluable in various engine testing and development activities at SSC since 1989. On several occasions, plume diagnostic methods have successfully detected a problem with one or more components of an engine long before any other sensor indicated a problem. More often, they provide corroboration for a failure mode, if any occurred during an engine test.

This paper gives a brief overview of our instrumentation and computational systems for rocket engine plume diagnostics at SSC. Some examples of successful application of exhaust plume spectroscopy (emission as well as absorption) to the SSME testing are presented. Our on-going plume diagnostics technology development projects and future requirements are discussed.

I. INTRODUCTION

The John C. Stennis Space Center (SSC) is NASA's designated Center of Excellence for large propulsion system testing. SSC has long been an advocate and the leader in rocket engine exhaust plume diagnostics for vehicle health management (VHM) in propulsion ground testing. The main objectives of the rocket exhaust plume diagnostics program are to enhance test operation efficiency and to provide for safe cutoff of rocket engines prior to incipient failure; thereby avoiding the potential destruction of a multimillion dollar engine and test complex, and preventing delays to a national priority space program. On several occasions, plume diagnostics has detected problems with one or more SSME components long before the traditional sensors.[1-6] More often, it provides corroboration for a failure mode, if any occurred during an engine test.[1-6]

Although we have considered and evaluated many exhaust plume spectroscopic technologies such as laser-induced fluorescence,[7,8] coherent anti-stokes Raman spectroscopy,[9] and Fourier transform infrared (FTIR) spectroscopy[10] for application to the rocket engine testing, most of our efforts and successful results come from the space shuttle main engine (SSME) exhaust plume emission spectroscopy.[1-6] The SSME is tested at SSC for improvement, development and flight certification. Because of the presence of high temperature regions in the SSME exhaust plume for the engine testing performed at the ambient-pressure test stands,

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the emission spectroscopic technique is extremely sensitive and specific.[5] A study carried out at SSC in 1989 established a database of SSME critical components and materials.[11] SSME components and materials and their constituent elements were prioritized depending upon the severity of their operating environments and consequent likelihood of degradation modes.[11] On this basis, the spectral data for the 10 most important SSME elements and 27 most important SSME materials was obtained at the Diagnostic Testbed Facility Thruster (DTFT) for Mach diamond. These results were published[12] in a NASA Reference Publication #1286.[12] It was previously shown by us that the temperature and pressure conditions of the SSME exhaust plume in the first Mach diamond are very nearly replicated in the first Mach diamond of the DTFT.[13]

For altitude test stands, where the engine exhausts into a diffuser, we utilize atomic absorption spectroscopy (AAS).[14] Because of much lower temperatures along the line of sight (LOS), AAS is much much less sensitive compared to the atomic emission spectroscopy (AES). Still some very useful results have been obtained. The most challenging aspects of AAS or AES technology development and application to the rocket engine test stands are the data acquisition and the data analysis. We have used many innovative approaches at each step to harness these technologies for rocket engine plume diagnostics. Brief outlines for our approaches for data acquisition and the spectral data analysis are given in the next two sections, respectively. Some illustrative results from both AES and AAS are presented and discussed in Section IV. A summary along with the current status of the rocket engine plume diagnostics at SSC is given in Section V. Some recommendations for additional work are also discussed in Section V.

II. SPECTROSCOPIC INSTRUMENTATION

ATOMIC EMISSION SPECTROSCOPY

A comprehensive overview of the SSME exhaust plume emission spectroscopy at SSC was published in Spectroscopy.[5] At high temperatures of exhaust plume Mach diamond region, most of the SSME constituent elements emit significantly in the ultraviolet and visible regions.[12] The metallic elements most useful for plume diagnostics are: Ni, Fe, Cr, Co, Mn, Cu, Ag, Al, Ca, and Pd.[5,15] Each test firing at the open air test stand is monitored primarily by three optical multi-channel analyzer (OMA) systems, one high speed polychromator, and three video imaging systems. One OMA system, internally designated as OMA-1, monitors the spectral region from 303 to 429 nm. Another OMA system, internally designated as OMA-4, monitors the spectral region from 319 to 415 nm. It incorporates a newer and more sensitive detector, and 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.[12] A third OMA system, internally designated as OMA-2, 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 above region. Two of the 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 temporal resolution of 1.0 ms. The three video systems on the 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 nozzle.

Our spectroscopic instrumentation including OMA systems and their calibrations are completely described in Ref. 5. For the sake of brevity, we will not repeat these details here. 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 following seven elements: Cr, Mn, Co, Fe, Ni, Ag, Cu and two OH spectral branch main heads in the 306.4 nm band system. The instrument currently used at SSC is a redesign of the Optical Plume Anomaly Detector (OPAD) system[16] developed and fabricated by Sverdrup Technology at the Arnold Engineering Development Center, Arnold Air Force Base, Tennessee. Main improvements in the HSPCS system are: doubling of temporal resolution compared to the old OPAD system, much higher signal to-noise ratio, and new data acquisition and control software. These improvements were achieved through a redesign of electronic and software components. Complete details of the HSPCS and the wavelength calibration procedure are available in Ref. 5.

ATOMIC ABSORPTION SPECTROSCOPY

For altitude simulation test stands where the SSME is exhausted into a self pumping diffuser to simulate operation at high altitudes, there is no readily accessible shock structure capable of providing the temperatures necessary for AES plume diagnostic measurements. Therefore, an AAS system has been developed at SSC that allows plume measurements in the diffuser. A nice history of this development and experimental details are available in Ref. 14. In it's current configuration, the AAS system uses a multi element hollow cathode lamp (HCL) spectral source and associated optics mounted in the source probe and the collection optics assembly in the receiver probe. The details of the probes and their placements and mountings on the diffuser to achieve the desired optical access and the line of sight are given in Ref. 14. The HCL currently in use has following elements: Cr, Fe, Ni, Ag, Cu with Ne as a fill gas. There is one optical output and one video output on the receiver probe for attaching a fiber optic cable and a video cable. The optical output is fed into the optical multichannel analyzer (OMA) AAS detection system that acquires and archives the data in the test stand hardcore. The AAS OMA system has a temporal resolution of 200 ms and a spectral resolution of 0.4 Å. The video output is a NTSC format signal fed into a VCR and monitor at the Test Control Center (TCC). The Macintosh® computer executes a LabVIEW® based front end for remote configuration of the OMA-1 AAS and data acquisition start signals for both systems. The Macintosh system processes the AAS data and provides a real time display during the test firing. Further details of the experimental set up and data acquisition system are given in Ref. 14.

III SPECTRAL DATA ANALYSIS

ATOMIC EMISSION SPECTROSCOPY

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 be automated as much as possible. The centerpiece of this automation process is the Engine Diagnostics Console (EDC).[2,5,17,18] 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.[11] Therefore, simply identifying elements in the plume does not adequately pinpoint degraded hardware. Because of the specialized environmental properties of SSME alloys,[11] 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. Figure 1 is a flow chart that shows the overall process the EDC uses to analyze spectral data from a typical engine test.

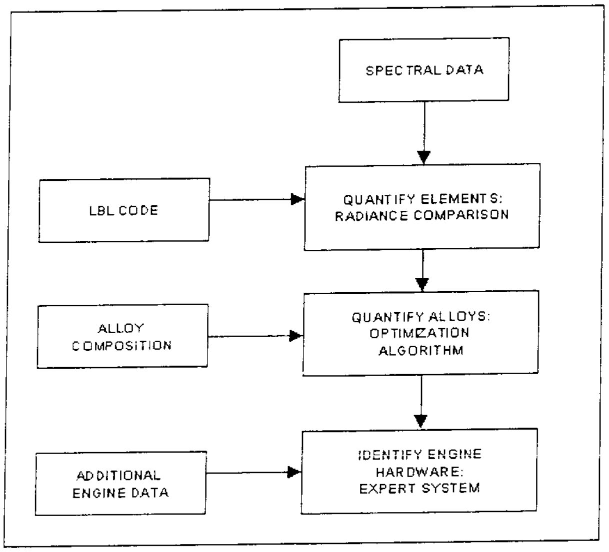

Figure 1: EDC Flow Chart

The EDC has been developed at SSC over several years with constant improvements in diagnostics capability, and upgrading of various software components.[2,5,17,18] Earlier versions of EDC are described in Ref. 2, 17 and 18. The latest version is featured in Ref. 5. Complete details on the EDC and its development are available in these references. Only a few pertinent points/features are discussed here for clarification and/or emphasis.

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.[2,3] 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 nm) of the atomic lines that the EDC uses.

Table 1. Wavelength (in nm) of the atomic lines used by the EDC.

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

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.[11] Elemental lookup tables are constructed by utilizing a line-by-line (LBL) spectral simulation code.[3,15,19]

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. In recent years, thrust profiles for some tests have included 80 and 111% RPL values. It is planned to extend the RPL range of the EDC by generating new lookup tables for 80 and 111% RPL. The LBL code was originally developed at NASA Ames Research Center. It is a very comprehensive, highly regarded and tested computer program for line-by-line calculation of spectra from diatomic molecules and atoms assuming a Voigt line profile.[19] The program 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. The program allows the simulation of a spectrum for either optically thin (no self-absorption) or optically thick (self-absorption) conditions.[19] NASA Ames LBL code has been modified by us for application to SSC exhaust plume spectral data analysis.

Our LBL calculations utilize multiple layers for radiance computation wherein each layer is specified by a different thermochemical and thermodynamic environment. This is vast improvement over the calculations based on a single layer of uniformly mixed gas of constant properties.[20] The line of sight through the SSME Mach diamond goes through varying temperature and pressure regimes with a pathlength of roughly 144 cm.[3] 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. 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.[3,20] 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 non-standard power level. It is important to note that there are no adjustable parameters in our radiance computations for generating lookup tables.

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. 2, 5, and 18.

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[11] 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 covered by the AES system. The EDC identifies hardware components by using NEXPERT object, an expert system shell developed by Neuron Data Incorporated, Palo Alto, CA. Further details are available in Ref. 5.

The EDC has been validated by successful application to the plume spectral data obtained from open air test stand engine firings over many 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.[2,3,5] Preliminary analysis reports of the plume spectral data is distributed to the engine testing personnel within 1 to 3 days of the engine firing. This report includes the significant elemental and alloy quantifications, if any. However, it should be noted that the detailed post-test 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.

ATOMIC ABSORPTION SPECTROSCOPY

In principle, the EDC system for SSME exhaust plume AAS is also achievable. Certainly, the elemental quantification of the effluent materials in the plume by utilizing the LBL code[19] is eminently feasible. We have appropriately modified and updated the LBL code for application to the SSME exhaust plume absorption spectral data obtained by the SSC AAS system. However, a major stumbling block has been the LOS CFD computations for flowfield properties. Due to the presence of a diffuser and associated turbulence, the CFD problem is too complex to obtain sufficiently reliable and physically consistent results with existing CFD development tools and codes at SSC. Qualitative analysis of the AAS spectral data can still be performed by utilizing the LBL code.

IV. APPLICATION TO THE SSME TEST PROGRAM

We have previously presented and published several cases of very successful application of the rocket engine plume diagnostics at SSC.[1–6,15,16] In this paper, we have chosen to illustrate our capabilities by presenting three distinct sets of spectral data and analyses from three different test series. The primary focus is on the atomic emission (Test firings #901-802 to #901-805), the molecular emission (Test firing #901-361) and the atomic absorption (Test firings #902-741 and #902-742), respectively. The spectral data from test firings #901-802 to #901-805 were first presented in Refs. 2 and 3. The other two cases have not been presented before.

ATOMIC EMISSION

As an example, we present and discuss here the spectral data from the SSME firings #901-802 to #901-805 conducted on A-1 test stand. Test firings #901-802 to #901-805 were conducted on Jan. 11, Jan. 13, Jan. 17, and Jan. 20, 1995, respectively, with engine #0423, high pressure oxidizer turbopump (HPOTP) unit #8010, low-pressure oxidizer turbopump (LPOTP) unit #2318, high-pressure fuel turbopump (HPFTP) unit #2134, and low-pressure fuel turbopump (LPFTP) unit #2022R2. The designation R indicates rebuild. HPOTP unit #8010 is a Pratt and Whitney alternate turbopump development (ATD) HPOTP. Test firings #901-800 and #901-801 were also conducted on engine #0423 with the same four turbopumps except HPFTP unit #4207R2 was used during firing #901-800. The pump end bearings in the LPOTP are made of AISI 440C. After each test, the axial shaft travel of the LPOTP is measured. Any significant increase in shaft travel usually indicates wear of the bearings. Bearing wear in the LPOTP results in AISI 440C being entrained into the exhaust plume. No AISI 440C was detected in the plume during test firings #901-800 and #901-801 and the post test hardware inspection reports showed insignificant or no shaft travel increase for turbopumps. However, AISI 440C was observed in the plume and identified by the EDC during test firings #901-802 to #901-805. At the same time, post test hardware inspection reports for all four tests indicated a steady increase in the shaft travel for LPOTP #2318. The increased shaft travel of the pump strongly suggested that LPOTP bearing wear was responsible for AISI 440C in the plume.

Detailed spectral data package encompassing data from the OMA systems as well as the HSPCS system are prepared for each test firing covered by the AES systems. Test #901-0802 showed low level emissions of Fe and Cr at E/S (engine start)+325 s to E/S+486 s indicating the presence of AISI 440C. Both tests #901-803 and #901-804 showed slightly higher levels of Fe and Cr for longer total durations. Test #901-803 was conducted for a programmed duration of 520 s (with 416 s at 104% RPL) and test #901-804 was conducted for a programmed duration of 503 s (with 381 s at 109% RPL).

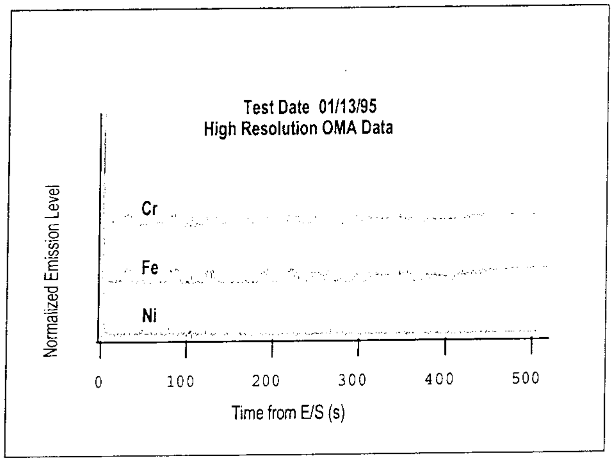

Figure 2: Time History of Ni, Cr, and Fe Emissions. Test #901-803.

Figure 2 plots normalized emission levels of nickel, iron, and chromium vs. time for test #901-803 as measured by the high resolution OMA system. Normalization is with respect to the spectral radiance at a continuum pixel at 375.55 nm. The data for Ni, Fe, and Cr is obtained from their emission lines at 361.94, 371.99, and 425.43 nm, respectively. Except for the start-up transient, which is always spectrally active, Ni emission is negligible. Emission of Fe and Cr begins at E/S+22.5 s and it is somewhat sporadic initially, but it becomes more continuous as the test progresses. From E/S+377.5 s until engine cut-off at E/S+520 s, Fe and Cr are continuously present in the plume. Just as in the case of test firing #901-802, Fe and Cr emissions are extremely well correlated, i.e., they occur or disappear simultaneously in the plume, indicating a common source. Since no other SSME related elements are observed, it narrows down the contributing alloys[11] to AISI 440C or 420 CRES which primarily consist of Fe and Cr. AISI 440C has 0.2% Ni and 0.5% Mn by weight. These weight percentages are too small for Ni and Mn to be observed and identified under relatively low overall concentrations of the AISI 440C in the SSME exhaust plume. The same is true for 420 CRES, which can have up to 1% Mn by weight.[11] However, 420 CRES is not extensively used in the SSME critical components, whereas AISI 440C was used in the fabrication of turbopump bearings, which are known to be one of the most critical components of the SSME.[11] This in conjunction with the increased LPOTP shaft travel pinpoints the source of the AISI 440C in the plume to be LPOTP 2318 bearing balls and races.

The spectral data for Ni, Cr, and Fe for firing #901-804 is shown in Fig. 3. Again, normalized emission levels are plotted vs. time. The same emission lines as in Fig. 2 are utilized. Normalization, in Fig. 3, is with respect to the spectral radiance at a continuum pixel at 401.85 nm. Again, Ni emissions are insignificant or very brief excluding the start-up transient. Simultaneous emission of Fe and Cr begins at E/S+81 s and it is continuously present in the plume until shutdown. Emission levels are slightly higher than the pervious test and the duration of emission is longer and continuous. As before, emission from other elements is mostly insignificant. The presence of AISI 440C in the plume is further confirmed by the SSME exhaust plume difference spectra. One such spectrum is shown in Fig. 4 for the spectral range of 330 to 429 nm. It is a difference spectrum (spectrum at E/S+87 s subtracted by spectrum at E/S+26.5 s) for test #901-804 wherein many more Fe and Cr lines are easily identified. In addition to the Cr transition at 425.43 nm, Cr transitions[12] at 357.87, 359.35, 360.53, and 427.48 nm can also be seen. The most prominent Fe lines occur at 371.99, 373.72, 374.59, 386.06, 387.91, and 388.65 nm.[12] In test #901-805, simultaneous emissions of Fe and Cr were observed at E/S+63 s and lasted for several seconds until water vapor recirculation obscured the optical path to the plume. At various times during the test, the optical path cleared momentarily and emission of Fe and Cr could be seen. From E/S+461 s until shutdown, Fe and Cr were continuously detected in the plume. It should be mentioned that the spectral data for test #901-802 was also affected by recirculation although not as severely as in the test #901-805. Test #901-803 was somewhat affected by recirculation. Test #901-804 is least affected by water vapor recirculation.

Based on information provided by Rocketdyne engineers at Canoga Park, SSC analysts converted shaft travel measurements to mass loss quantities from 13 bearing balls at the pump end. The details are available in Ref. 2. Since the shaft travel measurements were performed after each test firing, the amount of effluent material AISI 440C in the plume during each test firing could be ascertained. Of the four tests for which actual mass loss measurements are available (i.e., tests #901-802 to #901-805), test #901-804 is by far the most free of water vapor interference. For this test, the shaft travel measurements assuming uniform wearing of the bearing balls indicated a mass loss of 3.07 g of AISI 440C. By using the EDC with three layer LBL code, we obtained a mass loss of 2.67 g assuming uniform distribution of AISI 440C material in the plume. In subsequent test with LPOTP bearing wear, plume diagnostic estimates of bearing material mass loss produced accurate predictions of turbopump shaft travel.

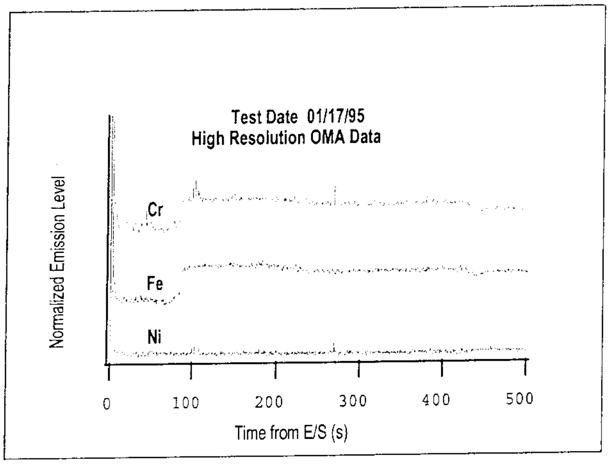

Figure 3: Time History of Cr, Fe, and Ni Emissions. Test #901-804.

MOLECULAR EMISSION

Test firing #904-361 occurred on September 3, 1998 on B-1 test stand with Block II engine 0523, HPOTP unit #8110, HPFTP certification unit #8010, LPOTP unit #4305, and LPFTP unit #2228R1. Both high pressure turbopumps are Pratt and Whitney ATD units. Test #904-361 ran to a programmed duration of 520 s with 429 s at 104.5% RPL. Very significant levels of Ni, Co, and Fe were observed in the plume starting at E/S+325 s and continuing for approximately 20 s with a sharp peak at E/S+338 s. These emissions were accompanied by significant levels of Cr and Mn emissions. The emission levels of all five elements were well correlated, indicating a common source.[21] No emission events of any significance were detected for the remainder of test duration, neither were any precursor events of any significance before the main event began. Total mass loss for Ni, Fe, Co, Cr, and Mn for this event were calculated by the EDC to be 0.820, 0.820, 0.393, 0.037, 0.002 g, respectively. Moderate levels of Cu and Ag elemental emissions were also observed during this event. All seven elements mentioned above were detected by high-resolution OMA-1 system. In addition, titanium was detected by means of its molecular emissions (TiO) through the spectral data obtained by the broadband OMA-2 system.[21,22] Several TiO emission bands were observed. TiO emission also started at about E/S+325 s and lasted for approximately 20 s with a very, very sharp peak at E/S+338 s. Titanium has been rarely observed in the plume. It was detected in only three tests

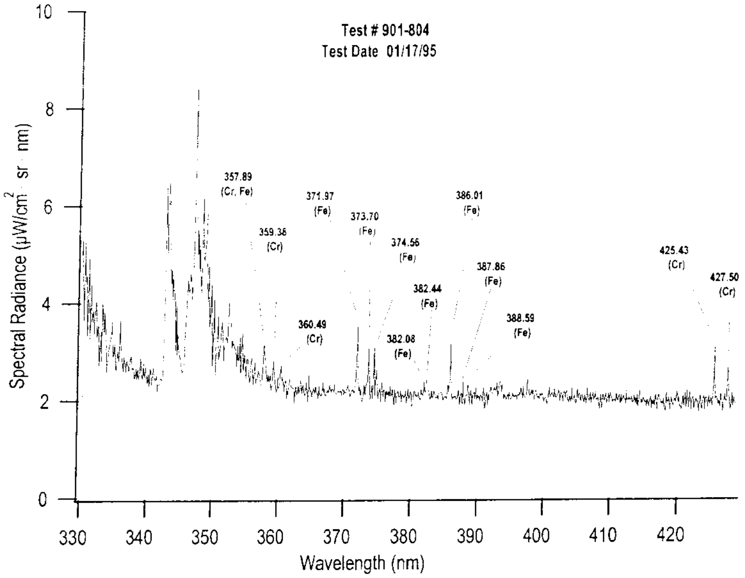

Figure 4: SSME Difference Spectrum [E/S+87 s minus E/S+26.5 s], 330 to 429 nm.

prior to this test. These are test firing #'s 901-853, 901-873, and 901-882. With the exception of last few seconds of hotfire on test #901-853, this test showed the highest levels of TiO emission ever detected in the SSME plume at SSC. TiO spectral radiance vs. time at 516.82 nm is shown in Fig. 5. Currently, Ti is not a part of EDC material loss quantification algorithms.

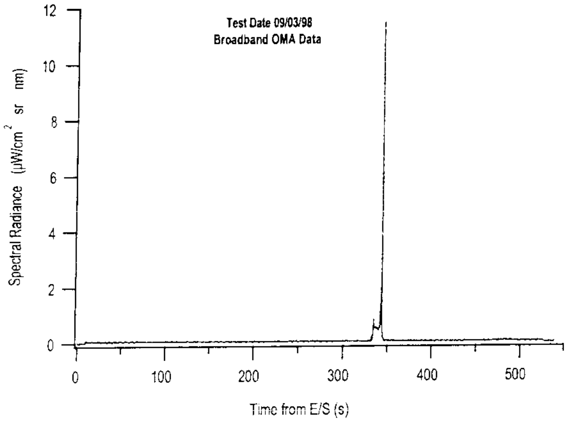

Figure 5: Time History of TiO Emissions at 516.82 nm. Test #904-361.

It is obvious that more than one alloy/material is responsible for all the elements observed in the plume.[11] EDC attributes Ni, Fe, Co, Cr and Mn emissions to Incoloy 909. However, the confidence level is not high. Spectral emissions correlate with several shifts seen in engine system operation from E/S+325 to E/S+340 s. Largest of these shifts were indicated by HPFTP FASCOS (Flight Accelerometer Safety Cut Off System) and HPFTP RASCOS (Red-Line Accelerometer Safety Cut Off System) readings showing an increase in amplitude after balance cavity pressure shifts. Therefore, these spectral anamolies were attributed to HPFTP unit #8010 since the pump vibration and thrust balance measurements correlated with the plume event.[23] Post test hardware borescope inspection report indicated light to moderate pump-side impeller tip seal rub (360 degrees around) and very light intermittent turbine-side impeller tip seal rub.[23] HPFTP/ATD unit #8010 certification testing was discontinued and the pump was returned to Pratt and Whitney for disassembly inspection. Disassembly summary report[24] indicated many distressed components with evidence of material loss both

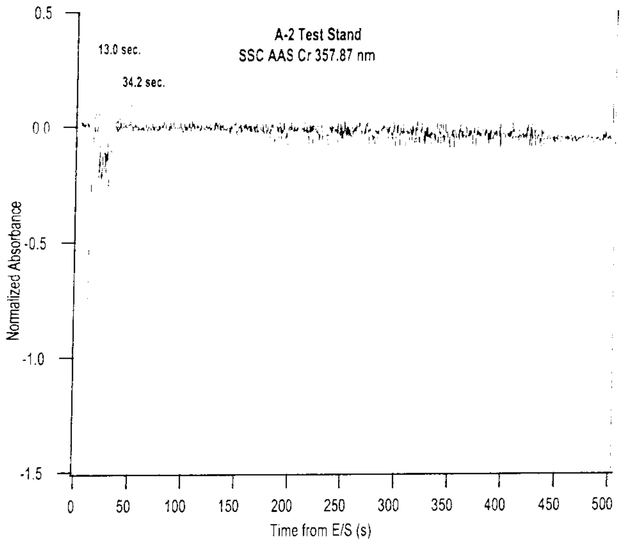

Figure 6: Time History of Cr Absorption. Test #902-741.

on the pump as well as turbine side. Most highly impacted of the components, the 3rd impeller and 3rd impeller pump side tip seal had heavy 360° rub from each other. This is obviously one of the source of TiO emissions in the plume, as the impellers are made of titanium. Thrust balance tip seals are made of Incoloy 909 on turbine-side and Inconel 718 on pump-side. Presence of both Incoloy 909 and Inconel 718 explains the low confidence levels given by the EDC for the alloy identification. Both Incoloy 909 and Inconel 718 contain Ni, Fe, Mn, and Cr.[11] Incoloy 909 also contains Co. The source of Cu and Ag effluent in the plume is most likely NARloy.[11] It is not possible to pinpoint the exact component because the amount of Cu and Ag in the plume is extremely small and no other correlating data was observed by the engine sensors.

ATOMIC ABSORPTION

During test firings #902-741 and #902-742, SSC Atomic Absorption Spectroscopy (AAS) system observed plume events containing Cr, Ni, Fe, and Cu. Both test firings were conducted on Block II engine 0525 with HPFTP/AT 8012. HPOTP/AT 8111R1, LPFTP 2431, and LPOTP 4502. Primary objectives of these tests were the evaluation of Block II engine 0525 and certification of HPFTP/AT unit 8012. Test firing #902-741 ran to a programmed duration of 502.8 s with 385.60 @ 111% RPL on December 2, 1999. The test was monitored using the SSC AAS system mounted on the A-2 diffuser lip with a line of sight across the SSME plume approximately 2 in. downstream of nozzle exit. The AAS system detected Cr, Ni, Fe, and Cu in the plume. All four elements were observed beginning at E/S+13 s and continuing until about E/S+34 s. Figure 6 shows time history of chromium absorption. The temporal characteristics of all four elements in the plume are similar, indicating a common source of components. At this time elemental quantification is not possible. Therefore, no alloy identification can be done. Considering that the AAS system sensitivity is much less compared to the AES system due to the considerably lower temperature plume LOS, the relative absorption seen here indicates some significant event. However, none of the engine sensors indicated any "out of family" data.

The test firing #902-742 was conducted on December 4, 1999 for a programmed duration of 745.7 s with 450.4 s at 106% RPL, 137.6 s at 98% RPL, and 120.6 s at 97% RPL. Several anomalous events of short duration were detected throughout the test. Figure 7 shows the time history for Cr absorption. Again, simultaneous absorption/detection of Cr, Ni, Fe, and Cu was observed. Again, no correlating anomalous data from any additional engine sensors was noticed. The AAS data was not obtained on test #902-743 due

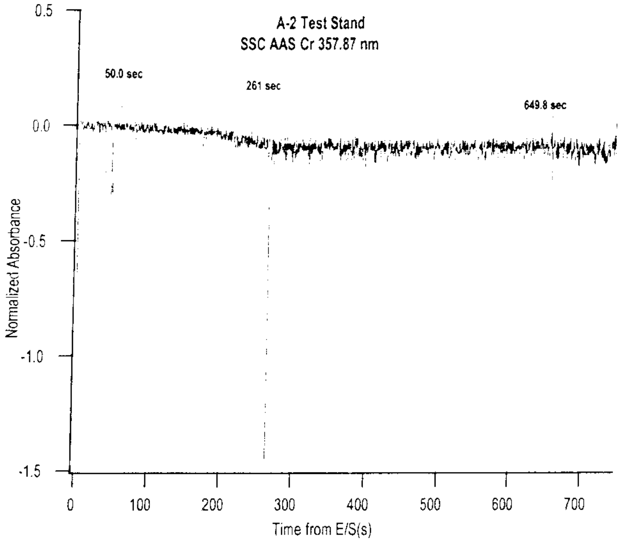

Figure 7: Time History of Cr Absorption. Test #902-742.

to a malfunction of the data acquisition computer. Subsequent to completion of this test series after the test firing #902-747, the HPFTP/AT 8012 certification unit was removed and sent to Pratt and Whitney for disassembly and inspection. Many components were found in various stages of distress including liberated pieces for some minor components.[25]

V SUMMARY AND RECOMMENDATIONS

An overview of the rocket engine plume diagnostics of SSC has been given in this paper. This technology has proven invaluable in the engine development and testing programs for the SSME especially during the very extensive testing and certification of HPFTP/AT and HPOTP/AT. It is clear that the AES has the capability to detect some of the SSME related metallic elements in the plume at parts per billion levels. Using innovative data reduction and data analysis techniques, we can quantify and identify the alloy(s) in the plume. This narrows down the list of components in hot gas path which may be under distress. In many cases, in conjunction with data from mechanical sensors, we can pin point the source of effluent material(s) to a single or a group of identical components. In many situations, plume spectral emission data has been successful in helping to identify the source of a problem from precursor events in the SSME exhaust plume.

Most of the SSME testing at SSC in last few years has been carried out under altitude simulation conditions. Therefore, the plume monitoring has been done by the AAS system. Since this technology is less sensitive for engine plume diagnostics, we have seen metallic effluent materials much less frequently. Another reason for rarity of the plume events is the fact that HPFTP/AT and HPOTP/AT are less prone to wear and tear. Even when the testing was resumed at the open air test stand since last year, the AES system has not observed too many significant plume events worth reporting. Nonetheless, we believe that the AAS analysis efforts should be continued and completed as soon as possible so that metallic elemental quantification is obtained just as it is routinely obtained for AES system. The added value to the overall analytical capability will be tremendous in case of significant plume events observed by the AAS system.

It should also be noted that our SSME critical components and materials database[11] has not been updated for the EDC. Obviously, it needs to be modified now that AT turbopumps are flight certified and routinely used in flight engines. In absence of up to date materials database, EDC can and does produce erroneous results which have to be reconciled with the AT components and materials database. Secondly, the EDC for AES is based on the LBL computations[15] for a small throat engine. It has not been modified for large throat BLOCK II engines. Even a small error of about 1 to 2% in the elemental quantification can throw off the alloy identification completely since the constituent elemental composition of many alloys utilized in SSME differs from one another ever so slightly.[11]

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