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Health Management System for Rocket Engines

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HEALTH MANAGEMENT SYSTEM FOR ROCKET ENGINES

ABSTRACT

The functional framework of a failure detection algorithm for the Space Shuttle Main Engine (SSME) is developed. The basic algorithm is based only on existing SSME measurements. Supplemental measurements, expected to enhance failure detection effectiveness, are identified.

To support the algorithm development, a figure of merit is defined to estimate the likelihood of SSME criticality 1 failure modes and the failure modes are ranked in order of likelihood of occurrence. Nine classes of failure detection strategies are evaluated and promising features are extracted as the basis for the failure detection algorithm.

The failure detection algorithm provides early warning capabilities for a wide variety of SSME failure modes. Preliminary algorithm evaluation, using data from three SSME failures representing three different failure types, demonstrated indications of imminent catastrophic failure well in advance of redline cutoff in all three cases.

SECTION 1 - INTRODUCTION

Currently rocket engine protection consists of a redline system that issues an engine cutoff if a measured value exceeds a pre-determined operation limit for any of several parameters. For the SSME, seven key engine parameters are monitored during mainstage and their limits are set at levels above which safe engine operation is impaired. Reliance on this system alone, however, has led to premature engine cutoff caused by combinations of normal excursions and engine-to-engine (and even test-to-test) variations of the redline parameters. Moreover, during developmental and operational firings, over forty severe failures have resulted in extensive damage to the engine and components even though the engine was being monitored with the redline system.

During a SSME ground test, about 500 measurements are normally recorded in addition to visual coverage such as film, video and crew observation. The measurement system acquires data on critical parameters such as pressures, temperatures, flowrates, rotational speeds, valve positions, etc., that reflect internal engine performance. Monitoring of some of these additional parameters using techniques more advanced than standard redlines is expected to provide more complete failure coverage for the engine and enable earlier failure detection. The System for Anomaly and Failure Detection (SAFD) is one such system being developed (ref. 1&2). It increases engine protection by monitoring a relatively large number of parameters (23), placing fairly tight tolerance bands around nominal values and/or a measured average for each parameter, and issuing a cutoff if a predetermined number of parameters exceed their tolerance bands (e.g. four anomalous sensors might be required for cutoff).

The goal of this program is to further enhance safety monitoring through development of an advanced framework for a failure detection system. The health management system for rocket engines (HMSRE) framework is the result of this effort.

A key feature of the failure detection strategy for the HMSRE framework is the determination of overall engine health from calculated engine level anomaly parameters. These parameters are a combination of individual, weighted sensor deviations correlated to provide either an overall anomaly value or indications of a specific degradation (e.g. loss of HPFT efficiency). This approach is in marked contrast to existing failure detection schemes which rely on definition of anomalies for individual parameters. Definition of engine level parameters allows the HMSRE to detect a wide variety of early failure indications, all of them applicable to the SSME. For example, the first indication of a failure may be a large deviation in only a few sensors or it may be subtle changes in a relatively large number of sensors. Since the HMSRE is not dependent on individual sensor anomalies, a group of subtle changes is as detectable as a few major deviations, even if some of the parameters never deviate enough to be considered "anomalous". This capability is especially attractive for relatively slow failures in which many parameters generally drift off nominal. Slow failures are of particular interest in this program since early detection of these failures is expected to significantly reduce the ensuing damage.

The HMSRE framework consists of engine level anomaly parameter algorithms working in parallel with the current redline, FASCOS, and SAFD systems to further extend SSME failure coverage and provide even earlier detection for many failures. The HMSRE complements existing systems by providing sensitivity to a wider variety of failure indications. For example, redlines are sensitive to failures indicated by a large change in a single parameter, SAFD reacts to failures resulting in smaller, but significant changes in several parameters, FASCOS (or RASCOS) detects abnormally high turbopump vibrations, and HMSRE is sensitive to failures indicated by weighted combinations of multiple sensor deviations - making HMSRE sensitive to subtle changes in a moderate number of parameters or large changes in only a few. Each system provides some unique advantages to the overall engine protection scheme, but a large degree of overlap also exists. Therefore, in addition to providing increased sensitivity to a wide range of early failure signatures, the overall observability of the system is increased. The SSME measurements used by each system and the basic failure detection strategies are represented in Figure 1-1 which shows the overall SSME protection strategy.

While each of these approaches offers some advantages and will provide the earliest indication for some failures, the system defined by the HMSRE framework provides the greatest overall utility in both failure coverage and earliness of detection.

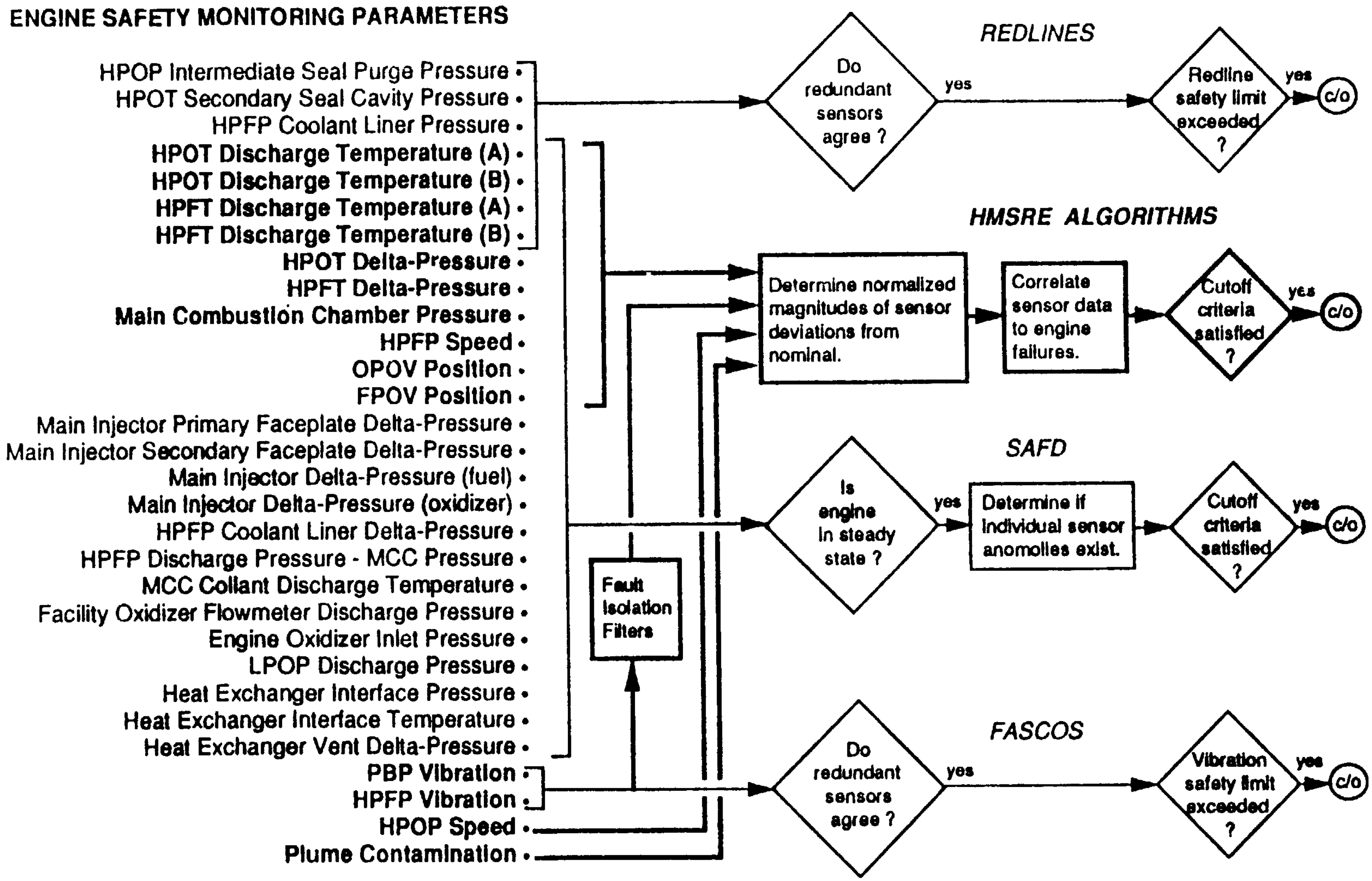


FIGURE 1-1 EXTENDED FAILURE COVERAGE WITH MULTIPLE SYSTEMS

SECTION 2 - PROGRAM OVERVIEW

The purpose of this program was to synthesize a frame.vork, or conceptual structure, for a health management system for rocket engines (HMSRE) and develop a plan for a breadboard implementation of the HMSRE. It is based on existing and/or near term technologies to enable ground testing within five years. Although the HMSRE will be used initially to support SSME ground tests, the design of the system does not preclude eventual utilization on SSME flights.

The program was divided into 4 tasks:

Task 1: Identification of Failure Modes,
Task 2: Methods to Detect and Minimize Damage,
Task 3: Framework for Health Management, and
Task 4: Plan for Breadboard Implementation.

In Task 1, the SSME failure modes and effects analysis (FMEA) and failure history were reviewed to identify critical SSME failure modes. A figure of merit (F.O.M.) was established and used to quantitatively rank the failure modes. Sensors expected, or observed in the failure history, to indicate each of the 45 highest ranked failure modes were identified.

In Task 2, damage minimization methods (compatible with the Block-II SSMEC) were evaluated. Failure detection methods, that address the types of failures identified in Task 1, were evaluated to characterize near term applicability to the SSME and general effectiveness of each.

Task 3 combined promising elements of the failure detection methods, evaluated in Task 2, and synthesized an HMSRE framework. The effectiveness of the framework was evaluated against current detection systems. In addition, a basic algorithm was coded and the conceptual HMSRE strategy was demonstrated for three SSME failures.

Finally, Task 4 generated an implementation plan for the development of the proposed HMSRE framework.

SECTION 3 - RANKING AND CHARACTERIZATION OF SSME FAILURE MODES

The effort described in this section consists of evaluation of potential SSME failure modes and identification of those failure modes most likely to occur. The SSME failure modes were ranked and characterized to (1) assist in definition of HMSRE system requirements and limitations and (2) to serve as a database for the development of failure detection techniques and system frameworks.

3.1 QUALITATIVE RANKING OF FAILURE MODES

The goal of this task is to qualitatively rank the SSME failure modes according to relative risk to the engine.

The critical failure modes of the SSME have been assessed previously (ref. 3) based on a review of the revised SSME Failure Modes and Effects Analysis and Critical Items List (FMEA/CIL), performed in 1987 and issued on 10/23/87. This assessment, the Critical Item Ordinal Ranking of the SSME (CIOR-SSME), was performed using NASA instructions which were to be applied to the entire NSTS on a uniform basis. The assessment used a subjective categorization procedure which yielded an ordinal ranking of all Critical Items.

The failure mode information collected for the ordinal ranking study was deemed a suitable database for the HMSRE quantitative ranking of failure modes.

Review of the data contained within the ordinal ranking study resulted in the following decisions: (1) determine a methodology which can result in a cardinal ranking of the failure modes in order to establish their relative magnitude of importance; (2) employ Quantitative Probabilistic Risk Assessment (QRA or PRA) methods using the already existing subjective assessment results as inputs; and (3) only the criticality 1, loss of vehicle, failure modes were to be considered.

<u>FIGURE OF MERIT PROCESS (FOM)</u>

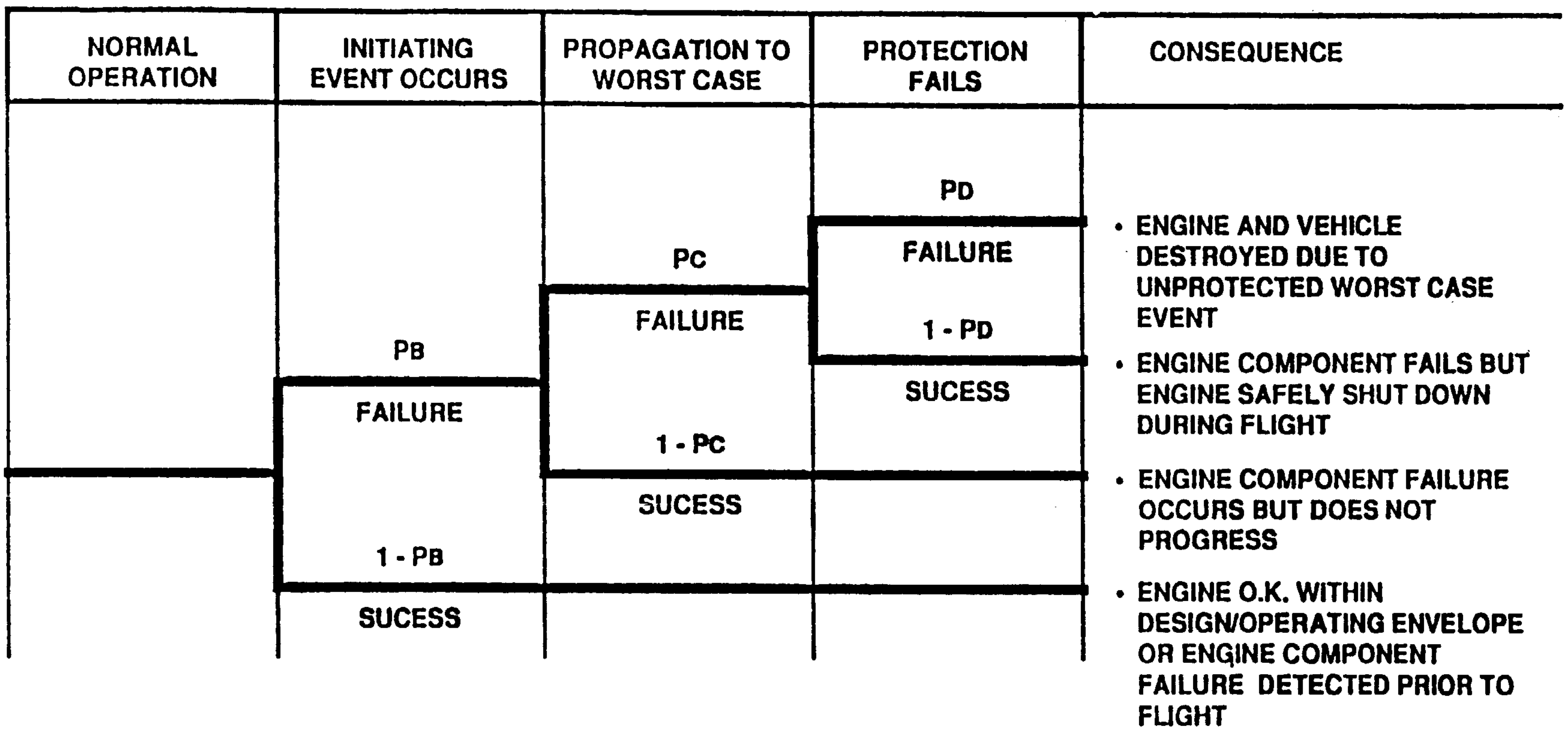
The FOM process uses a probabilistic approach with expert judgments as inputs. This is in the line of Bayesian reasoning which is extensively used in QRA. In Bayesian reasoning, probabilities are associated with individual events and not merely sequences of events. Since probabilities of failure modes are not known, they are substituted by subjective estimates of the likelihood of occurrence. The probability of a worst case event to occur is divided into three probability parts which, in turn, are determined by aggregation of attributes. The attributes are the products of weighting factors, and of discrete factors (1 or 0) which express the existence or non-existence of the attributes. The weighting factors were determined by a survey of expert opinions from SSME test operations, SSME systems engineering, SSME controls and monitoring). The discrete attribute factors were obtained from the CIOR-SSME. The probabilities were normalized and combined to produce a single value as discussed in the next sections.

All Criticality 1 events were subjected to this subjective probability calculation and ranked according to their risk (highest risk equals highest rank).

EVENT TREE

Any quantitative method of determining risk is based on the usual engineering definition of risk as the product of failure probability and failure consequence. Since most of the CIL events (i.e., 310 out of over 400) had "engine and vehicle loss" as the worst consequence, the analysis was restricted to these worst cases. Therefore, the consequence for each event is the same; and the risk quantification reduces to a probability quantification.

In order to aid the visualization of the probabilistic approach, an event tree for SSME Criticality 1 failures was constructed (Figure 3-1). This event tree is similar to those extensively used at Rocketdyne for nuclear reactor safety analyses. The event tree in Figure 3-1 shows the propagation of failure events which is necessary to lead to the consequence listed in the right column. During normal operation, a probability of P_B exists that an initiating event occurs. Given an initiating event occurs, a probability P_C exists that the initiating event progresses to the worst case, barring protection by design measures. Given the initiating event occurs and propagation to worst case has started, a probability P_D exists that protection measures fail. The overall, or aggregated, probability for the worst case scenario is therefore the product of the first probability, P_B, and the conditional probabilities P_C and P_D.



AGGREGATED PROBABILITY = $P_B \times P_C \times P_D = P_I$

FIGURE 3-1 EVENT TREE FOR SSME FAILURES

The three probability elements are determined from subjective judgments and actual experience. This is discussed in the following paragraphs.

PROBABILITY OF INITIATING EVENT

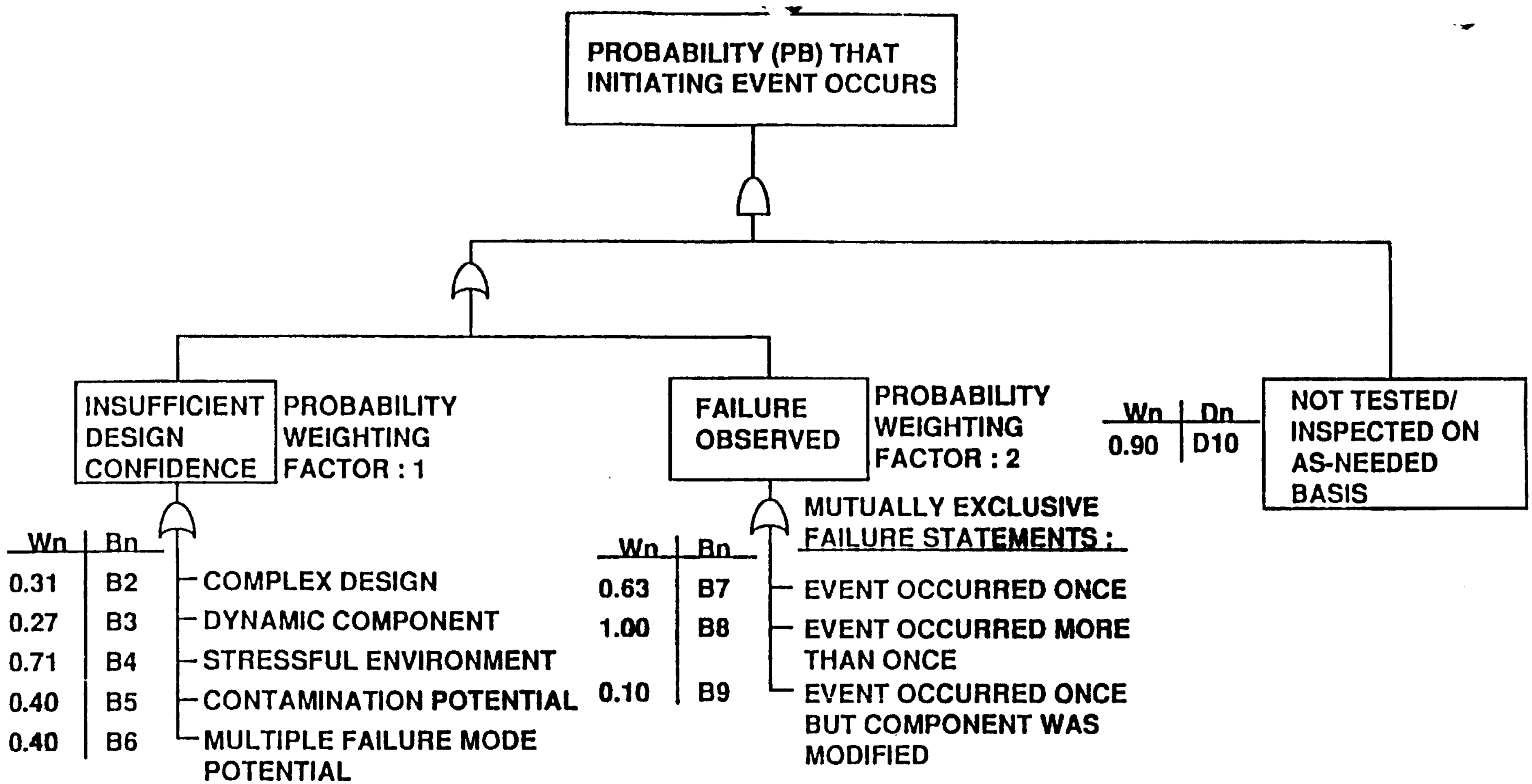
Figure 3-2 depicts how the individual subjective judgments and test history are combined using a "probabilistic tree" (similar to a fault tree). The top two branches are the inherent probability that the initiating event occurs (P_{Bi}), made up of "design confidence" and "failure observation", and the probability that the initiating event is not detected during inspection (P_{Bd}). P_{Bi} is determined by the probability that there is insufficient design confidence (weighted once) or there have been failures observed (weighted twice), given that there is no testing/inspection on an as-needed basis. Inspections are conservatively estimated to sucessfully identify 10% of initiating events, therefore, P_{Bd} equals 1.0 if no inspections are performed and 0.9 if appropriate inspections are implemeted. The overall probability of an initiating event occuring during a hot-fire test is the product of P_{Bi} and P_{Bd}.

All probability attributes were first weighted (W_n) and then multiplied by a discrete factor,B_n, noting that they either exist (B_n=1) or do not exist (B_n=0). The weighting factors are to be understood as "allocated probability weights", as determined by an expert opinion survey of six Rocketdyne engineering specialists.

The factors B_n and D_{10} were obtained from the previously cited CIRA document. All discrete factors for the 310 failure modes ranked highest in the CIRA document are summarized in binary form. The top 37 are shown in Figure 3-3. The five attributes for "insufficient design confidence" are all possible; therefore, that part of the probability P_B was normalized by dividing by the sum of the weights. The three attributes for "failure observed" are mutually exclusive; therefore, this part of P_B was normalized to a range of 0 to 1 by dividing the weighted sum (which only includes one of the three possible scenarios) by the maximum possible weight. Therefore, the worst case scenario (B8) is normalized to 1.0 while the other scenarios represent less risk and have correspondingly lower, weighted values.

PROBABILITY OF EVENT PROPAGATION

Figure 3-4 presents the probability tree for event propagation to worst case. The two branches of the probability that the event propagates to the worst case (P_C) consists of the existence of propagation factors (weighted once), combined by an "or" with the existence of a failure history (weighted twice). Again, the allocated probability weights were determined by expert opinion, and the discrete C-factors were those contained in the binary summary. Normalization was obtained by dividing by the sum of weights for propagation factors, and by the maximum weight for the mutually exclusive failure history attributes. The maximum possible value for P_C is 1.0; the minimum value is 0.



$$PB = \underbrace{\left[\left(\frac{1/3\sum_{2}^{6} Wn \cdot Bn}{\sum_{2}^{6} Wn}\right) + \left(\frac{2/3\sum_{7}^{9} Wn \cdot Bn}{(Wn)\ max}\right)\right]}_{P_{Bi}} \underbrace{\times\, [1 - (1 - W10)D10\,]}_{P_{Bd}} ;\ Bn = 0 \text{ or } 1$$

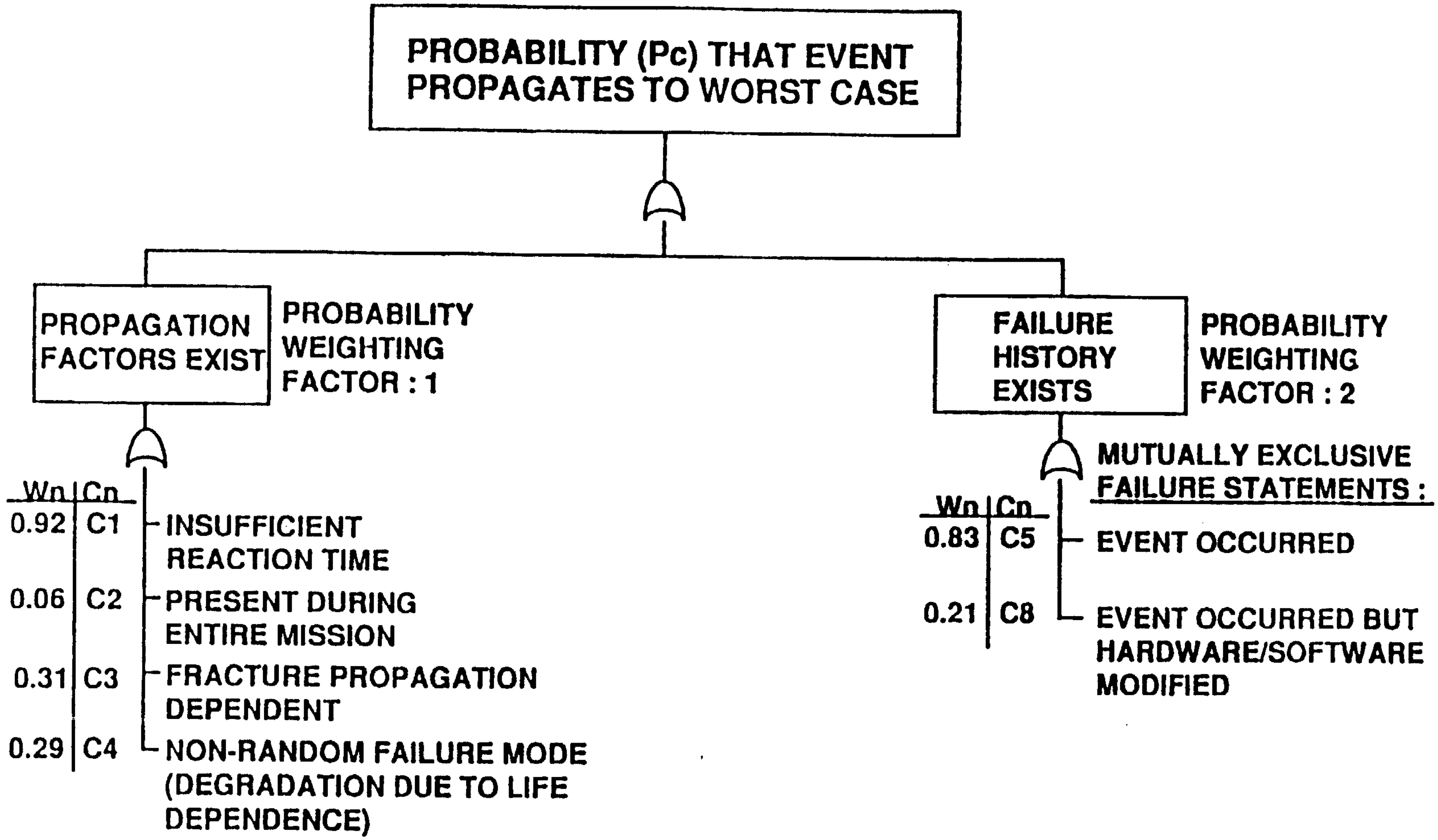
$$\sum_{2}^{6} Wn = 2.09$$

$$(Wn)\ max = 1.0$$

FIGURE 3-2 PROBABILITY TREE FOR INITIATING EVENT

1	LRU-FM	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	C5	C8	C7	C8	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
2	TOTAL FM's	X	X	X	X		1												8	2	X	X	12	X	X	8	3	X	X	3	X	31	19	
3	A150-01					1				1		1		1		1	1	1		1													1	
4	B200-04					1		1	1	1	1	1		1		1	1	1					1											1
5	A600-04					1		1		1	1	1		1		1	1						1											1
6	D110-01					1		1			1	1		1		1		1					1											1
7	A340-02					1				1		1		1		1	1	1					1											1
8	B400-03					1		1	1	1	1	1		1		1	1	1																1
9	B400-07					1		1	1	1		1		1		1	1	1																1
10	B400-22					1		1	1	1				1		1	1	1																1
11	B600-06					1		1			1	1		1		1		1	1															1
12	A200-09					1		1		1		1		1		1	1	1																1
13	A330-02					1				1		1		1		1	1	1																1
14	D500-06					1		1		1				1		1	1	1																1
15	K103-01					1				1		1		1		1	1	1																1
16	B400-14					1		1	1	1	1	1		1		1	1	1																1
17	C200-11					1		1			1	1	1			1		1		1														1
18	E150-14					1		1		1	1	1	1			1	1	1																1
19	B800-06					1		1	1		1	1	1			1	1	1	1															1
20	B400-23					1		1	1	1			1			1	1	1																1
21	B400-13					1		1	1	1	1	1			1	1	1	1																1
22	B400-20					1		1		1	1	1			1	1	1	1																1
23	D300-03					1		1		1	1	1			1	1	1	1																1
24	B200-16					1		1	1	1	1	1				1	1	1																1
25	B200-17					1		1	1	1	1	1				1	1	1																1
26	B400-18					1		1	1	1	1	1				1	1	1																1
27	A200-06					1		1		1	1	1	1			1	1	1					1										1	
28	G100-01					1		1			1	1	1			1		1	1													1		
29	D220-06					1		1		1	1	1		1		1	1																	1
30	B800-02					1		1	1	1	1	1	1					1																1
31	E120-09					1		1		1	1	1	1				1	1																1
32	C200-07					1		1		1	1	1	1			1																		1
33	A200-05					1		1		1	1		1			1	1																	1
34	D130-03					1		1		1	1		1			1	1																	1
35	B200-24					1		1	1	1	1	1				1		1																1
36	A700-04					1		1		1	1	1			1	1	1																	1
37	D500-08					1		1		1	1	1			1	1	1																	1
38	B800-01					1		1	1	1	1	1						1																1
39	B200-10					1	1	1	1	1					1			1																1

FIGURE 3-3 DISCRETE EVALUATION FACTORS



$$Pc = \left(\frac{1/3 \sum_{1}^{4} Wn \cdot Cn}{\sum_{1}^{4} Wn} \right) + \left(\frac{2/3\,(W5C5 + W8C8)}{(Wn)\ max} \right) \quad ; \quad Cn = 0 \text{ or } 1$$

$$\sum_{1}^{4} Wn = 1.58$$

$$(Wn)\ max = 0.83$$

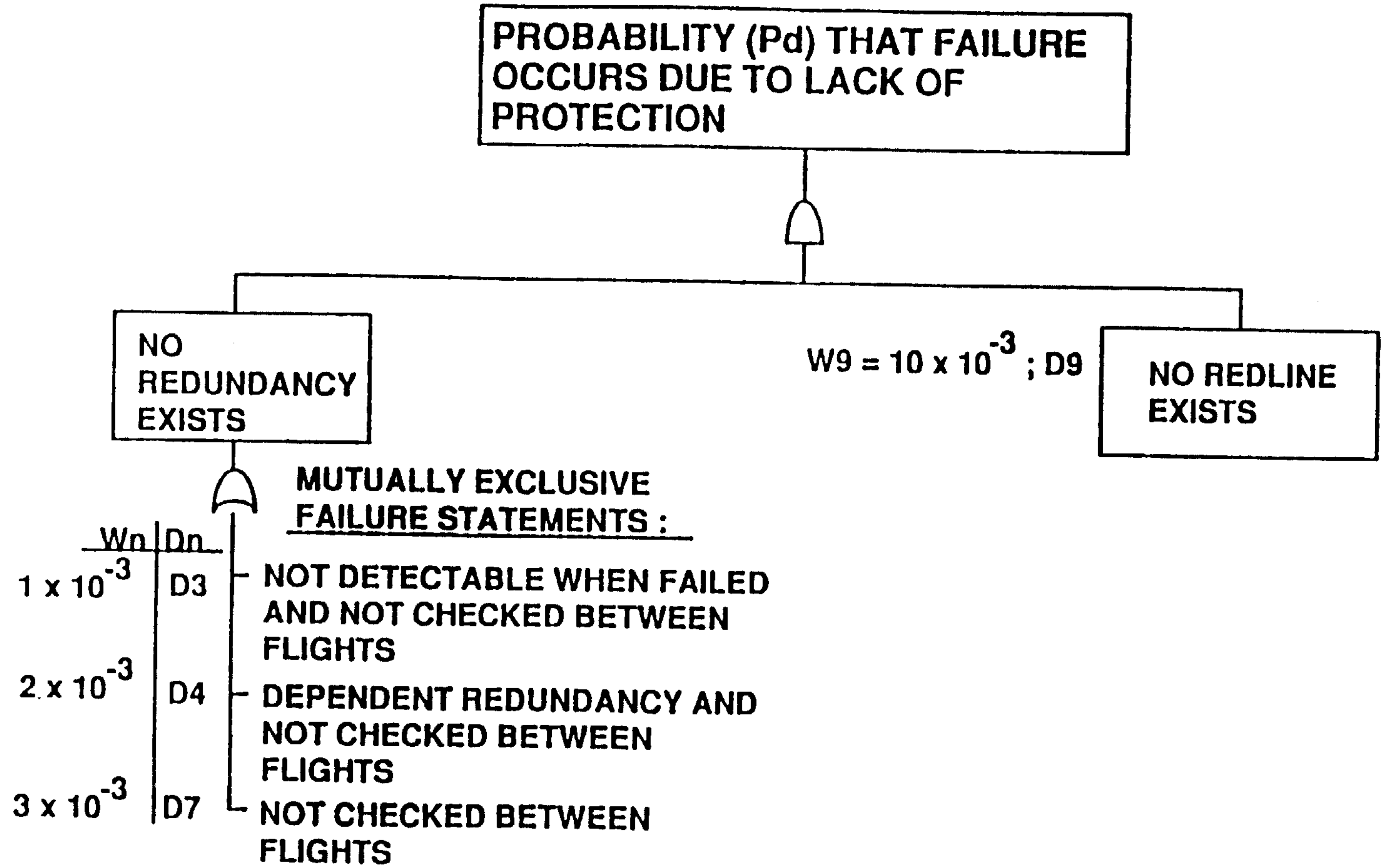
FIGURE 3-4 PROBABILITY TREE FOR EVENT PROPOGATION

PROBABILITY OF PROTECTION FAILURE

Figure 3-5 shows the probability tree for protection failure. The two branches of the probability that failure occurs due to lack of protection (P_D) consist of the fact that no redundancy exists and that no redline parameter is measured. The two facts exacerbate each other and are therefore combined multiplicatively. The attributes of no redundancy are listed in ascending order of their potential contribution to a failure. These attributes are mutually exclusive within the design approach of the SSME. The magnitude of their weights was determined by considering that simple hardware, software or functional redundancy decreases failure probabilities by one or two orders of magnitude. Redundancies were considered to be a more effective protection device than redlines. The maximum possible value for P_D is 1.0; the minimum value is $1x10^{-5}$. Only 45 failure modes fall into the category where the failure probability is mitigated by either redundancy or redline parameters.

RESULTS OF FAILURE MODE RANKING BY FOM

The three probabilities were combined multiplicatively, as indicated in Figure 3-1. An example of the FOM methodology is shown in Figure 3-6. The top part of Figure 3-6 indicates data for CIL number A150-01. The numerical results of the three equations for P_B, P_C and P_D were multiplied and gave 0.713 for overall normalized failure probability. This represents the failure mode with the highest criticality as defined by the F.O.M. process. Attachment 1 presents the ranking results of all 310 criticality 1 failure modes. The failure modes, and corresponding rank, are shown for each LRU in Attachment 2.



$$Pd = [1 - (1 - Wn)Dn] \times [1 - (1 - W9)D9] \;;\quad n = 3, 4, 7$$
$$Dn = 0 \text{ or } 1$$

FIGURE 3-5 PROBABILITY TREE FOR EVENT PROTECTION

CIL NUMBER : A150-01
LRU : HEAT EXCHANGER
FAILURE MODE : COIL FRACTURE/LEAKAGE
FAILURE CONSEQUENCE : LOSS OF VEHICLE
FROM SSME CRITICAL ITEM RANKING REPORT (RSS-8790, 3/25/88):

n	Bn
2	0
3	0
4	1
5	0
6	1
7	0
8	1
9	0

n	Cn
1	1
2	1
3	1
4	0
5	1
8	0

n	Dn
3	0
4	0
7	0
9	0
10	1

$$P_B = \left[\frac{1}{3 \times 2.09}\left(0.71 + 0.40\right) + \frac{2}{3 \times 1.0}\left(1.0\right)\right]\left(1 - 0.1\right) = 0.760$$

$$P_C = \frac{1}{3 \times 1.58}\left(0.92 + 0.06 + 0.31\right) + \frac{2}{3 \times 0.83}\left(0.83\right) = 0.939$$

$$P_D = \left(1 - 0\right)\left(1 - 0\right) = 1.0$$

$$P_f = P_B \times P_C \times P_D = 0.714$$

FIGURE 3-6 EXAMPLE OF F.O.M. METHODOLOGY

Due to rounding of numbers, the highest ranked failure mode listed in Attachments 1 and 2 has a slightly different probability estimate (0.695) compared to that of the example in Figure 3-6 (0.714).

In the final ranking list (Attachment 1), the 40 highest ranked failure modes using the FOM procedure include the 20 highest CIRA-ranked failure modes; however, in a different order.

3.2 CHARACTERIZATION OF HIGHEST RANKED FAILURE MODES

The 45 highest ranked (most likely) failure modes were selected to represent the failure scenarios expected on the SSME. These failure modes were characterized to provide a database of failure indications for subsequent detection method and framework efforts.

Each failure mode was characterized by identifying 1) possible causes, 2) possible effects, 3) correlated test cases, and 4) available sensors expected to indicate the failure. Possible causes for each failure mode were identified in the SSME FMEA/CIL documentation. Possible effects were determined through the SSME FMEA/CIL and consultation with SSME test operations and system engineers. SSME incident test cases were correlated to specific failure modes on the basis of failure indication (rather than root cause). For example: Failure A340-02 is a nozzle fuel leak, a failure that in many cases results from an earlier failure. A test case is considered correlated to this failure mode if a nozzle leak occurs at any point during the failure sequence. This is appropriate since the purpose of the effort is to characterize observable anomalies that indicate a failure, regardless of the cause. Finally, by examining correlated test cases and through consultation with SSME test operations personnel, available sensors expected to provide failure indications were identified. The results of this effort are summarized in Attachment 3 for each failure mode. Summaries of each test case can be found in the SAFD Phase I Report (ref. 1).

3.3 IDENTIFICATION OF HIGH PAYOFF FAILURE MODES

The 45 most likely failure modes (as determined by the figure of merit process) were evaluated on the basis of detectability and damage minimization potential. The objective of the failure mode classification was to systematically evaluate the most likely, critical failure modes (identified in Task 1) to determine which of those, if addressed as part of the HMSRE, had the highest potential for improving engine protection.

The methodology used for the failure mode classification is shown in Figure 3-7. Three key issues influencing the effectiveness of HMSRE implementation were addressed: 1) detectability (Phase I), availability of detailed failure signatures (Phase II), and effectiveness of current detection systems (Phase III).

Phase I - Failure Mode Detectability

The primary goal for phase I was to determine which of the 45 highest ranked failure modes were likely to provide early failure indications. The rationale behind the phase I sort is that failure modes with no detectable, early failure indications (anomalies) provide no basis for early detection.

The possibility of early indications was determined using two complementary sources of data: 1) detailed evaluation of the available test history, and 2) an assessment of each failure mode's propagation scenario by SSME test operations personnel.

Based on the investigation results, the failure modes were grouped according to the likelihood of detectable, early indications and the availability of related test histories. The failure modes were placed into one of four categories:

1. failure modes with expected anomalies and no related test history.
2. failure modes with expected anomalies and related test history.
3. failure modes with no expected anomalies and a related test history.
4. failure modes with no expected anomalies and no related test history.

Those failure modes judged to provide no early failure indications and having no related test history were eliminated from further evaluation. In addition, the test data was evaluated for the one failure mode with a test history and no expected anomaly (B400-22) and no early warnings were identified. Therefore, this test was also eliminated from further evaluation.

The results of the phase I investigation are shown in Table 3.1. Of the total 45 failure modes: 13 were in the first category, 17 in the second, 1 in the third, and 14 in the fourth.

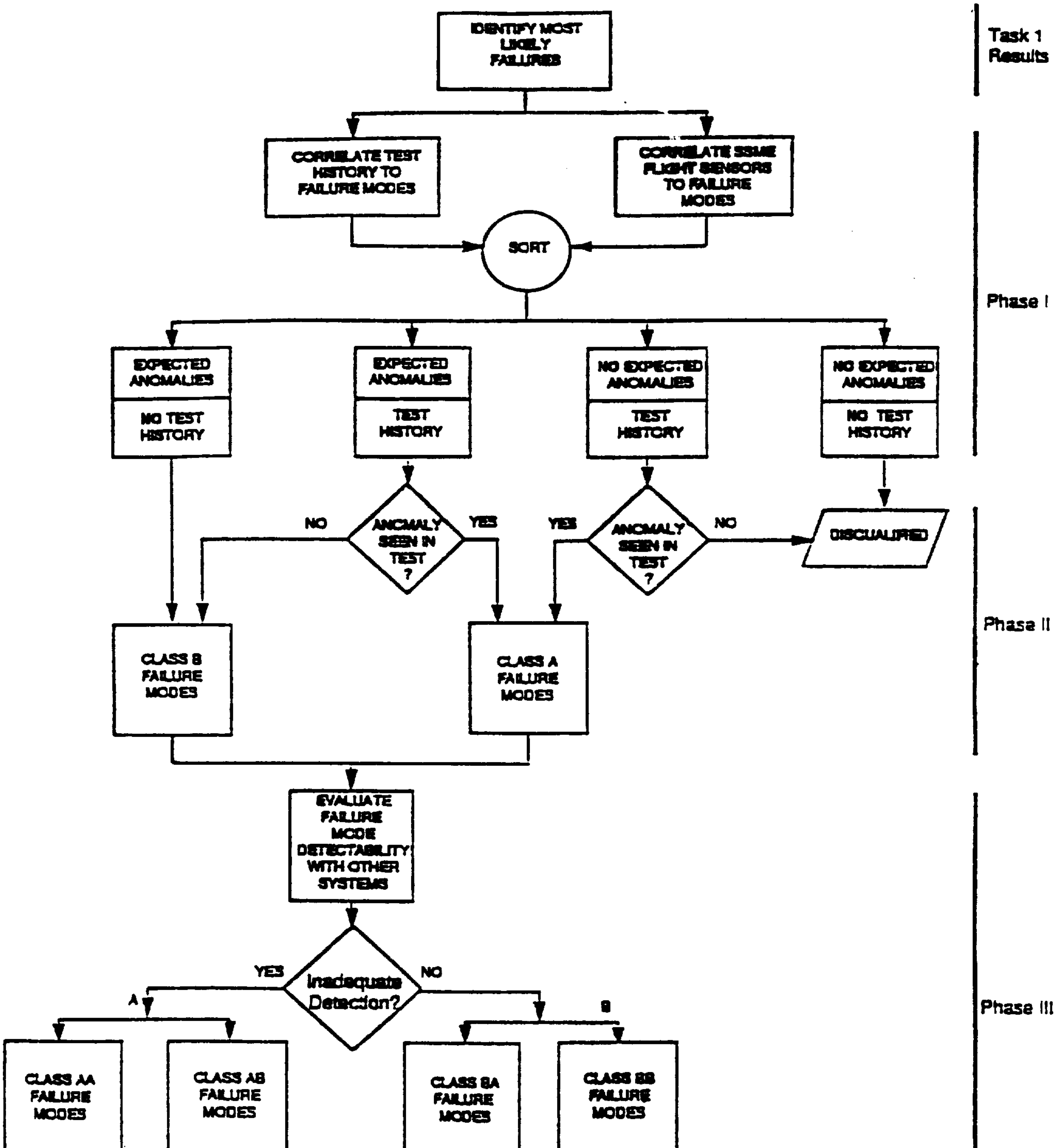


FIGURE 3-7 FAILURE MODE CLASSIFICATION METHODOLOGY

TABLE 3.1 FAILURE MODE SORT - ANOMALIES AND TEST HISTORY

ANOMALIES EXPECTED, NO TEST HISTORY

Rnk	LRU-FM	Component	Failure Mode
9	B600-06	LPFTP	FUEL LEAKAGE PAST LIFT-OFF SEAL.
10	B400-03	HPOTP	TURBINE BLADE STRUCTURAL FAILURE.
15	A330-02	MCC	FUEL LEAKS INTO THE CLOSED CAVITY (LINER & JACKET)
16	K103-01	LPFTP DUCT	FAILS TO CONTAIN HYDROGEN
18	D300-01	ANTI-FLOOD VLV	LEAKAGE DURING PROPELLANT CONDITIONING.
20	B800-06	LPOTP	LOSS OF SUPPORT AND POSITION CONTROL.
22	E150-14	CCV ACT.	SEQUENCE VALVE LEAKS - CNTRL PRESSURANT DOWNSTREAM.
24	B400-23	HPOTP	TURBINE PIECE PART STRUCTURAL FAILURE
27	K203-01	OX BLD FLX LIN	FAILS TO CONTAIN OXIDIZER.
39	D300-03	ANTI-FLOOD VLV	LOW FLOW RESTRICTED OR SHUT OFF.
40	A700-02	OPB	LOSS OF FUEL TO ASI.
43	B400-18	HPOTP	LOSS OF COOLANT TO BEARINGS.
45	B200-23	HPFTP	LOSS OF BALANCING CAPABILITY.

ANOMALIES EXPECTED, RELATED TEST HISTORY

Rnk	LRU-FM	Component	Failure Mode
1	A150-01	HEX	COIL FRACTURE/LEAKAGE.
2	C200-11	PCA	FAILURE TO SUPPLY HELIUM PRESSURANT.
3	B200-04	HPFTP	STRUCTURAL FAILURE OF TURBINE BLADES.
4	A340-02	NOZZLE	EXTERNAL RUPTURE.
5	D110-01	MFV	INTERNAL LEAKAGE.
6	A600-04	FPB	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT
7	B200-15	HPFTP	LOSS OF SUPPORT OR POSITION CONTROL.
8	A200-06	MAIN INJ	LOX POST CRACK.
11	B400-14	HPOTP	LOSS OF AXIAL BALANCING FORCE.
12	B400-07	HPOTP	FAILURE TO TRANSMIT TORQUE.
13	A200-09	MAIN INJ	INTERPROPELLANT PLATE CRACKS.
25	A330-03	MCC	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE.
32	C200-07	PCA	INSUFFICIENT OR NO NITROGEN PURGE FLOW
36	B400-13	HPOTP	LOSS OF SUPPORT, POSITION CONTROL, ROTORDYNAMIC STABILITY
37	B200-07	HPFTP	TURBINE DISCHARGE FLOW BLOCKAGE.
41	B200-16	HPFTP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS.
42	B200-17	HPFTP	LOSS OF COOLANT FLOW TO TURBINE DISCS.

NO ANOMALIES EXPECTED, RELATED TEST HISTORY

Rnk	LRU-FM	Component	Failure Mode
14	B400-22	HPOTP	PUMP PIECE PART STRUCTURAL FAILURE.

NO ANOMALIES EXPECTED, NO TEST HISTORY

Rnk	LRU-FM	Component	Failure Mode
17	D500-06	GOX CNTL VLV	MAINTAIN STRUCTURAL INTEGRITY.
19	K106-02	HP FUEL DUCT	FAILS TO CONTAIN HYDROGEN
21	A200-07	MAIN INJ	EXTERNAL RUPTURE.
23	D220-06	OX BLD VLV	FRETTING OF INTERNAL PARTS.
26	B200-26	HPFTP	STRUCTURAL FAILURE.
28	D120-05	MOV	PIECE PART STRUCTURAL FAILURE.
29	A050-02	POWERHEAD	SHELL OR PROPELLANT DUCT RUPTURE.
30	A600-11	FPB	EXTERNAL RUPTURE.
31	D120-04	MOV	STRUCTURAL FAILURE.
33	A200-05	MAIN INJ	PARTIAL BLOCKAGE OF AN OXIDIZER ORIFICE.
34	D130-03	FPOV	SHAFT SEAL LEAK.
35	D120-06	MOV	FREETING OF INTERNAL PARTS.
38	B400-20	HPOTP	LOSS OF COOLANT TO 1st & 2nd STAGE TURBINE COMPONENTS.
44	B200-24	HPFTP	FAILURE TO RESTRAIN SHAFT MOVEMENT at TURBOPUMP STARTUP

Phase II - Availability of Detailed Failure Signatures

The goal of Phase II was to determine which of the 45 highest ranked failure modes had correlated test data that could be used for development of HMSRE algorithms. Correlated test data enables detailed failure signatures to be identified for the associated failure mode and increases the likelihood of successful algorithm development.

Only those failure modes with an expected anomaly were evaluated during Phase II. (The possibility of a failure mode with no expected anomaly actually having an indication in the test data was considered but was not observed.) The failure modes were classified into two categories:

Test Class A - Failure modes for which an anomaly was expected and correlated test data was identified.

Test Class B - Failure modes for which an anomaly was expected but no correlated test data could be identified.

The failure modes which had no related test history identified in Phase I were automatically classified as Class B failure modes. Those which had a related test history were evaluated to determine if the failure history provided sufficient data to characterize the failure signature of the associated failure mode. If sufficient data seemed to exist, the failure mode was designated Class A. Otherwise, it was designated as a Class B failure mode.

The results of the Phase II investigation are shown in Table 3.2. Of the 30 failure modes, correlated hot-fire test data was available for 11.

Phase III - Effectiveness of Current Detection Systems

The goal of Phase III was to estimate the effectiveness of existing detection systems for detection and minimization of engine damage for the failure modes under consideration. This factor enables the payoff of HMSRE implementation to be estimated for each failure mode. In other words, the greatest payoff will be achieved with an HMSRE that addresses failure modes which are not adequately detectable with existing systems. Little benefit is realized with detection of failure modes adequately protected against with existing systems.

TABLE 3.2 FAILURE MODE SORT - CORRELATED TEST DATA

TEST CLASS A: CORRELATED TEST DATA

Rnk	LRU-FM	Component	Failure Mode
1	A150-01	HEX	COIL FRACTURE/LEAKAGE.
3	B200-04	HPFTP	STRUCTURAL FAILURE OF TURBINE BLADES.
4	A340-02	NOZZLE	EXTERNAL RUPTURE.
5	D110-01	MFV	INTERNAL LEAKAGE.
6	A600-04	FPB	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT
8	A200-06	MAIN INJ	LOX POST CRACK.
13	A200-09	MAIN INJ	INTERPROPELLANT PLATE CRACKS.
36	B400-13	HPOTP	LOSS OF SUPPORT, POSITION CONTROL, ROTORDYNAMIC STABILITY
37	B200-07	HPFTP	TURBINE DISCHARGE FLOW BLOCKAGE.
41	B200-16	HPFTP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS.
42	B200-17	HPFTP	LOSS OF COOLANT FLOW TO TURBINE DISCS.

TEST CLASS B: NO CORRELATED TEST DATA

Rnk	LRU-FM	Component	Failure Mode
2	C200-11	PCA	FAILURE TO SUPPLY HELIUM PRESSURANT.
7	B200-15	HPFTP	LOSS OF SUPPORT OR POSITION CONTROL.
9	B600-06	LPFTP	FUEL LEAKAGE PAST LIFT-OFF SEAL.
10	B400-03	HPOTP	TURBINE BLADE STRUCTURAL FAILURE.
11	B400-14	HPOTP	LOSS OF AXIAL BALANCING FORCE.
12	B400-07	HPOTP	FAILURE TO TRANSMIT TORQUE.
15	A330-02	MCC	FUEL LEAKS INTO THE CLOSED CAVITY (LINER & JACKET)
16	K103-01	LPFTP DUCT	FAILS TO CONTAIN HYDROGEN
18	D300-01	ANTI-FLOOD VLV	LEAKAGE DURING PROPELLANT CONDITIONING.
20	B800-06	LPOTP	LOSS OF SUPPORT AND POSITION CONTROL.
22	E150-14	CCV ACT.	SEQUENCE VALVE LEAKS - CNTRL PRESSURANT DOWNSTREAM.
24	B400-23	HPOTP	TURBINE PIECE PART STRUCTURAL FAILURE
25	A330-03	MCC	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE.
27	K203-01	OX BLD FLX LIN	FAILS TO CONTAIN OXIDIZER.
32	C200-07	PCA	INSUFFICIENT OR NO NITROGEN PURGE FLOW
39	D300-03	ANTI-FLOOD VLV	LOW FLOW RESTRICTED OR SHUT OFF.
40	A700-02	OPB	LOSS OF FUEL TO ASI.
43	B400-18	HPOTP	LOSS OF COOLANT TO BEARINGS.
45	B200-23	HPFTP	LOSS OF BALANCING CAPABILITY.

Failure modes contained in test classes A and B were evaluated to determine how effectively they would be detected with existing health monitoring and fault detection systems. The systems evaluated were redline monitoring, SAFD, and FASCOS. In each case a grade was assigned to each failure mode for each of the health monitoring and fault detection systems considered.

Grading was based on the degree of engine damage expected to occur when detected by each system, according to the following scale:

1. Not detectable
2. Detectable - No Reaction Time
3. Detectable - Serious Damage (Engine Level)
4. Detectable - Moderate Damage (Component Level)
5. Detectable - Minor Damage (Sub-component Level)
6. Detectable - No Damage

The results of this evaluation are shown in Table 3.3. The estimated effectiveness of SAFD, FASCOS, and redlines are indicated in columns 1, 2, and 3. Column 4 indicates the highest level of protection available if all of these systems are active. Detection of a failure mode, with the detection systems evaluated, was defined to be adequate if at least one of the existing systems was expected to detect the failure and cause engine shutdown with only minor damage (grade 5). These failure modes were classified as Detection Class B failure modes. Otherwise, the failure modes were classified as Detection Class A failure modes, indicating that the existing detection systems were inadequate for that specific failure mode. The Detection Class determined for each failure mode is shown in Table 3.3 under the DETECT. heading. Existing failure detection methods were estimated to be adequate (B) for 10 of the failure modes. The TEST column indicates the test class (see Table 3.2) of each failure mode.

TABLE 3.3 EXISTING FAILURE PROTECTION EFFECTIVENESS

Rnk	LRU-FM	SAFD	REDLINES	FASCOS	BEST. AVAIL	DETECT.	TEST
1	A150-01	1	3	1	3	A	A
2	C200-11	1	1	1	1	A	B
3	B200-04	3	<3	3	3	A	A
4	A340-02	4	5	1	5	B	A
5	D110-01	2	5	1	5	B	A
6	A600-04	1	3	1	3	A	A
7	B200-15	1	1	3.5	3.5	A	B
8	A200-06	4	3	1	4	A	A
9	B600-06	1	1	1	1	A	B
10	B400-03	1	1	4	4	A	B
11	B400-14	1	1	4	4	A	B
12	B400-07	4	3	3	4	A	B
13	A200-09	4	3	1	4	A	A
15	A330-02	4	5	1	5	B	B
16	K103-01	4	1	1	4	A	B
18	D300-01	5	1	1	5	B	B
20	B800-06	1	3	4	4	A	B
22	E150-14	1	3	3	3	A	B
24	B400-23	1	3	1	3	A	B
25	A330-03	1	3	3	3	A	B
27	K203-01	1	1	1	1	A	B
32	C200-07	1	1	1	1	A	B
36	B400-13	4	1	3.5	4	A	A
37	B200-07	4	3	1	4	A	A
39	D300-03	5	3	1	5	B	B
40	A700-02	5	4	1	5	B	B
41	B200-16	5	1	3	5	B	A
42	B200-17	5	1	3	5	B	A
43	B400-18	5	1	4	5	B	B
45	B200-23	5	3	3	5	B	B

Overall Failure Mode Classifications

The result of the failure mode classification is that each of the 45 most likely failure modes that has an expected anomaly is classified into one of the four categories defined below:

Class AA: These failure modes are not adequately protected against with existing detection systems. Therefore, HMSRE implementation of a detection scheme capable of more rapid detection has the potential for significant payoff. In addition, hot-fire test data has been correlated to each failure mode enabling greater confidence in detailed signature definition and increasing the likelihood of effective algorithm development.

Class AB: These failure modes are not adequately protected against with existing detection systems. Therefore, HMSRE implementation of a detection scheme capable of more rapid detection has the potential for significant payoff. However, no hot-fire test data has been correlated to the failure modes; and effective algorithm development is somewhat uncertain.

Class BA: These failure modes are adequately protected against with existing detection systems. Therefore, HMSRE implementation of a detection scheme capable of more rapid detection has little potential for significant payoff. Hot-fire test data has been correlated to each failure mode enabling greater confidence in detailed signature definition and increasing the likelihood of effective algorithm development.

Class BB: These failure modes are adequately protected against with existing detection systems. Therefore, HMSRE implementation of a detection scheme capable of more rapid detection has little potential for significant payoff. No hot-fire test data has been correlated to the failure modes and effective algorithm development is somewhat uncertain.

The overall classification of each failure mode is shown in Table 3.4. Of the 30 failure modes evaluated, 7 were classified as AA, 13 as AB, 4 as BA, and 6 as BB.

The seven failure modes classified as AA were estimated to provide the highest likelihood of significant payoff if specific detection methods were implemented as part of the HMSRE. These failure modes are: 1) fracture and leakage of the heat exchanger coil, 2) structural failure of turbine blades in the high pressure fuel turbopump, 3) non-uniform fuel flow in the fuel preburner injection elements, 4) cracking of the LOX posts in the main injector, 5) interpropellent plate cracks in the main injector, 6) loss of position control in the high pressure oxidizer turbopump, and 7) blockage of the high pressure fuel turbine discharge.

TABLE 3.4 FAILURE MODE CLASSIFICATION - LIKELIHOOD OF EFFECTIVE HMSRE IMPLEMENTATION

CLASS AA FAILURE MODES

Rnk	LRU-FM	Component	Failure Mode
1	A150-01	HEX	COIL FRACTURE/LEAKAGE.
3	B200-04	HPFTP	STRUCTURAL FAILURE OF TURBINE BLADES.
6	A600-04	FPB	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT
8	A200-06	MAIN INJ	LOX POST CRACK.
13	A200-09	MAIN INJ	INTERPROPELLANT PLATE CRACKS.
36	B400-13	HPOTP	LOSS OF SUPPORT, POSITION CONTROL, ROTORDYNAMIC STABILITY
37	B200-07	HPFTP	TURBINE DISCHARGE FLOW BLOCKAGE.

CLASS AB FAILURE MODES

Rnk	LRU-FM	Component	Failure Mode
2	C200-11	PCA	FAILURE TO SUPPLY HELIUM PRESSURANT.
7	B200-15	HPFTP	LOSS OF SUPPORT OR POSITION CONTROL.
9	B600-06	LPFTP	FUEL LEAKAGE PAST LIFT-OFF SEAL.
10	B400-03	HPOTP	TURBINE BLADE STRUCTURAL FAILURE.
11	B400-14	HPOTP	LOSS OF AXIAL BALANCING FORCE.
12	B400-07	HPOTP	FAILURE TO TRANSMIT TORQUE.
16	K103-01	LPFTP DUCT	FAILS TO CONTAIN HYDROGEN
20	B800-06	LPOTP	LOSS OF SUPPORT AND POSITION CONTROL.
22	E150-14	CCV ACT.	SEQUENCE VALVE LEAKS - CNTRL PRESSURANT DOWNSTREAM.
24	B400-23	HPOTP	TURBINE PIECE PART STRUCTURAL FAILURE
25	A330-03	MCC	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE.
27	K203-01	OX BLD FLX LIN	FAILS TO CONTAIN OXIDIZER.
32	C200-07	PCA	INSUFFICIENT OR NO NITROGEN PURGE FLOW

CLASS BA FAILURE MODES

Rnk	LRU-FM	Component	Failure Mode
4	A340-02	NOZZLE	EXTERNAL RUPTURE.
5	D110-01	MFV	INTERNAL LEAKAGE.
41	B200-16	HPFTP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS.
42	B200-17	HPFTP	LOSS OF COOLANT FLOW TO TURBINE DISCS.

CLASS BB FAILURE MODES

Rnk	LRU-FM	Component	Failure Mode
15	A330-02	MCC	FUEL LEAKS INTO THE CLOSED CAVITY (LINER & JACKET)
18	D300-01	ANTI-FLOOD VLV	LEAKAGE DURING PROPELLANT CONDITIONING.
39	D300-03	ANTI-FLOOD VLV	LOW FLOW RESTRICTED OR SHUT OFF.
40	A700-02	OPB	LOSS OF FUEL TO ASI.
43	B400-18	HPOTP	LOSS OF COOLANT TO BEARINGS.
45	B200-23	HPFTP	LOSS OF BALANCING CAPABILITY.

SECTION 4 - DAMAGE MINIMIZATION TECHNIQUES

The goal of this effort was to define HMSRE actions which most effectively minimize damage to the engine after a failure is detected. To ensure near term applicability and compatibility with the current SSME, the techniques evaluated were limited to those available through the SSME Block-II controller.

The basic damage minimization actions available to the HMSRE are: 1) actuator lockup, 2) downthrust, and 3) shutdown. Evaluation of each technique led to the conclusion that in a test stand environment (where damage minimization is the only concern), engine shutdown is the appropriate HMSRE action whenever a failure is detected. In flight, however, downthrusting becomes a viable option for extending engine life and minimizing damage within mission completion constraints.

Each damage minimization action is discussed below.

Actuator Lockup

Actuator lockup results in each control actuator being "locked" into its current position. Two locking mechanisms are available on the SSME, hydraulic lockup and electrical lockup. Hydraulic lockup is in response to a loss of hydraulic power. In this case, the hydraulic lines are sealed off; locking the actuators in their current positions. Electrical lockup is in response to unresolvable faults in the controller. New commands are inhibited, and the actuators are maintained at their current positions.

Actuator lockup enables the engine to continue firing (although in a degraded mode) in the event of control system failure, but provides no damage minimization capabilities beyond those already available through the action of the Block-II controller.

Downthrust

Downthrusting minimizes engine strain by reducing pressures, temperatures, speeds, and vibrations throughout the engine. If damage has occurred, the damage is likely to continue propagating through the system, but at a reduced rate. Therefore, in situations where the engine can be safely shutdown (e.g. on a test stand), the HMSRE would never downthrust an engine. Engine shutdown at the earliest "probable failure" indication would minimize damage.

In flight applications, however, engine shutdown could result in a loss of mission. In this case it would not be practical to shutdown an engine at the earliest "probable failure" indication. Two options exist in flight: 1) continue normal operation, or 2) downthrust, when possible, to reduce the rate of failure propagation. In both cases the engine could still be shutdown if an impending catastrophic failure is indicated.

The basic strategy for downthrusting an engine would be to downthrust, if possible, when a "probable failure" is indicated and continue operation until the mission ends or an impending catastrophic failure is indicated.

Implementation of this capability requires propulsion level coordination to maintain the required vehicle thrust and manage issues such as: 1) mission completion requirements, 2) status of other engines, 3) available abort modes. For example, if mission success requires three engines at 109% thrust, an engine indicating a probable failure would not be allowed to downthrust. However, if mission success requires three engines at 100% thrust, an engine indicating a probable failure could be downthrust to 82%. The other two engines would be upthrust to 109% to compensate for the lost thrust. This approach reduces the strain on the engine indicating a probable failure, without jeopardizing mission success. The reduced strain and failure propagation rate would result in the minimum engine damage within the constraints of mission success.

Shutdown

Damage is expected to be minimized in all cases if an engine is shutdown immediately upon detection of a failure. This action would confine the existing damage by preventing further propagation of the failure.

The primary shutdown mechanism of the Block-II controller is a hydraulic shutdown in which the actuators are actively sequenced by the controller. This mechanism is initiated through a command to the controller and is completed in just over 5 seconds. A pneumatic shutdown sequence is also available. The pneumatic shutdown is a passive sequence initiated by a loss of controller electrical power. The pneumatic system is orificed such that the passive pneumatic sequence matches the actively controlled hydraulic sequence. Since the valve sequencing is identical (or very similar) with either shutdown mechanism, no damage minimization advantage between them could be established on that basis. However, one advantage exists in that the hydraulic shutdown system is backed up by the pneumatic system. Directly initiating a pneumatic shutdown removes a level of redundancy in the system and offers no benefit to the engine.

Therefore a commanded hydraulic shutdown was selected as the HMSRE response to a detected failure.

5.0 EVALUATION OF METHODS TO DETECT FAILURES

This section discusses the various failure detection techniques evaluated and considered for inclusion in the HMSRE framework.

5.1 OVERVIEW

The failure detection techniques evaluated during this program can be divided into nine types:

1. Advanced Redlines
2. Parameter Correlation
3. Analytical Models to Predict Remaining Life
4. Non-Intrusive Measurement Approaches
5. Model Based Failure Detection
6. Data Trending
7. Operational Envelope Based Failure Detection
8. Power Level Dependent Algorithms
9. Vibration Monitoring

The failure detection techniques evaluated were candidates for inclusion in the HMSRE. The results of these evaluations provided the basis for key features of the framework described in Section 6.

The techniques were evaluated to identify current SSME applications, strengths, and weaknesses. In addition, compatibility with the Block-II SSME was evaluated. The failure detection techniques and evaluation results are discussed in the following sections.

5.2 ADVANCED REDLINES

Advanced redlines are based on a different philosophy than existing redlines. The current redlines are defined to be values at which severe engine damage is inevitable. For example, a temperature redline might be set at 1800R if the maximum operating temperature of some component is 1825R. This philosophy is fine for avoiding catastrophic engine failures caused by a specific component failure. However, engine failures go undetected until this limit is reached, often resulting in considerable damage.

Advanced redlines, applicable to the HMSRE, set limits on a different basis. These limits are set such that a significant anomaly, not necessarily dangerous in itself, is detectable. An example of this might be a temperature redline set at twice the usual deviation from its nominal operating point. The tighter limits allow a faster response to engine failures. The major issues with this approach are identification of the nominal value and definition of a significant anomaly. A "significant anomaly" obviously must be greater than the expected variation in the monitored parameter. These variations can be reduced (thereby enabling tighter limits) by using a longer averaging interval. The averaging interval selected would try to optimize the trade between signal smoothness and response time.

Significant anomalies can be readily determined through a statistical analysis of the redline parameter for both nominal and engine failure test cases. Nominal values, however, change with power level and differ significantly between engines. Figures 5-1 to 5-4 show nominal test data (turbine discharge temperatures) for 8 different engines over the entire range of power levels. Each data point represents a 1 second average and is plotted at the corresponding power level. Clearly, in order to accurately define a nominal value, power level and engine specific correction strategies must be used.

For example, consider the HPOT discharge temperature (Figure 5-1). An advanced redline, applicable to all engines and power levels, would have to be set above 1500R. Assume a value of 1550R is selected. This value is only about 50R above the highest value expected and would detect deviations as small as 50R above the nominal value for the high end of the expected range. However, at lower power and with another engine, the operating value could be as low as 950R. In this situation a deviation of 600R would be required before the redline is exceeded. Clearly, this parameter would be better monitored if the engine to engine variation and power level were accounted for.

Some indication of the corrections needed, to accurately define a nominal value, is provided by the ratio of typical signal noise and engine to engine deviation (or power level deviations). For example, if a temperature signal typically deviates by 50R for a single engine, engine to engine corrections are of little value if the engine to engine variation is only 10R. A summary of this information is shown in Table 5.1 for several advanced redline candidates. A large signal to noise ratio indicates that an advanced redline will be more effective if appropriate correction strategies are applied.

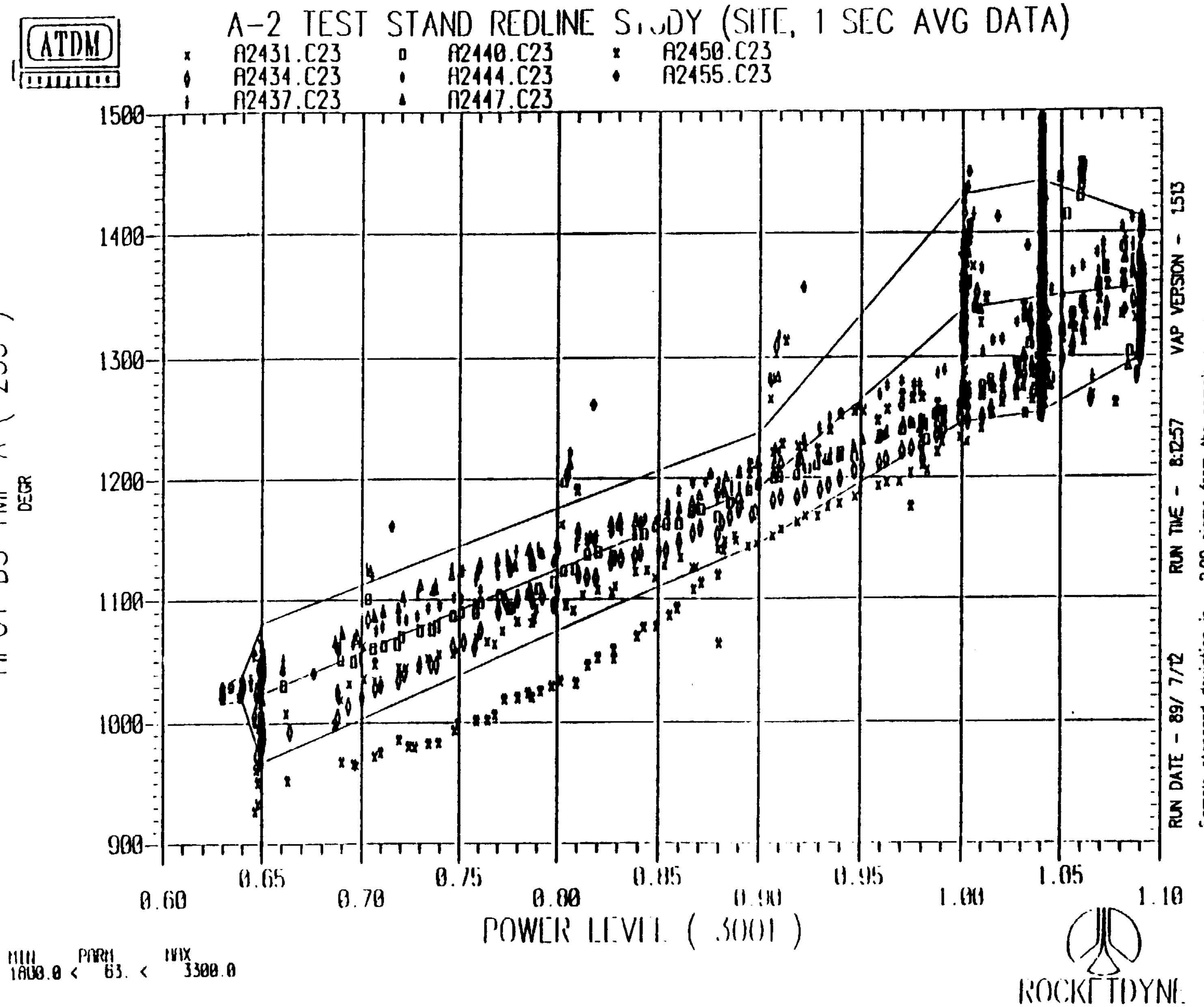


FIGURE 5-1 ENGINE TO ENGINE VARIATIONS - HPOT DS TMP A

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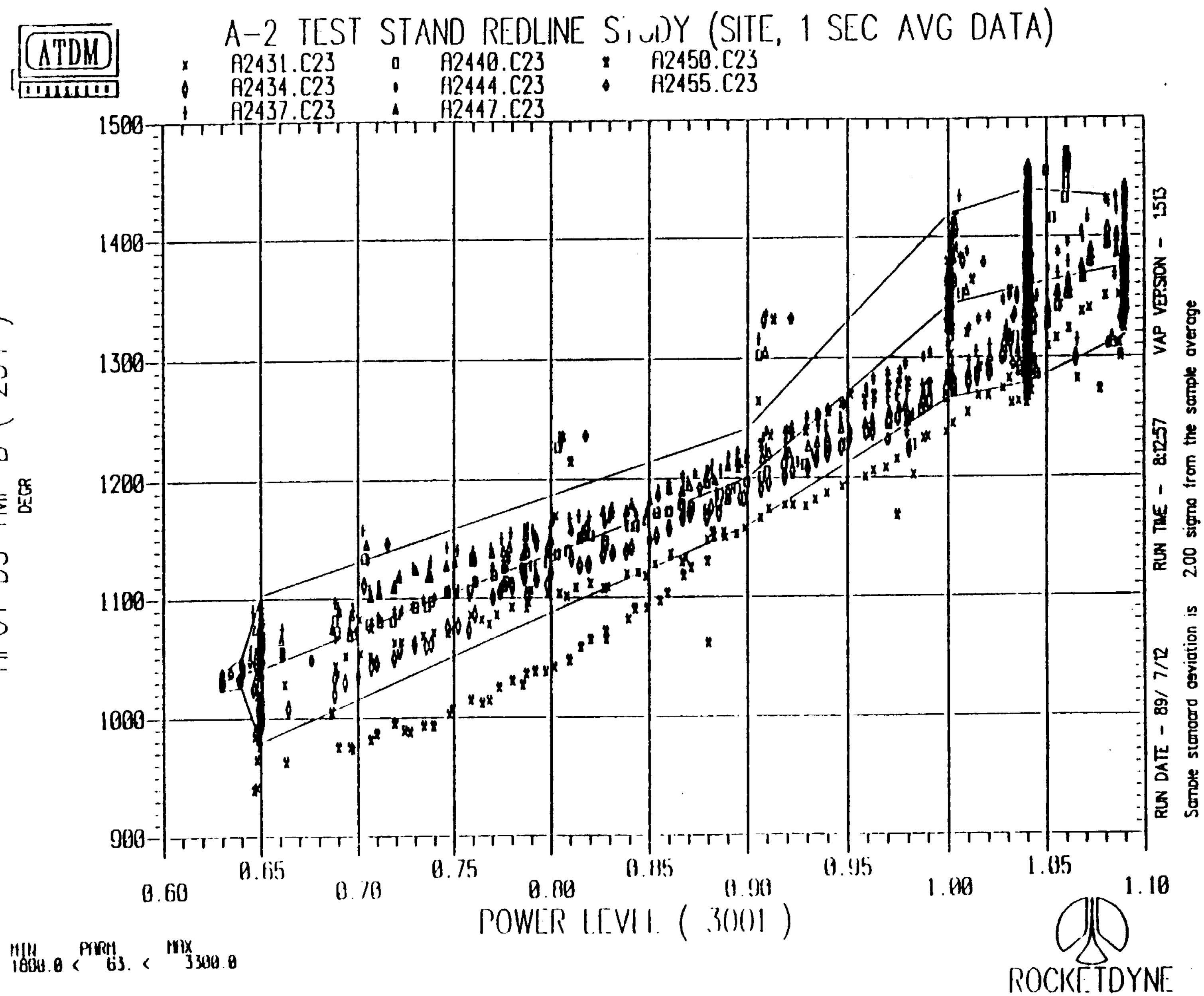

FIGURE 5-2 ENGINE TO ENGINE VARIATIONS - HPOT DS TMP B

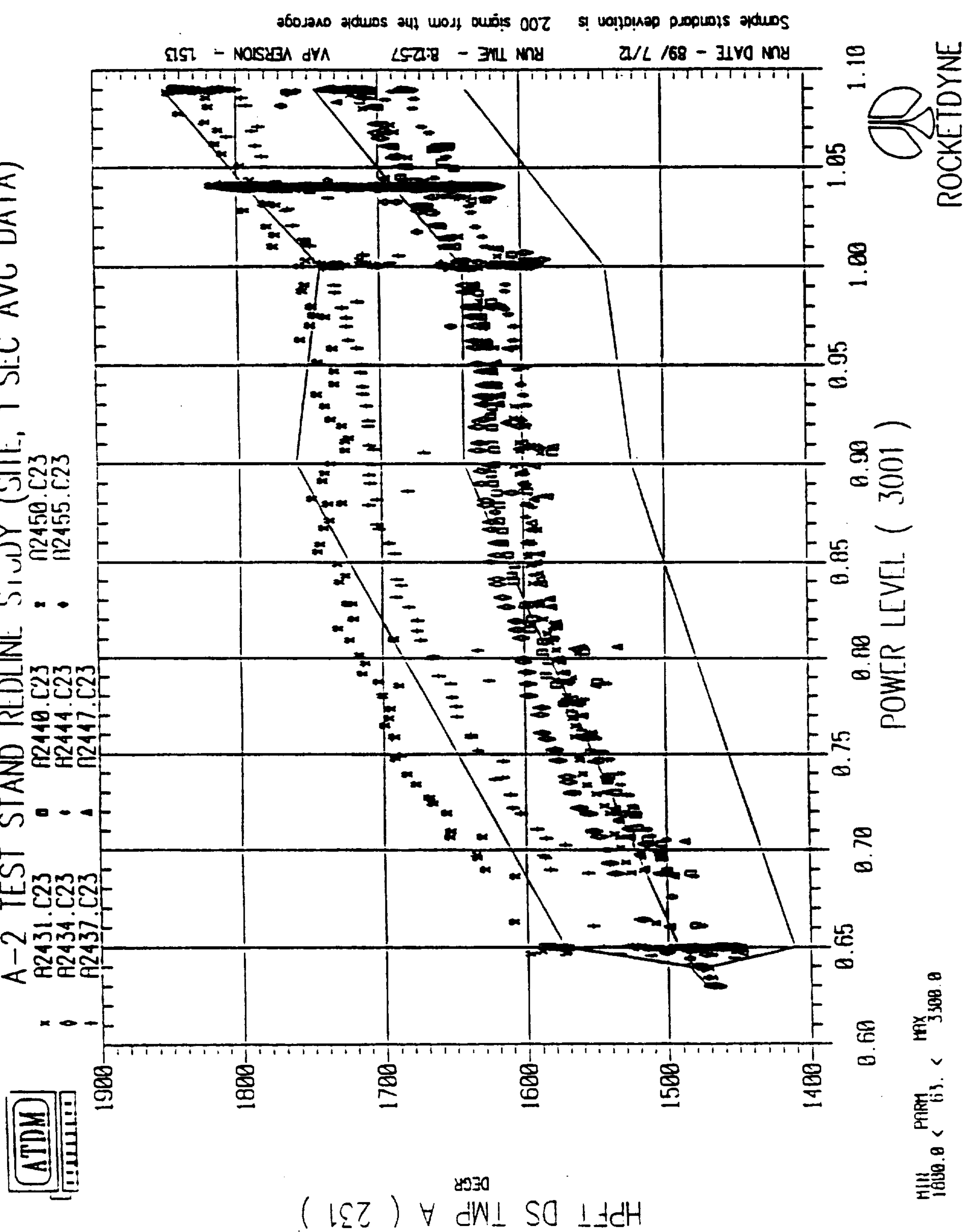

FIGURE 5-3 ENGINE TO ENGINE VARIATIONS - HPFT DS TMP A

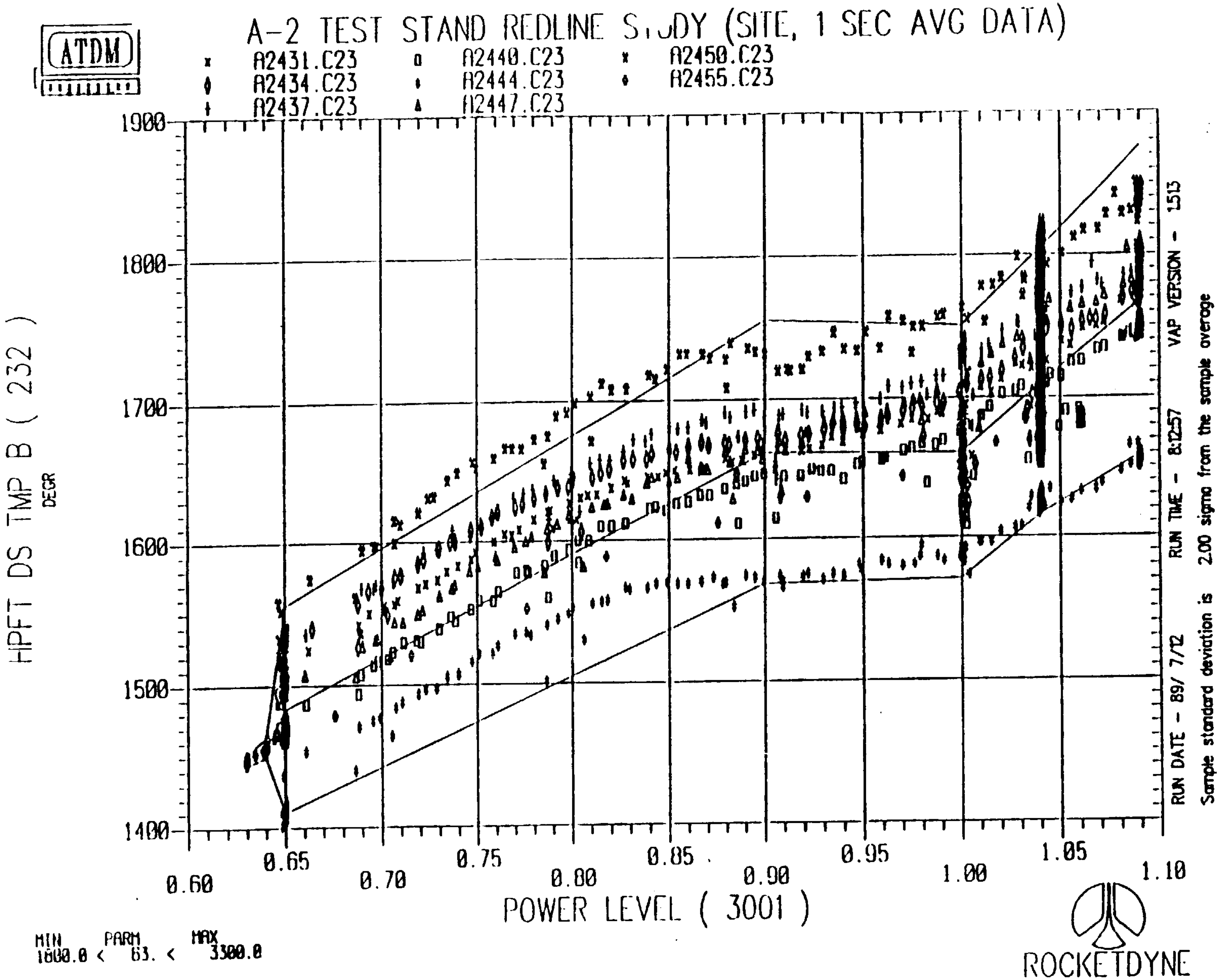

FIGURE 5-4 ENGINE TO ENGINE VARIATIONS - HPFT DS TMP B

TABLE 5.1 SIGNAL TO NOISE RATIO FOR ENGINE SPECIFIC AND POWER DEPENDENT REDLINES

Measurements	Max Engine to Engine Variation	Typical Signal Noise	S/N	Nominal RPL to FPL Variation	Typical Signal Noise	S/N
HPFT DS T A	175°R	±11°R	15.9	93°R	±11°R	8.5
HPFT DS T B	110°R	±8.7°R	12.6	93°R	±8.7°R	10.7
HPOT DS T A	140°R	±12°R	12.0	87°R	±12°R	7.3
HPOT DS T B	145°R	±10°R	14.5	87°R	±10°R	8.7
FPOV Act Pos	3.5%	±0.41%	8.5	3.7%	±0.41%	9.0
OPOV Act Pos	4.3%	±0.56%	7.7	4.4%	±0.56%	7.9
HPFP Speed	635 rpm	±925 rpm	0.7	2189 rpm	±925 rpm	2.4
MCC Pc Avg	0.5 psia	±9.2 psia	0.1	271 psia	±9.2 psia	29.5
MCC Coolant Discharge Tmp	60°R	±3.3°R	18.2	12°R	±3.3°R	3.6

As shown by Table 5.1, the effectiveness of most redlines would be greatly enhanced if engine to engine and power level variations are accounted for in the definition of a nominal value.

Power level variations are easily addressed since the changes are analytically predictable. A power dependent redline could simply be changed in accordance with the test or flight thrust profile. An example of what a power level dependent redline might look like is shown in Figure 5-5.

Engine to engine variations are considerably more difficult to predict analytically since the changes are caused by subtle differences in the manufactured hardware. Two general approaches have been identified to address this issue. The first approach is to base the nominal value on values observed during prior tests of the same engine. It should be noted that replacement of a line replaceable unit (LRU) may yield different operating levels and therefore constitutes a different engine. Since LRUs are routinely changed, this approach has limited applicability.

The second approach is to observe an operating point during the initial seconds of steady state, and define this value to be nominal. This approach provides accurate engine specific information even if the engine has never been fired before. Another advantage is the ability to account for test to test variations in a parameter. While these variations are not as large as those between engines or power levels they can be significant. Figures 5-6 to 5-9 show the test to test turbine discharge temperature variations for four firings of the same engine. A drawback to this approach is that failures cannot be detected during the start transient or the first few seconds of mainstage. However, if the parameter continues to increase (or decrease) the relatively tight limits set for an advanced redline would detect the failure shortly after monitoring begins.

Several general considerations, on the use of redlines, should be addressed. First, a single sensor malfunction should not cause an engine to shutdown. This would obviously be the case if a redline parameter was measured by only a single sensor and that sensor began to drift. Therefore, advanced redlines are limited to those parameters for which multiple measurements can be obtained. Secondly, confidence that an engine failure is occurring is relatively small if only one measurement is indicating an anomaly. Finally, redlines provide possible failure indications with a minimum of computational time.

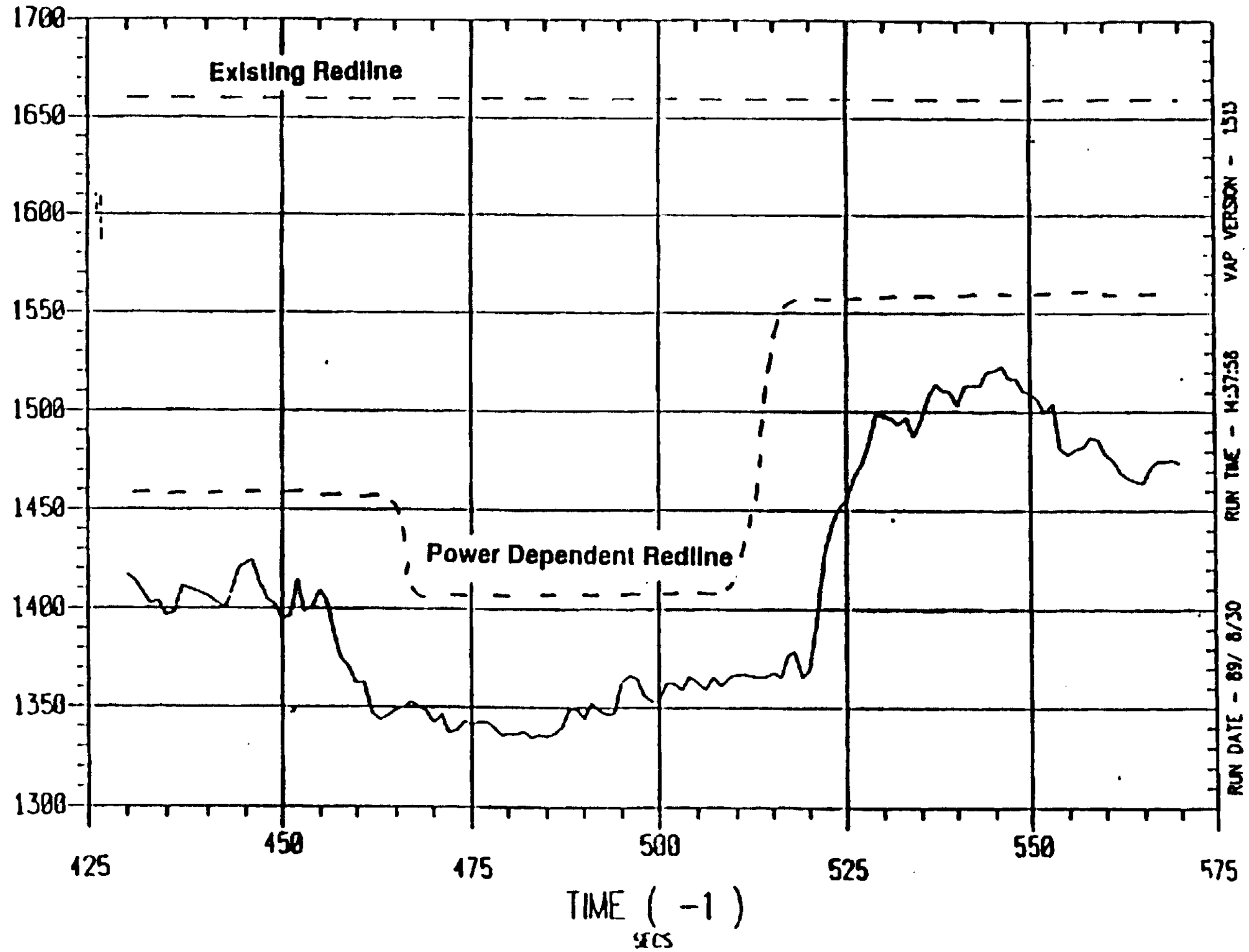

FIGURE 5-5 POWER LEVEL REDLINE

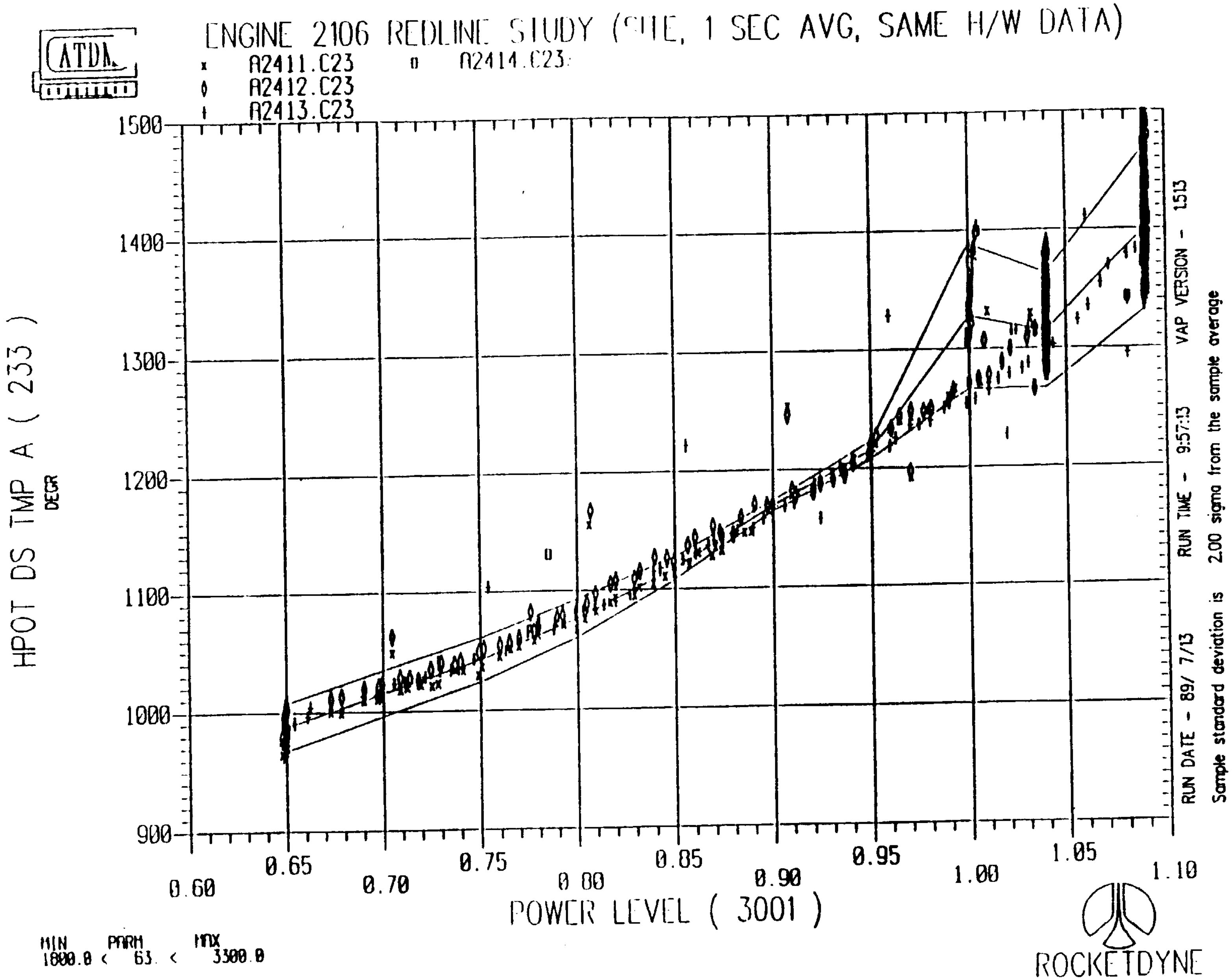

FIGURE 5-6 TEST TO TEST VARIATIONS - HPOT DS TMP A

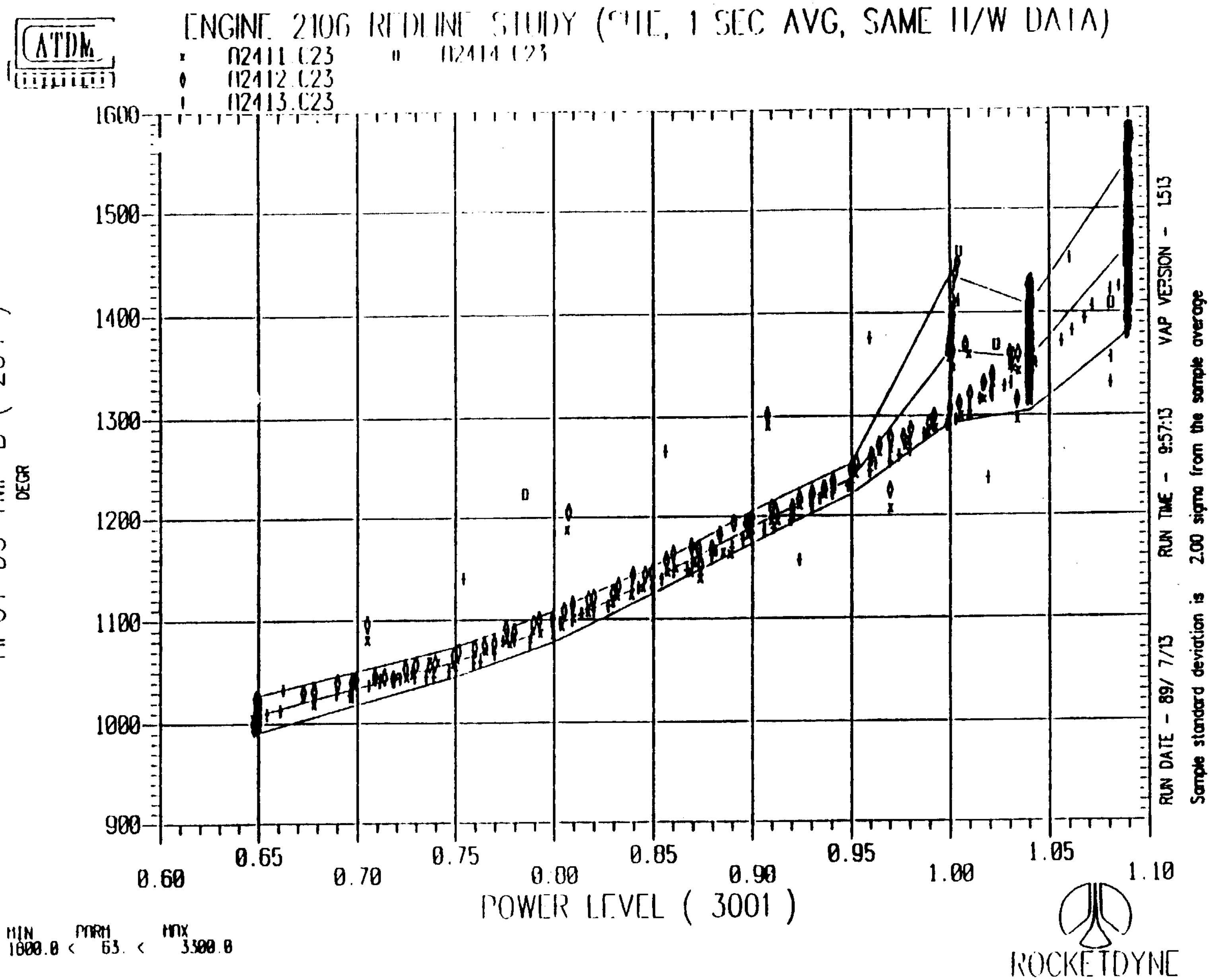

FIGURE 5-7 TEST TO TEST VARIATIONS - HPOT DS TMP B

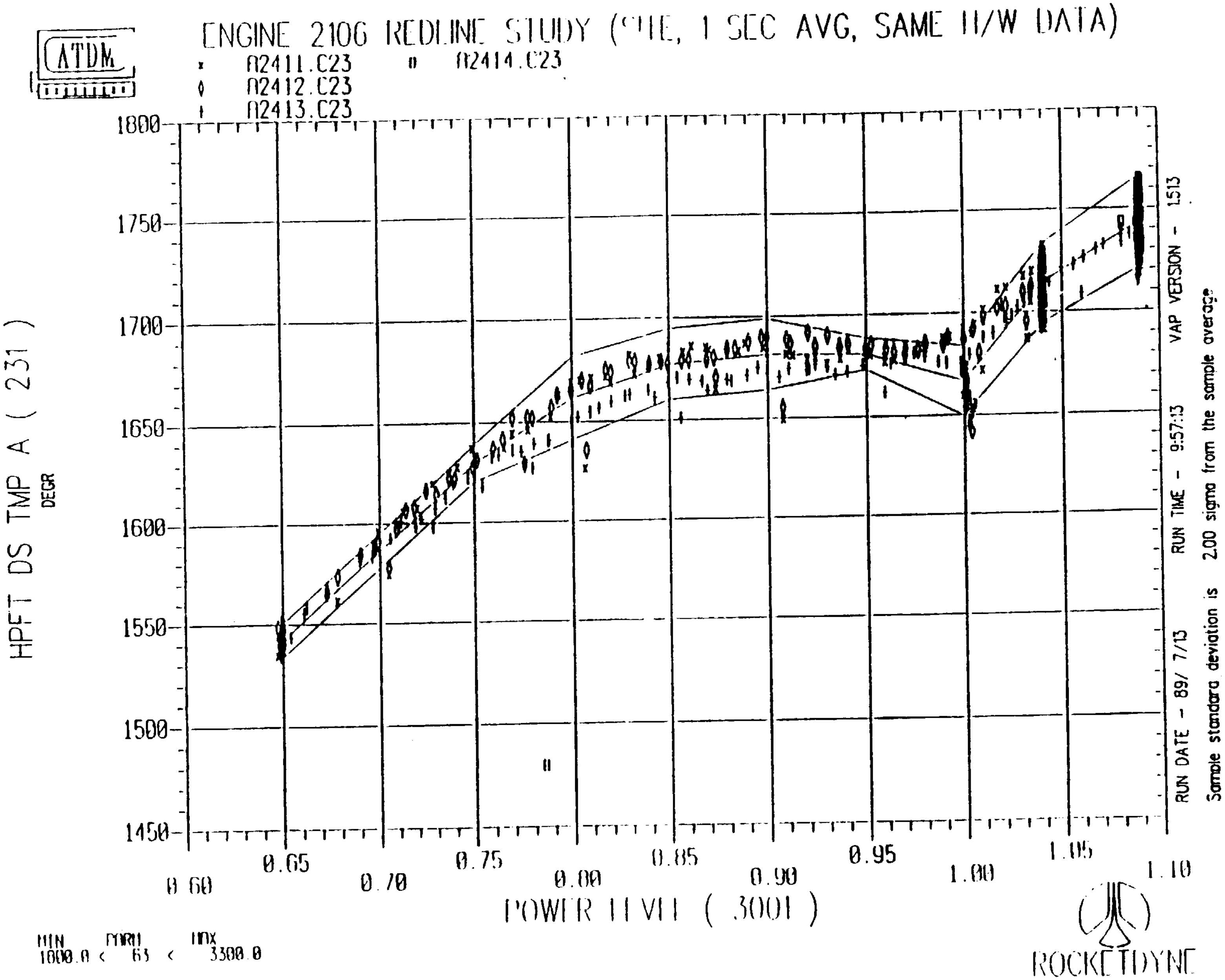

FIGURE 5-8 TEST TO TEST VARIATIONS - HPFT DS TMP A

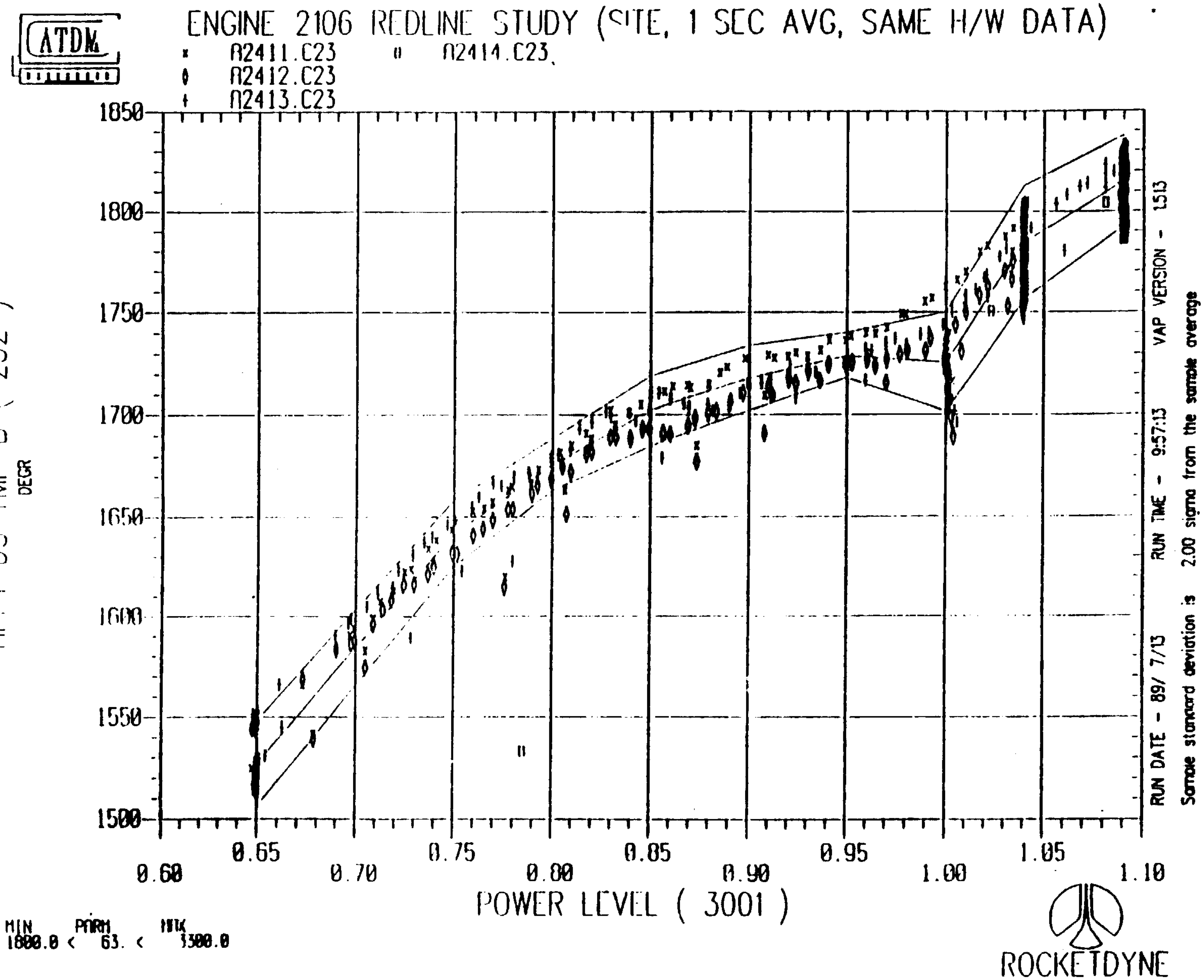

FIGURE 5-9 TEST TO TEST VARIATIONS - HPFT DS TMP B

Redlines alone are not adequate for an effective damage minimization system due to their inherent limitations. However, they could be a valuable element of a more encompassing detection system by providing rapid information at very little computational cost.

5.3 PARAMETER CORRELATION

Early failure indications can be classified into three distinct groups for analysis: 1) those that are directly observable with available instrumentation (e.g. increased HPFP speed), 2) those that are not directly observable, but cause observable changes in the measured parameters (e.g. loss of HPFP efficiency), and 3) those that are not observable with existing instrumentation (e.g. cracked turbine blades).

This section discusses the second group of early failure indications, those that are not directly observable. Two approaches were evaluated for estimating these parameters. In the first, the parameter is calculated from measured parameters. Ideally, this provides an accurate estimate of the actual value. However, the calculation is dependent on a complete set of data and the loss of a single measured parameter (i.e. a sensor failure) could invalidate the estimate. Since sensor failures are far more common than other types of failures on the SSME, this represents a major weakness for the approach.

The second approach for estimating parameters, that are not directly observable, is to correlate changes in measured parameters. For example, a loss of HPFP efficiency is expected to result in an increased HPFT discharge temperature and a decreased HPOT discharge temperature (Since the degraded HPFTP requires a disproportionately greater amount of energy in the turbine to obtain the required pump output). Therefore, if an increase in the HPFT discharge temperature is measured and a decrease in the HPOT discharge temperature is measured, a change in the HPFP efficiency can be postulated and a value approximated. For the class of failures resulting in degraded HPFP efficiency, the correlated value "HPFP efficiency" provides an earlier failure indication than either of the turbine discharge temperatures evaluated individually. This approach is unable to provide an absolute value for unobservable parameters, but quantitatively indicates changes. Since failures are generally indicated by changes in key operating parameters, this is not seen as a deficiency. The major advantages of this approach are the relatively simple computations required and insensitivity to sensor failures.

Correlation of individual sensor values to estimate changes in key engine operating parameters, for the purpose of failure detection, is a well established technique used on jet engines known as gas path analysis.

Evidence that multiple failure indications exist and potentially represent correlated sets for rocket engine failures is obtained by evaluating the available SSME test history (Figure 5-10). The top section of this figure represents the direction of the observed changes in individual sensors for a set of SSME failures. As can be seen for the case of LOX post failure, which represents the largest group of similar failures, a fair degree of correlation exists in the observed sensor anomalies. For example, both turbine discharge temperatures increase in 5 of the 6 failure cases. Additionally, multiple sensor indications are observed for all cases. In fact, 8 or more anomalies were seen for 13 of the 21 cases evaluated.

Four specific parameters were evaluated for the HMSRE: 1) HPOTP efficiency, 2) HPFTP efficiency, 3) MCC combustion efficiency, and 4) Fuel leakage. The first three represent key engine operating parameters while fuel leakage provides an example of how correlation of measurable parameters can be applied to specific failure detection.

Decreases in pump operational efficiency can result from hydraulic losses, disk friction losses, mechanical losses, and leakage losses. Similarly, turbine operational efficiency is degraded by nozzle losses, blade losses, leakage or clearance losses, disk friction losses, and mechanical losses. Therefore, even though failures that increase these losses may not be specifically observed, they can be correlated to, and will be indicated by, efficiency degradations.

Specific correlations between measurable SSME quantities and the parameters listed above were determined using the SSME engine balance model. For each of the cases identified, two sets of data were generated. The first set listed key, measurable SSME quantities using a nominal value for the "unobservable" parameter. In the second set, a degraded value was used (e.g. a 5% loss of HPFP efficiency). Differences between these sets were calculated and tabulated. The model results indicated that definite correlations exist in the set of SSME measured parameters for each of the cases evaluated. Complete model results are provided in Attachment 4.

The number of individual sensor anomalies observed for each SSME failure, the commonality demonstrated for similar failures, and the correlations predicted by the SSME engine balance model indicate that correlation of

TEST	901-173	901-331	LOX POST FAILURES 750-148	901-183	902-198	901-307	902-249	901-340	901-383	902-118	901-436	901-364	902-200	750-175	901-110	901-136	901-225	SF10-01	901-284	901-485	SF6-01
MEASUREMENT																					
HPFP DS T1 A	♦	♦	♦	♦	♦	·	♦	·	♦	♦	♦	♦	♦	·			♦	♦	·		♦
HPFP DS T1 B	♦	♦		♦	♦	·	♦	♦	·	♦	♦	♦		·			♦	♦			♦
HPOT DS T1	♦	♦	♦	♦	♦	·	♦	·	♦	·	♦	·	♦	·	♦	♦	♦	♦	·	♦	♦
HPOT DS T2	♦	♦	♦	♦	♦	·	♦	·	♦	·	♦	·	♦	·	♦	♦	♦	♦		♦	♦
FPOV ACT POS							♦	♦	·	♦	♦	♦	♦								
OPOV ACT POS						·									♦	♦		♦	·		
HPFP SPEED							♦	·	♦	·	·	♦	·	·			♦				
CLNT LNR delta-P						·		♦	♦	♦	♦	·									
HPFP delta-P	♦	·	·		♦			♦	·	♦	♦	♦									
HPOT delta-P	·	·	·		♦			♦	♦	♦	♦	·									
MCC OX INJ PR - MCC PC	·	♦	·	♦		·								·			♦				
MCC CLNT DS T		♦	♦	♦	♦									·							
LPOP DS PR	·	♦	♦		·	·								·					♦		
HPOT PRSL DR T															·	♦					
SEC INJ FCPLT delta-P	·	·	·	·	·																
HG INJ delta-P	♦	♦	♦	·	·																
MCC PC	·	·	·		·												♦		♦		·
PRI INJ FCPLT delta-P	·	·	·	·	·												·				
HPFP DS PR - MCC PC	·	·	·	·	·														·		

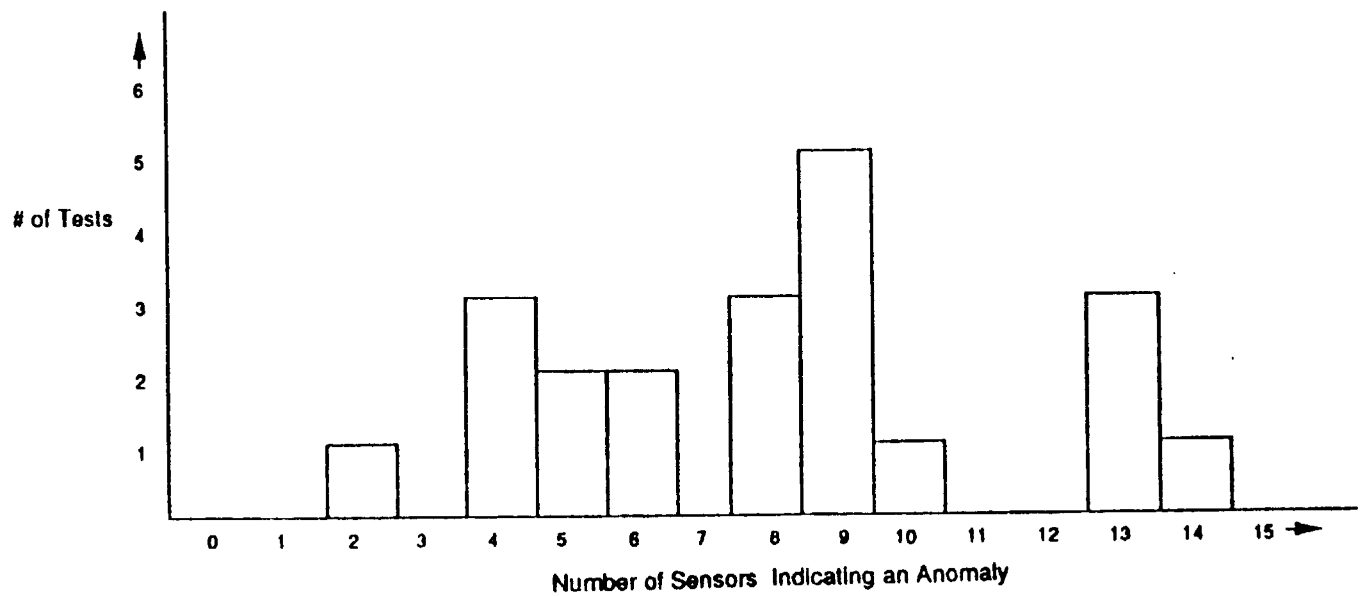

FIGURE 5-10 OBSERVED SENSOR ANOMALIES FOR SSME FAILUES

measured parameters can enhance failure detection by estimating system level parameters sensitive to a large number of failure modes.

5.4 ANALYTICAL MODELS TO PREDICT REMAINING LIFE

Two classes of analytic life prediction models were identified. The first class consists of models based on past performance of similar components and/or calculations of expected life. An example of this approach is the Automated Cycle Time System (ACTS) used by Rocketdyne for the SSME. In this case, the number of starts, time at a given temperature, maximum pressure reached, and other similar parameters are recorded for individual components. Each factor is assumed to reduce the life of a component by a predetermined amount. When the estimated useful life of a component is expended, the part is inspected and/or replaced. This system provides valuable maintenance information, but due to the somewhat inexact nature of the useful life estimates, this approach is not suitable for real-time monitoring of the engine.

The second class of remaining life models are those that predict remaining life based on real-time monitoring of some attribute of the specific component. The actual parameter measured in this approach is the amount of component degradation, not remaining life. Remaining life is inferred based on previous experience, calibration tests, or theoretical relationships. An example of this approach is monitoring specific bearing frequencies and correlating measured amplitudes to the amount of degradation in the bearing. While these models are useful in calling attention to a specific component (for either maintenance or more thorough evaluation), their use is limited in a real time system, due to the inability of existing algorithms to provide the confidence and resolution required for real time decisions. The confidence and resolution of these models increase as the failure becomes more immediate. Therefore, one possible scheme to use these models may be to issue a shutdown command if a failure is imminent. The "time before failure" when an engine cutoff command is issued could be gradually extended as the algorithm is refined and confidence is gained in the results.

Analytical remaining life models may provide early engine cutoff for specific component failures, but are too limited in scope to provide an adequate damage minimization system. These models are best utilized to address specific problems not adequately covered by a more comprehensive failure detection scheme.

5.5 NON-INTRUSIVE MEASUREMENT APPROACHES

Benefits of these sensors include greater accuracy since they do not perturb what they try to measure and less physical restriction since they do not require a mechanical interface for the measurement. Consequently, they should be relatively simple to implement with minimal hazard to the existing engine. Some of these sensors are unique in that they can be ground-based and monitor the engine during test on a stand and possibly during the first minutes of flight. Sensors which do not require any modification of the engine or engine components also save time and money that would be spent on redesign and evaluation of the new design for safety and operational verification.

This section discusses advanced instrumentation concepts which might be suitable for health and condition monitoring during test stand operation and eventual flight application.

The sensors listed in Table 5.2 were selected for consideration due to their potential for health monitoring capabilities. This list was then pared to four candidates (Table 5.3) based upon the requirements of 1) minimal program risk, 2) real time anomaly indication, 3) operation remote from the engine, 4) applicability to unmodified engine, and 5) 4-6 year implementation. Plume tomography, raman spectroscopy, and induced flourescence were estimated to be unavailable in the 4-6 year time frame since they are still in the laboratory phase of development. Bearing/shaft monitoring technologies were deemed intrusive, requiring either intrusive instrumentation or alteration to internal engine components. Delamination, fatigue, and acoustic measurements (EMAT) are between flight technologies and are therefore not applicable to a real-time HMSRE.

The four candidates: plume emission spectrometry, remote leak detection, thermography, and acoustic monitoring are discussed in the following subsections. Plume spectrometry is discussed in the greatest detail since this technology is well established and is included in the baseline HMSRE framework. The other three candidates are briefly discussed. Each represents a potentially significant improvement in rocket engine health monitoring, but it is felt that none of these systems are sufficiently developed for implementation under this program.

5.5.1 Plume Emission Spectrometry

Radiant energy is both emitted and absorbed by rocket engine exhaust plume gases at wavelengths characteristic of the combustion species present. These spectral signatures are uniquely representative of the material makeup of the plume. Each atomic and molecular species is recorded as its own spectral line, band, or continuous structure within a spectral record and describes either nominal or anomalous engine behavior. Anomalous behavior evident in the emission spectra is a result of damage, erosion, or wear of engine components. It is manifested by the erratic behavior of spectral line amplitude as a function of time or an unusual amplitude of the spectral signature of the material or materials representative of the component in question. Unique materials can be traced to the source engine component.

Plume emission spectrometry is a proven technology. Spectrometers are currently in use at the MSFC test stands for plume monitoring. Additionally, Rocketdyne has an in house system used for monitoring engine tests at the Santa Susana Field Laboratory (SSFL).

Examples of the data available with a plume monitoring system are provided by the data obtained by Rocketdyne as indicated in Table 5.4. Characteristic spectra for nominal tests have been determined but anomaly thresholds still need to be established. Some failure data has been recorded and emission spectra from events such as engine hardware erosion, and foreign material contamination stand in marked contrast to the spectra normally seen during engine hot-firings. Also shown in Table 5.4 is a list of plume anomalies observed during 100 plus recorded tests along with the materials exhibiting anomalous behavior. A more complete list of materials observed in the plumes, and possible sources of contamination, is shown in Table 5.5. Attachment 5 presents a list of SSME failure modes expected to show plume anomalies and the materials expected.

TABLE 5.2 ROCKETDYNE ADVANCED INSTRUMENTATION APPLICABLE TO SSME

TECHNOLOGY	APPLICABILITY		
	Preflight	In-Flight	Test Stand
LEAK DETECTION	●	●	●
SPECTROMETRY - PLUME			
EMISSION/ABSORPTION		●	●
TRACKING		●	
TOMOGRAPHY			●
RAMAN			●
PLANAR LASER INDUCED FLOURESCENCE			●
THERMOGRAPHY/PYROMETRY			
PLUME		●	●
NOZZLE	●	●	●
ENGINE	●		●
BEARING/SHAFT MONITORING			
ACCELEROMETERS/STRAIN		●	●
ISOTOPE	●	●	●
DELAMINATION/CRACK DETECTION	●		●
FATIGUE DETECTION	●		●
ACOUSTICS		●	●
ELECTROMAGNETIC ACOUSTIC TRANSDUCER	●		●

TABLE 5.3 NON-INTRUSIVE MEASUREMENT CANDIDATES

TECHNOLOGY	APPLICABILITY		
	Preflight	In-Flight	Test Stand
LEAK DETECTION	●	●	●
SPECTROMETRY - PLUME EMISSION/ABSORPTION		●	●
THERMOGRAPHY/PYROMETRY			
PLUME		●	●
NOZZLE	●	●	●
ENGINE	●		●
ACOUSTICS		●	●

While the principle of analyzing plume emitted radiant energy is not new, the adaptation of digitized plume data to real-time processing is required for safety/damage minimization systems. Rocketdyne has done this with the in-house spectrometry system. This system scans from the near-ultraviolet (UV) to the near-infrared (IR), and has been interfaced to a PC-AT type computer. The computer executes programmed data acquisition and orchestrates analysis of the data. Control signals and data are transferred via an IEEE bus. The spectrometer has software selectable spectral scan times as small as 10 ms, internal analog to 14 bit digital conversion, and a 4 Megabyte RAM memory. These capabilities allow automated evaluation of plume spectra and the capture of transient engine events. A pictorial description of spectrum analysis is shown in Figure 5-11. The recorded data is used to produce two types of graphs. The first is a plot of intensity versus wavelength also plotted against time (Waterfall Plot) as in Figure 5-12, while the second is a plot of the intensity of a specific spectral line against time as in Figure 5-13. These two types of plots are useful in identifying and characterizing key features of the spectra.

Of the one hundred plus tests observed in the past three years, four are of particular note. During an OTV test, in January of 1987, a fuel turbopump bearing seized. Material from the damaged cage is clearly seen in Figures 5-12 and 5-13 (as CaOH) prior to the redline cutoff of the engine. A similar event befell an SSME development engine in April of the same year when an oxidizer turbopump bearing seized. The second example shows what was observed when a large piece of copper tape, used during a leak check procedure, is left inside the main combustion chamber (see Figure 5-14). Even though the tape quickly burned away, the spectrometry system was able to record increased levels of copper compounds in the plume. The key aspect of this test is validation that copper is detectable and identification of compounds created. This is key to SSME combustion device failure detection since several key combustion device components (e.g. baffles) are made from copper alloys. The third example was a high speed view of the SSME startup transient that showed foreign material contamination flushed from the engine. A fourth example shows preburner faceplate erosion caused by a purposely bent injector post. In this test, chromium is readily observed in the plume. Other structural materials were also indicated though not as strongly as the chromium spectral line. All of these examples serve to characterize the spectral signatures of foreign materials within the plume.

The plume spectrometry system has proven capability to provide failure information, not otherwise available, and therefore represents an unique asset to a failure detection system.

TABLE 5.4 ROCKETDYNE'S GROUND-BASED PLUME SPECTROMETRY STATUS

HOT-FIRINGS OBSERVED

- 48 SSME (O_2/H_2)
- 16 OTV/ICE ENGINE (O_2/H_2)
- 18 ALS-CONCEPT ENGINE (O_2/CH_4)
- 35 SMALL THRUSTER (O_2/H_2)
- EXTENSIVE LABORATORY EFFORTS WITH CONTAMINANT COMBUSTION (O_2/H_2 TORCH)
- 5 XLR-132 (NTO/NMH)

OBSERVED/IDENTIFIED ANOMALIES:

- PREBURNER FACEPLATE EROSION
- BEARING CAGE DISTRESS
- FOREIGN MATERIAL CONTAMINATION
- METALLIC POWDER FLUSHING FROM POWERHEAD REBUILD
- METALS SEEN:

• IRON	• CALCIUM
• COPPER	• SODIUM
• NICKEL	• POTASSIUM
• CHROMIUM	• STRONTIUM
• LITHIUM	• VANADIUM

TABLE 5.5 OBSERVED SPECTRAL FEATURES IN SSME PLUMES

SPECIES	WAVELENGTH (nm)	OCCURRENCES IN 28 TESTS	PERCENTAGE OF OCCURRENCE	POSSIBLE SOURCE
Na	589.0/589.6	28	100	Propellants
K	404.4/404.7	11	39	Propellants
	766.5/769.9	28	100	
CaOH	555	28	100	Propellants, Bearing Cages
	603	26	93	
	623	28	100	
	645	28	100	
OH	306.4	28	100	O_2/H_2 Combustion
Li	670.8	28	100	Dry Film Lube
Ca	422.7	24	86	Propellants, Bearing Cages
CaO	420–430	23	82	Propellants, Bearing Cages
Ni/OH	341–352	16	57	Structural Materials, O_2/H_2 Combustion
Cr	425–428/520.6	11	39	Structural Materials
Fe	371–375/386	11	39	Structural Materials
Sr	460.7	1	4	Structural Materials
SrOH	606/682	1	4	Structural Materials
CuOH	537	1	4	Copper Tape, Baffles, MCC
CuH	428–433	1	4	Copper Tape, Baffles, MCC
Cu	324.8/327.4/510.6	1	4	Copper Tape, Baffles, MCC

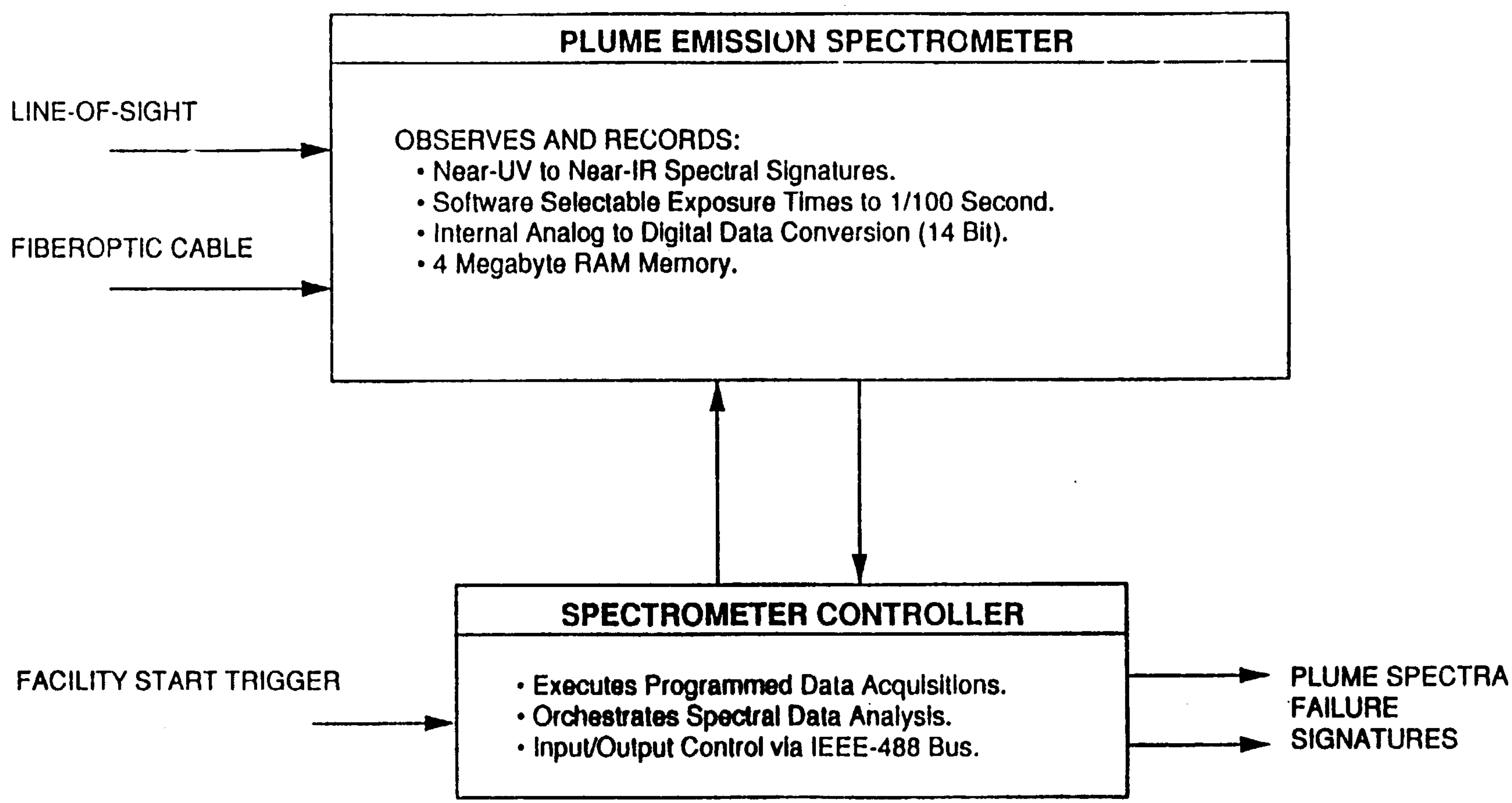

FIGURE 5-11 PLUME EMISSION/ABSORPTION ANALYSIS

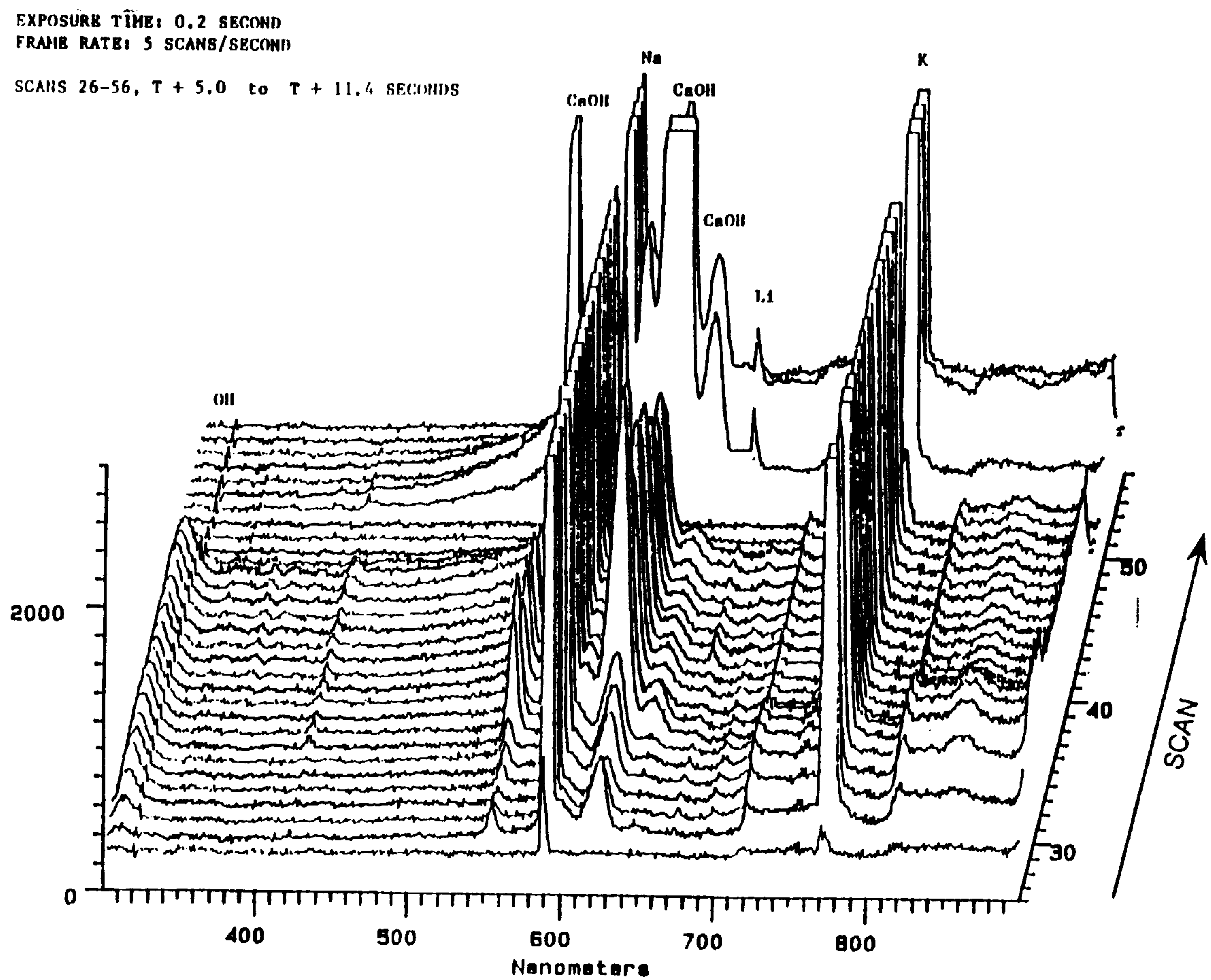

FIGURE 5-12 EXAMPLE PLUME SPECTRAL SIGNATURE - TIME DEPENDENT

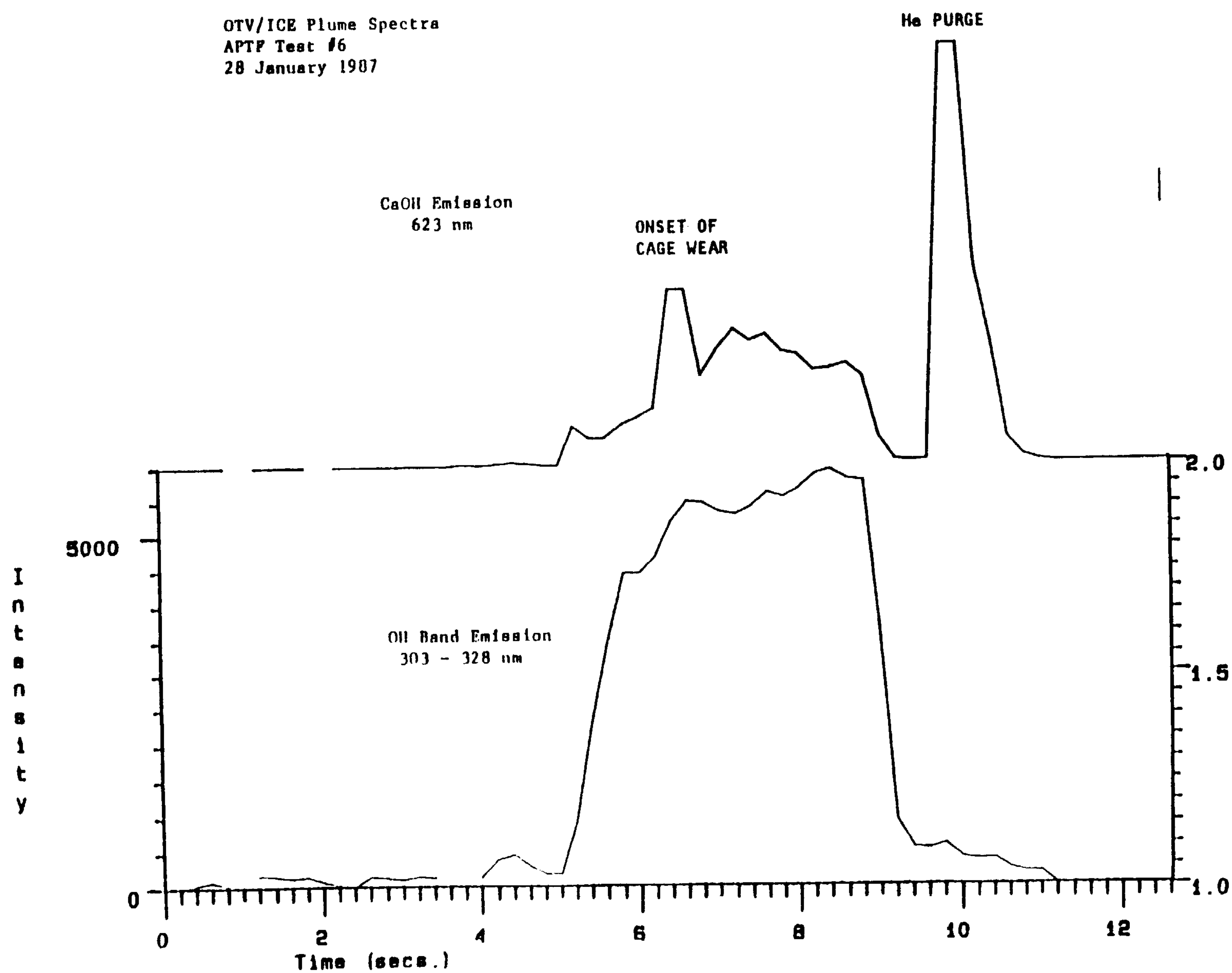

FIGURE 5-13 PLUME SPECTRAL SIGNATURE - BEARING CAGE FAILURE

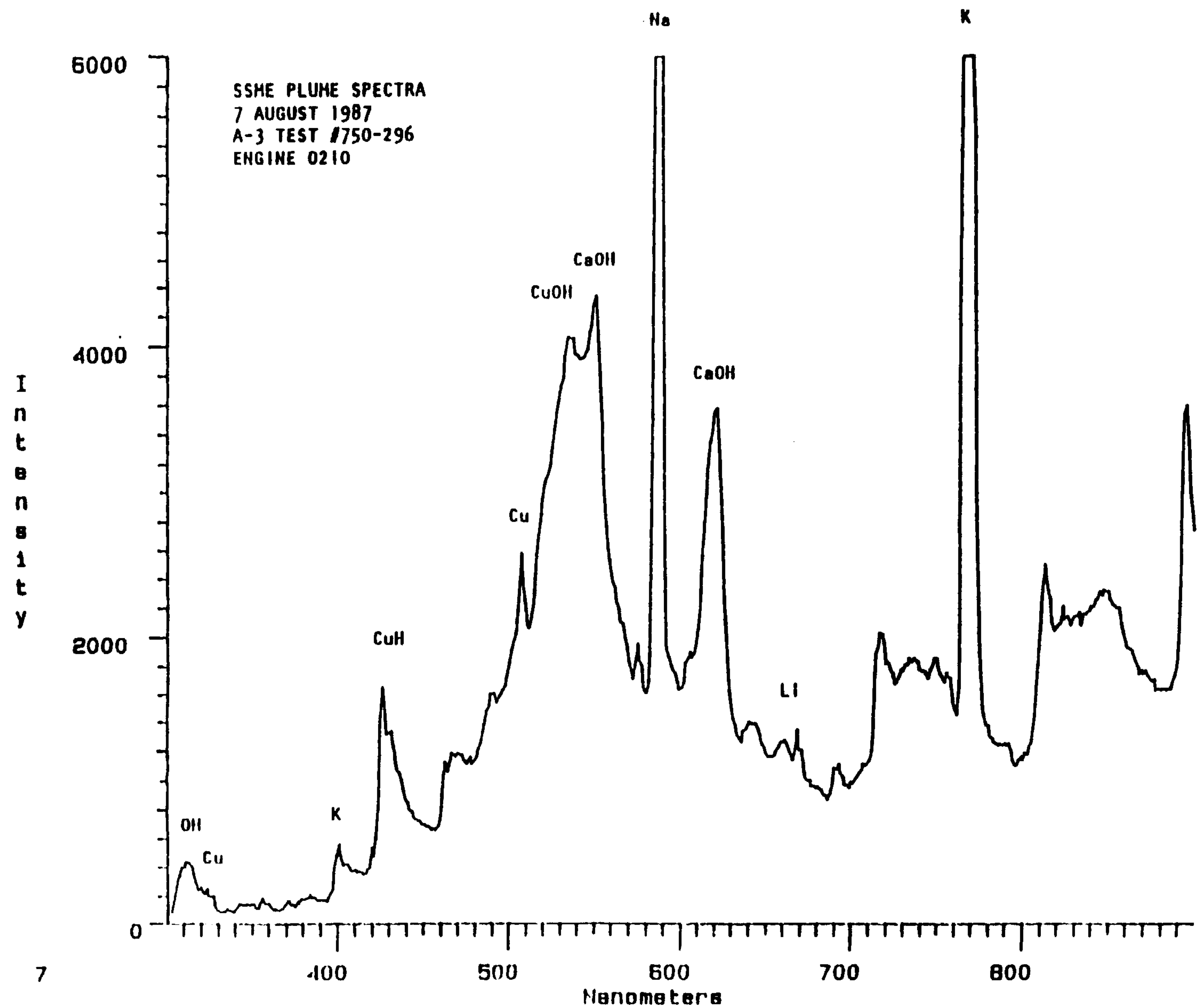

FIGURE 5-14 PLUME SPECTRAL SIGNATURE - COPPER

5.5.2 External Leak Detection

Two general methods are being developed for performing external leak detection of propellents on rocket engines, mass spectrometry and optical measurements. With current technology, neither system meets the requirements for a real-time, SSME failure detection system as defined in this program. For early detection, a small propellent leak must be identified and the source isolated (e.g. a leak in the powerhead is worse than a nozzle leak). Mass spectrometry provides accurate detection of propellent gasses but is unable to isolate the source of leakage. Optical measurements, on the other hand, provide an image of the engine and enable isolation of leaks, but are currently unable to accurately detect propellent gases. A brief discussion of optical methods is presented below to illustrate the development currently underway to enable detection of propellent gases.

During flight or on a test stand, the gases available for leak detection are O2, H2, and H2O. Radiant emission and absorption bands for water and oxygen can be found in the UV and in the near-IR. The near-IR absorption lines are easily accessed using commercial lasers. The UV spectrum can be accessed by flash lamps. Rocketdyne has demonstrated the detection of oxygen to as small as one percent of the ambient atmosphere using this optical UV method. The H2O leaks of interest would be comprised of leaking steam and could be monitored with an IR detector without electromagnetic stimulation from a laser or flash lamp source. Another promising method for remote monitoring of propellent leaks is a small Raman scattering system that Rocketdyne is currently investigating (for hydrogen leaks).

5.5.3 Thermography/Pyrometry

Engine Hardware - Remote thermal monitoring of engine hardware can aid in the detection of hot gas leaks, hardware cracks, debonds, and delaminations. Many engine parts are insulated but serious problems may still be manifest in these areas especially if they involve leaking hot gases. Hydrogen fires, invisible to the naked eye, can easily be spotted thermographically. During an SSME test previous to this study, Rocketdyne thermography detected an external nozzle fire which was otherwise undetected. Inspection of the hardware after conclusion of the test verified the fire and the damage caused.

Plume - Thermographic monitoring of the plume can provide valuable information regarding plume temperatures. Plume temperatures and temperature distribution are related to mixture ratio, mixing efficiency, burn efficiency, and engine stability. Although decisions may not be made on this information alone, it may provide anomaly information which corroborates or clarifies other sensor data and which is valuableto the decision process.

5.5.4 Acoustic Monitoring

Acoustic monitoring of the engine may provide information on leaks, turbopump conditions, engine instability, or other anomalies. Although the SSME produces approximately 150 decibels of acoustic output, it is not clear where the spectrum drops off or how quickly it drops. This should be investigated more completely. Anomaly information may be provided by signals in spectral regions of low acoustic output from the engine or from the variation with time of relevant spectral bands.

5.6 MODEL-BASED FAULT DETECTION

Two areas were investigated for this type of failure detection: 1) analytical sensor redundancy, and 2) model based engine failure detection.

5.6.1 Analytical Sensor Redundancy

There are three approaches to sensor redundancy: 1) hardware, 2) analytical, and 3) temporal. Hardware redundancy utilizes many sensors to measure the same variables. In the analytical approach, a model is used that estimates the required parameter/variable via information of dissimilar sensors. Temporal redundancy makes use of redundant information from successive samples of the output of a given sensor to identify failures. Range and rate checks are common examples of the latter method.

With analytical redundancy, values of parameters are derived from mathematical models, based on actual or simulated inputs, and are compared with the measured values of the corresponding parameters. This approach provides redundancy through analytically derived information that is computed on-line real-time and can eliminate the need for hardware redundancy (or provide redundancy where none currently exists) in many cases.

In general, one would first study the system observability characteristics and would prefer a reduced order observer that will function under failed sensors/actuators. Under these conditions tne system matrices would be modified to reflect the failed sensor or actuator reductions.

An example of how analytical redundancy could be used to increase the reliability of a monitoring system is provided by the case of the HPOTP intermediate seal drain helium pressure. Presently, this parameter is measured by one pressure transducer with two channels upstream of the seal. In flight conditions there is no helium flowrate sensor. Thus, flowrate is inferred from helium bottle pressure, density, skin temperature and volume. The flowrate is normally at 240 standard cubic feet per minute and the redline minimum on the pressure is 170 psia. If the pressure transducer experiences a hard failure (i.e., reads zero or 650 psia), then it is disqualified and the engine operates without a pressure redline on helium.

However, in order to avoid such dangerous elimination of sensors, there is an alternate approach that enhances the functional reliability of the overall engine control system by reconstructing or estimating the critical signals from dissimilar types of sensors under the assumption of "sufficient observability." For the pressure sensor of the above mentioned seal, the pressure can be inferred analytically on-line real-time and compared with the sensor readings. In case there is a sensor failure, the analytically redundant sensor can be utilized as backup.

Since many parameters on the SSME are represented by only single measurements, analytical redundancy provides a means of significantly improving the reliability of a failure detection system.

Additionally, the same basic approach can be applied to verification of actuator responses. Input signals to actuators are sometimes not implemented in a desirable manner, thus producing off-nominal outputs. Analytical approaches toward the identification of such anomalies presently exist in the SSME controller. Namely, the Rotary Variable Differential Transformer (RVDT) output of the actuator signal is compared to the actuator model output to detect out-of-limit actuator operation. Moreover, actuator rate changes are monitored via servo-actuation error indicator interrupts, whereby the vehicle is commanded to shut down in case of significantly anomalous behavior. Thus, analytical techniques are currently in use in the SSME controller, providing advantages that enhance overall engine reliability and performance.

5.6.2 Model Based Engine Failure Detection

Most model-based methods rely on analytical redundancy. Using present and/or previous measurements of certain variables in conjunction with the mathematical model describing their relationship, analytical values are generated and compared with measured values. The difference between the analytical and measured values is called a residual. Thus, the failure detection procedure in the model-based approaches rests on three tasks: 1) residual generation, 2) statistical testing and signature generation, and 3) decision making and diagnostics (in case of identification and isolation).

Model based diagnostics generally are most useful for detection and identification of specific failure types. Therefore to illustrate the concept, a fuel leak detection scheme, in which the oxidizer flow is mathematically modelled, is presented below as an example.

Example: Model Based Fuel Leak Detection

An analytical approach that calculates mixture ratio (of oxygen to hydrogen) and compares the result with the internally generated mixture ratio, can determine the existence of leakage in the fuel lines.

Simulations were carried out on the SSME analytical model and leaks were introduced to evaluate the concept. The results of the simulations indicate clearly the introduction of leaks in several parameter outputs. For this study, leaks of 2, 5, and 10 lb/sec (just downstream of the main fuel valve) were simulated to demonstrate the potential leak detection and engine mixture ratio control using the alternate mixture ratio computation.

A direct approach is taken whereby the oxygen flow calculation is used to compute the MR in the SSME more accurately, reflecting the effects of a fuel leak on the various engine parameters. To accurately estimate the total oxygen flow used by the engine, three paths must be considered: 1) MCC flow, 2) FPB flow, and 3) OPB flow.

Oxygen flow from the Main Oxygen Valve (MOV) to the main combustion chamber is given by the following equation:

$$\dot{w}_{Pc} = 24.2\,(P_{do} - P_c)^{1/2} \qquad \text{---(1)}$$

where P_{do} is the HPOTP discharge pressure and P_c is the main chamber pressure.

The following equation provides the oxygen flow through the fuel (hydrogen) preburner:

$$\dot{w}_{FPB} = \left| \frac{P_{PDO} - P_{FP}}{0.2143 + 116.5/A_F^{\,2}} \right|^{1/2} \qquad \text{---(2)}$$

where P_{PDO} is the preburner oxygen (boost) pump discharge pressure, P_{FP} is the fuel preburner pressure, and A_F is the fuel preburner oxidizer valve flow area.

In order to calculate the oxidizer flow through the oxidizer preburner, the assumption was made that the oxygen and hydrogen preburner pressures are equal in steady-state conditions. Since the oxidizer preburner pressure is not measured during flight, the fuel preburner pressure was used as an estimate.

Table 5.6 shows the ratio of pressure drop from the preburner pump discharge to the oxidizer preburner to the same pressure drop for the fuel preburner. The largest variation is 5.5% (65% power level compared to 109% power level). Since the flowrate is proportional to the square root of pressure drop, the maximum oxidizer preburner flow error is 2.7%. At 65% power level, the oxidizer preburner flow is about 2.5% of the total oxidizer flow. Therefore, the maximum mixture ratio error is only 0.07% due to using the fuel preburner pressure for the oxidizer preburner.

Table 5.6 Ratio of OPB Pressure Drop to FPB Pressure Drop

power level (%)	109	104	100	90	80	70	65
$\frac{WP_{oxpb}}{WP_{fupb}}$	0.966	0.968	0.970	0.980	0.996	1.1010	1.1020

The equation estimating oxygen flow through the oxidizer preburner is therefore given by:

$$\dot{w}_{OPB} = \left| \frac{P_{PDO} - P_{FP}}{1.576 + 2082.6/A_o^2} \right|^{1/2} \quad \text{---(3)}$$

where A_o is the oxygen preburner oxidizer valve flow area.

The sum of equations (1), (2), and (3) yields the total oxidizer flow estimate and MR is calculated by dividing the total oxygen flow by the total hydrogen (fuel) flow. A flowmeter provides the fuel flow. The inputs to the oxygen flow calculations require measurements of the main chamber pressure, HPOTP discharge pressure, fuel preburner pressure, preburner boost pump discharge pressure, and fuel and oxygen pump oxidizer valve positions. All of these are available from existing sensor measurements. These equations were incorporated into the SSME digital transient model to verify the feasibility of the concept of leak detection. The results of a computer simulation of the engine dynamics of the SSME indicated that the approach proposed herein is valid during steady-state operation. Table 5.7 shows how closely the oxidizer flow as calculated, using the alternate approach, agrees with the design value at steady-state conditions, for five different power levels.

Table 5.7 Comparison Between Analytical Oxidizer Flow Model and Design Values

power level (%)	109	104	100	90	65
OX flow design value	975.58	931.28	895.85	807.17	584.82
OX flow as calculated using analytical model	976.41	930.99	895.77	805.88	582.25

A simulated fuel leak was introduced into the model between the High Pressure Fuel Turbopump (HPFTP) and the main fuel valve and the analytical model was used to calculate MR. One computer simulation was run under nominal operating conditions and three runs were made under 2 lb/sec, 5 lb/sec, and 10 lb/sec fuel leaks. The results are shown in Figures 5-15 and 5-16. Figure 5-15 shows the calculated MR, using the analytical model to determine oxidizer flow. Figure 5-16 shows the current SSME mixture ratio calculation.

As can be seen from these plots, for a given point in time, calculated MR generally increases using the model based MR estimate, and generally decreases using the current SSME MR estimate for increasingly greater fuel leaks. Figure 5-16 indicates that the mixture ratio is lower for increasingly greater fuel leaks when in fact the mixture ratio should be higher for increasingly greater fuel leaks, as Figure 5-15 indicates. Differences between the values obtained with each method potentially indicates the existence of a fuel leak.

Model based diagnostics provide a means of detecting subtle failures within the SSME if sufficient observability exists for the condition being monitored. However, their use appears too limited in scope to provide an adequate damage minimization system. These models are best utilized to address specific problems not adequately covered by a more comprehensive failure detection scheme.

5.7 DATA TRENDING

Monitoring trends in the data enables early detection of anomalies. This detection is based on estimates of where a value will be at some future time. To evaluate the utility of this approach, a basic algorithm was developed and simulations run.

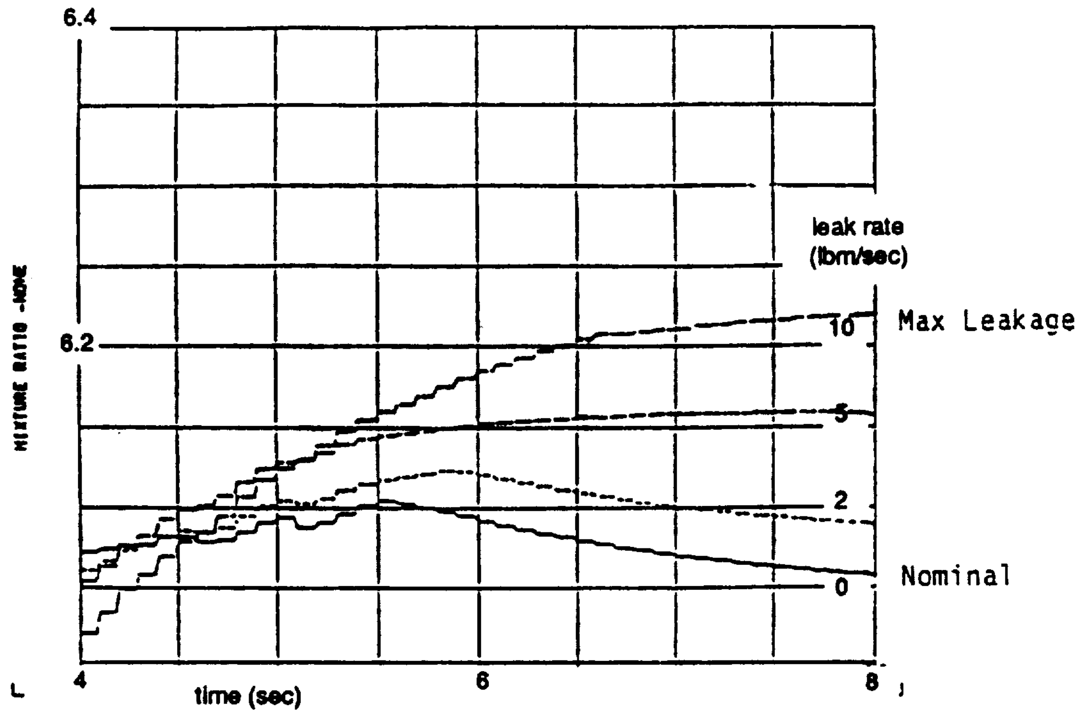

FIGURE 5-15 ALTERNATE MIXTURE RATIO CALCULATION RESULTS

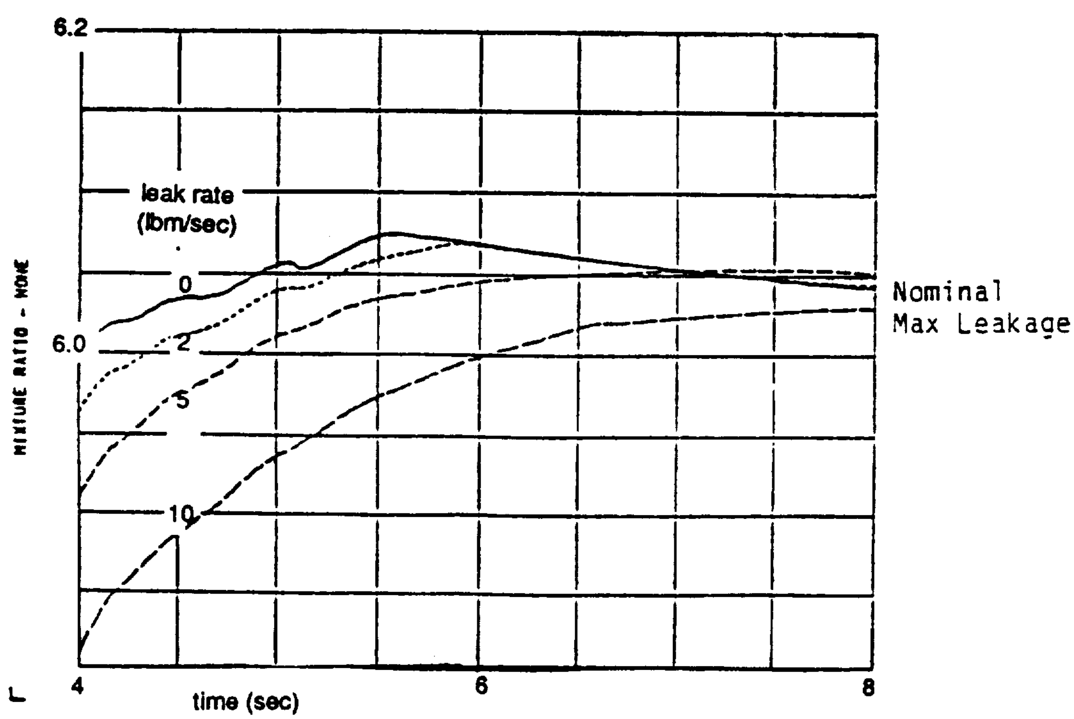

FIGURE 5-16 CURRENT MIXTURE RATIO CALCULATION RESULTS

The data trending algorithm evaluated is a modification of the System for Anomaly and Failure Detection (SAFD) algorithm. The fundamental difference being in the decision signal; the average value of parameters for the SAFD versus the slope between consecutive averages for a trending algorithm. Different averaging intervals for each parameter may be required since some parameters have a relatively steady behavior while others have more extreme excursions, even under normal operation. Thus, it is prudent to determine the averaging interval based on the history of excursions of the parameter values.

The slope-average algorithm is initialized with the slope-average computed for the interval immediately following the establishment of steady state (a number close to zero) as the "expected" value. A one sigma "anomaly" band is defined and centered around the average value.

Another modification that may enhance the performance of the algorithm is to update the expected slope (s_o) every several seconds if the variations of the slope-averages slice-to-slice are within a reasonable limit, (otherwise slow trends would not be identifiable). This approach has to be simulated further in order to assess the slice-to-slice variation effects relative to normal and anomalous operating conditions.

Data from two SSME tests, during which engine degradations were the reason for premature engine cutoff, were evaluated using the SAFD algorithm and the slope-average approach and the results were compared. The results of applying the SAFD algorithm and the slope-average approach to tests 901-364 and 901-225 are shown in Attachments 6 and 7, respectively. The slope-average profiles of Attachment 7 suggest that this test could have been shutdown earlier, perhaps at about 252 seconds, as opposed to the SAFD algorithm cutoff time of 255.59 seconds.

Although, evaluation of more tests and failure simulations are needed to assess the overall benefits of this approach, the simulation results suggest that the data trending approach could complement SAFD. For some parameters, the SAFD functions better than the slope-average approach while for others, the latter might provide an earlier cutoff. Thus, further analysis would be necessary to have a good understanding of the slope-average approach and to develop the failure detection logic. The potential for use of this approach to transient conditions is also possible.

Data trending enhances the sensitivity of the failure detection process by utilizing the slope of average signals rather than the averages themselves. Thus, in many situations when signals have a tendency to change slowly due to "slow" failures, the slope average may be suitable to detection of subtle changes in slope. Furthermore, when the slope-average continues with the same sign (in the same direction) for several consecutive calculations, this indicates a trend which (if sufficiently many signals give the same indication) can be utilized for failure detection.

5.8 FLEETWIDE OPERATING ENVELOPES

Nominal value envelopes can be determined by utilizing the extensive SSME hot-fire test database and associated data analysis experience. Many of the nominal envelopes have already been developed and are currently used to evaluate new hot-fire test data. These envelopes are the basis of a proven technique for determining the reasonableness and validity of measured hot-fire parameters. While other techniques such as comparisons of two or more redundant measurements, exist for validating measured parameters, the nominal envelope technique is especially useful for validating non-redundant parameters.

Fleetwide envelopes are relatively large during steady state (due to engine to engine variation) and do not provide sufficient resolution for effective failure detection. However, they are well suited to identifying anomalies during transients. Transient operation is observed to vary between acceptable engines and even between nominal tests. The range of values is due to minor effects within the engine that give a somewhat statistical nature to the events (e.g. preburner and MCC ignitions during the start transient). Therefore, transient anomalies are indicated by a value significantly "out of range", rather than by deviations from a single nominal value as in the case of most steady state anomaly detection schemes.

Transient nominal envelopes are defined by formulating a time-dependent envelope based on previous hot-fire experience. These envelopes are composed point by point from nominal tests in the SSME hot-fire test database. Maximum and minimum observed nominal values, over the fleetwide data, are determined for each time slice during a transient. One example of such an envelope is presented in Figure 5-17 for the HPOT discharge temperature. This envelope is one currently used by Rocketdyne for post-test analysis for SSME hot-fire tests. A more extensive set of nominal envelopes for the start transient is included as Attachment 8.

In Figure 5-17, the maximum and minimum lines which make up the envelope (based on 232 nominal tests) are indicated by solid lines. The dashed line represents the HPOT discharge temperature measured during test 902-471.

The figure shows that the HPOT discharge temperature for this test dropped below the minimum nominal level between about 1.8 and 2.7 seconds after engine start. In this case, the anomaly was indicative of a slower than normal Oxidizer Pre-Burner (OPB) ignition. The SSME can, and did, start successfully under these conditions, so this single anomaly would not warrant shutting down the engine or any other real-time corrective action. After post test evaluation, an engineer might recommend an increase in the OPB oxidizer valve open loop command for the next test in order to allow more oxidizer into the OPB chamber during start. Definition of significant anomalies during the start transient will require careful evaluation by experienced SSME test operations and performance analysis engineers.

However, failures during the start transient can be expected to show large deviations from the nominal range as illustrated by the following test case. On October 3, 1978 SSME #0006 experienced an anomaly during its start transient. The test was terminated at +2.36 seconds by a low chamber pressure confirmation redline and a HPFT discharge temperature redline. Analysis of test data indicated that the HPFP speed buildup was slow and the oxidizer dome primed early causing an abnormally LOX rich condition during engine start. Figure 5-18 indicates this anomaly. The shaded region indicates the nominal max/min envelope determined from 237 tests. The solid line and small dashed line are the measured values for two successful tests of engine #0006. The large dashed line indicates the measured value for the test during which the failure occurred. In the failure test, the HPFP speed is well out of the nominal range about 0.75 seconds before the engine was cutoff. A more complete set of data plots for this test series is provided as Attachment 9.

Two independent conditions were found that contributed to the LOX rich atmosphere in the engine. The main oxidizer valve (MOV) had a manufacturing problem. The MOV valve/actuator was mislocked open resulting in the ball valve being open 3.5% more than normal, causing the

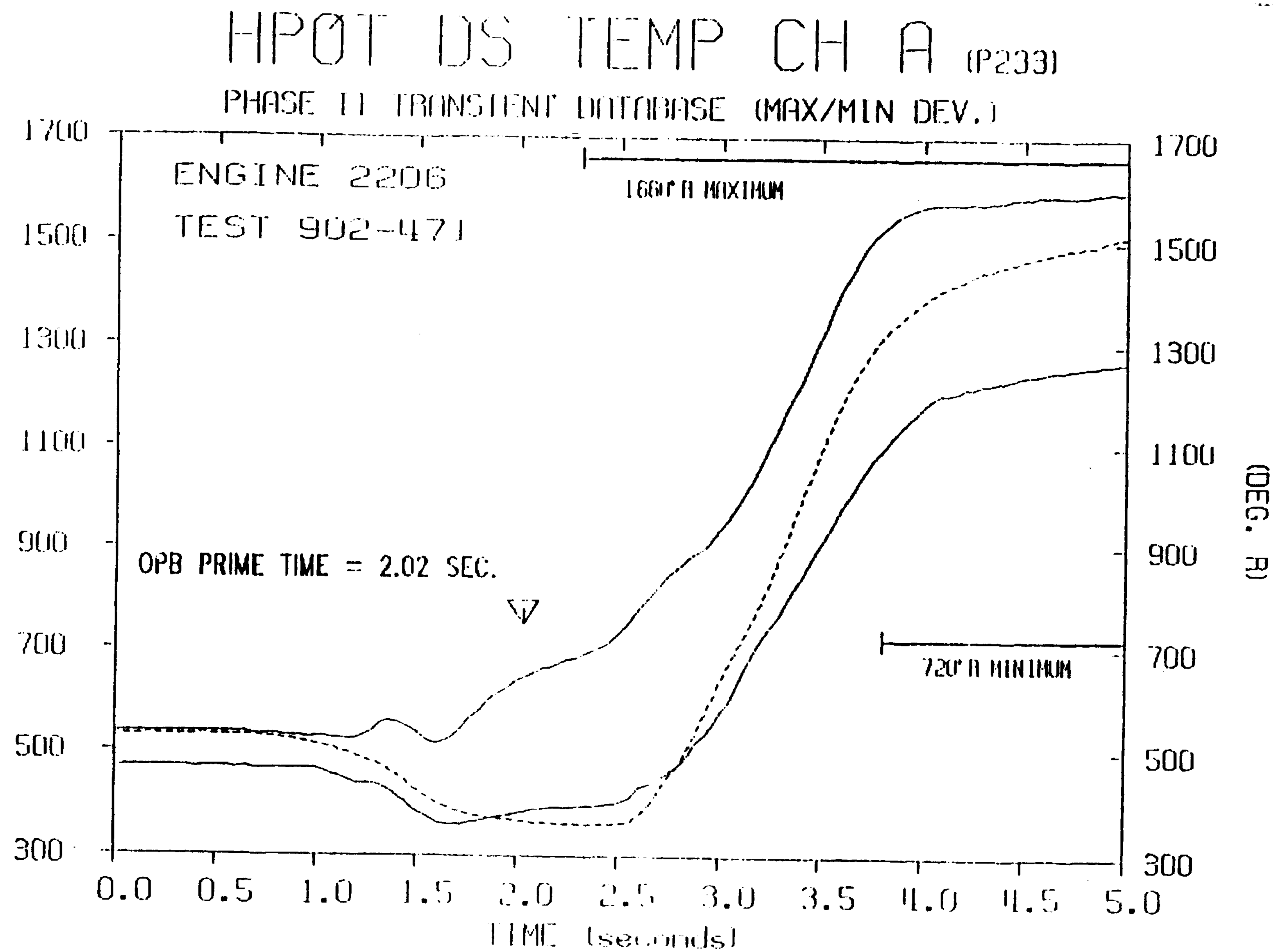

FIGURE 5-17 FLEETWIDE OPERATING ENVELOPE - START TRANSIENT

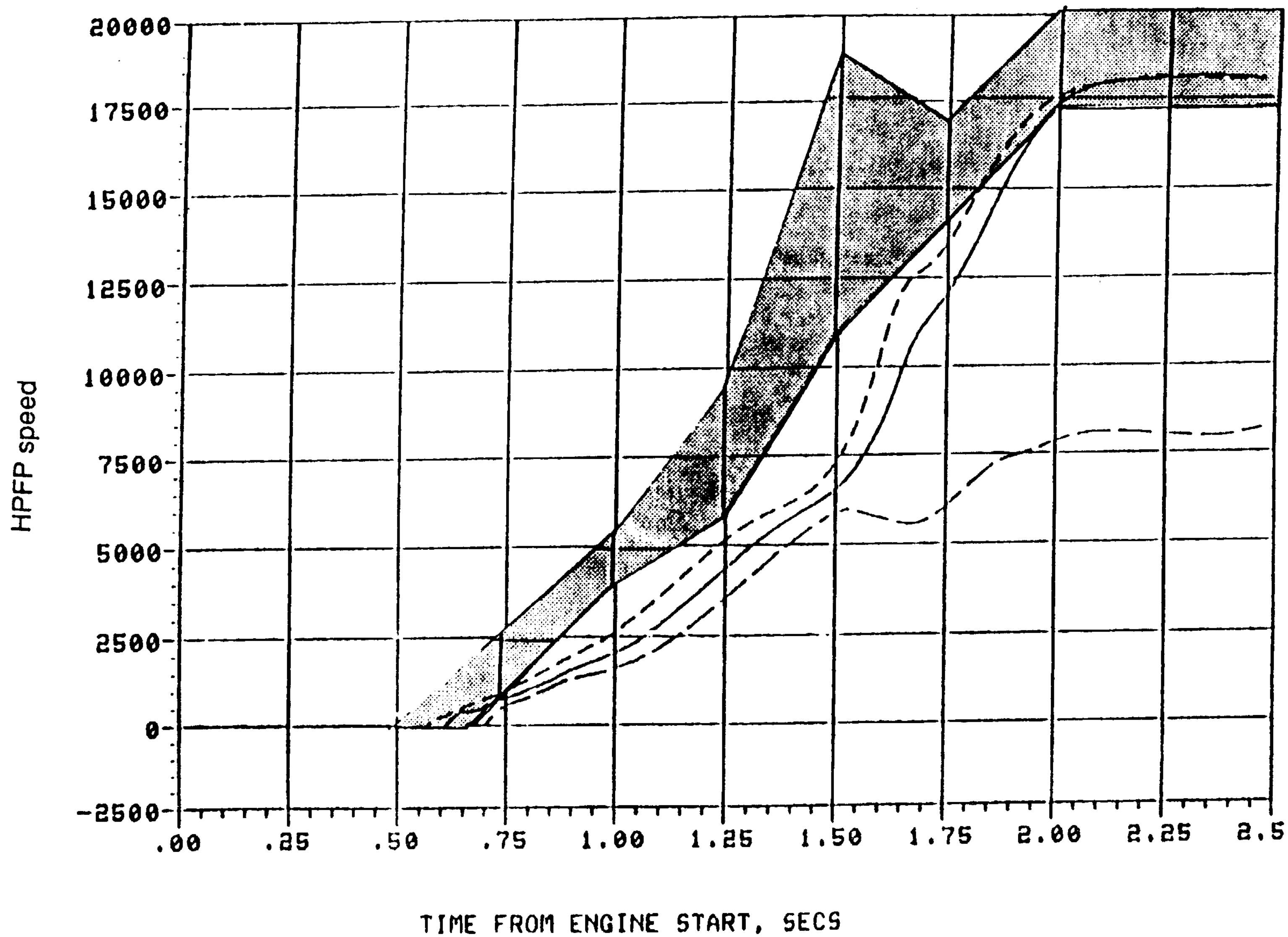

FIGURE 5-18 FLEETWIDE OPERATING ENVELOPE - ANOMALY INDICATION

early prime in the LOX dome (excessive oxidizer present at ignition). The HPFP was late in breaking away due to binding of the third stage impeller with the deteriorated repaired area in the high pressure orifice region of the balance piston cavity and interstage seal rubbing.

Post-test inspection revealed damage to the HPFTP turbine and the hotgas manifold liner (on the fuel preburner side) and the main injector (136 injector elements eroded between faceplates). Teardown inspection of the engine disclosed the HPFTP turbine had sustained damage from burning and erosion. A housing repair in the area of the high pressure balance piston orifice had failed and heavy rubbing of the second stage interstage seal had occurred.

Based on the anomalies observed, this test could have been confidently cutoff earlier using the fleetwide nominal envelope approach to anomaly detection.

5.9 POWER LEVEL DEPENDENT ALGORITHMS

The behaviors of a number of SSME performance parameters are highly dependent on engine power level. Parameters included in this list are turbine discharge temperatures, other turbopump inlet and discharge temperatures and pressures, turbopump speeds, propellant flow rates, and valve positions. Using relations between these parameters and engine power level, algorithms based on power level can be derived for use in calculating or predicting expected, measured parameter behaviors and in inferring values for parameters which are not measured.

Various forms of these power level dependent algorithms are successfully being utilized throughout Rocketdyne to perform off-line analysis as well as real-time analysis of SSME data. Two algorithm forms of particular interest are reasonableness curves and influence coefficients.

Reasonableness curves are empirically derived algorithms, based on a third-order polynominal fit of SSME hot-fire test data as a function of power level. They are currently included in the SSME Data Reduction Model as a method of detecting sensor failures by performing a reasonableness check of input data derived from sensor values. The reasonableness check entails comparing measured parameters to calculated parameters using a reasonableness band. While suited for their intended purpose, reasonableness curves are relatively unsophisticated compared to influence coefficients.

Like reasonableness curves, influence coefficients generated by the SSME Power Balance Model, can be used to estimate parameter magnitudes. However, the accuracies of these parameter value estimates are greatly improved by the ability of the influence influence coefficients to adjust operating parameters for changes in engine performance caused by engine inlet condition changes. The influence coefficients define "adjustments" to the nominal power level dependent estimate to account for off-nominal inlet conditions to a system or subsystem. Additionally, influence coefficients have the capability of being tailored to a specific engine when required. In this ype of application, they serve as both an engine-specific and power-level-dependent calculation and prediction method. The greater accuracy provided by the influence coefficient method allows a tighter band to be considered when evaluating sensor data.

Figure 5-19 is a comparison of measured and predicted values of HPOTP turbine discharge temperature during test 901-516 on engine number 2105. Presented in the figure are: 1) plots of the measured parameter values, 2) parameter values predicted solely with a power level dependent algorithm and 3) parameter values predicted with the same power level dependent algorithm combined with adjustments for varying inlet conditions. The inlet conditions adjusted for in this case were LOX and fuel engine inlet pressures and temperatures. LOX and fuel tank repressurization flow rates, and engine mixture ratio.

The figure indicates that the power level dependent algorithm predicted the correct relative magnitude of the parameter, but the failure to account for parameter variations due to changes in inlet conditions greatly reduced the prediction accuracy. The prediction accuracy was considerably increased by adjusting for inlet conditions. The inlet condition adjustments act to reduce the deviation from the predicted value and allow for tighter envelopes to be used for flagging abnormal parameter values. It should be noted that the algorithms used to generate Figure 5-19 were based on SSME fleet averages. Much more accurate predictions could have been made by instead basing the algorithms on earlier tests of engine 2105.

The advantages of utilizing influence coefficient analysis in a real-time health management system include: 1) influence coefficients are a fast and relatively accurate means of predicting operating parameter behavior, and 2) they are relatively simple to develop, to tailor to specific hardware, and to implement. The only significant disadvantage is that influence coefficients provide a simplified estimate of the "nominal" value and some subtlties of engine operation may not be accounted for. When combined with an appropriate operating envelope, influence coefficient based sensor data checking and anomaly identification provide a very effective tool for real-time health management of rocket engines.

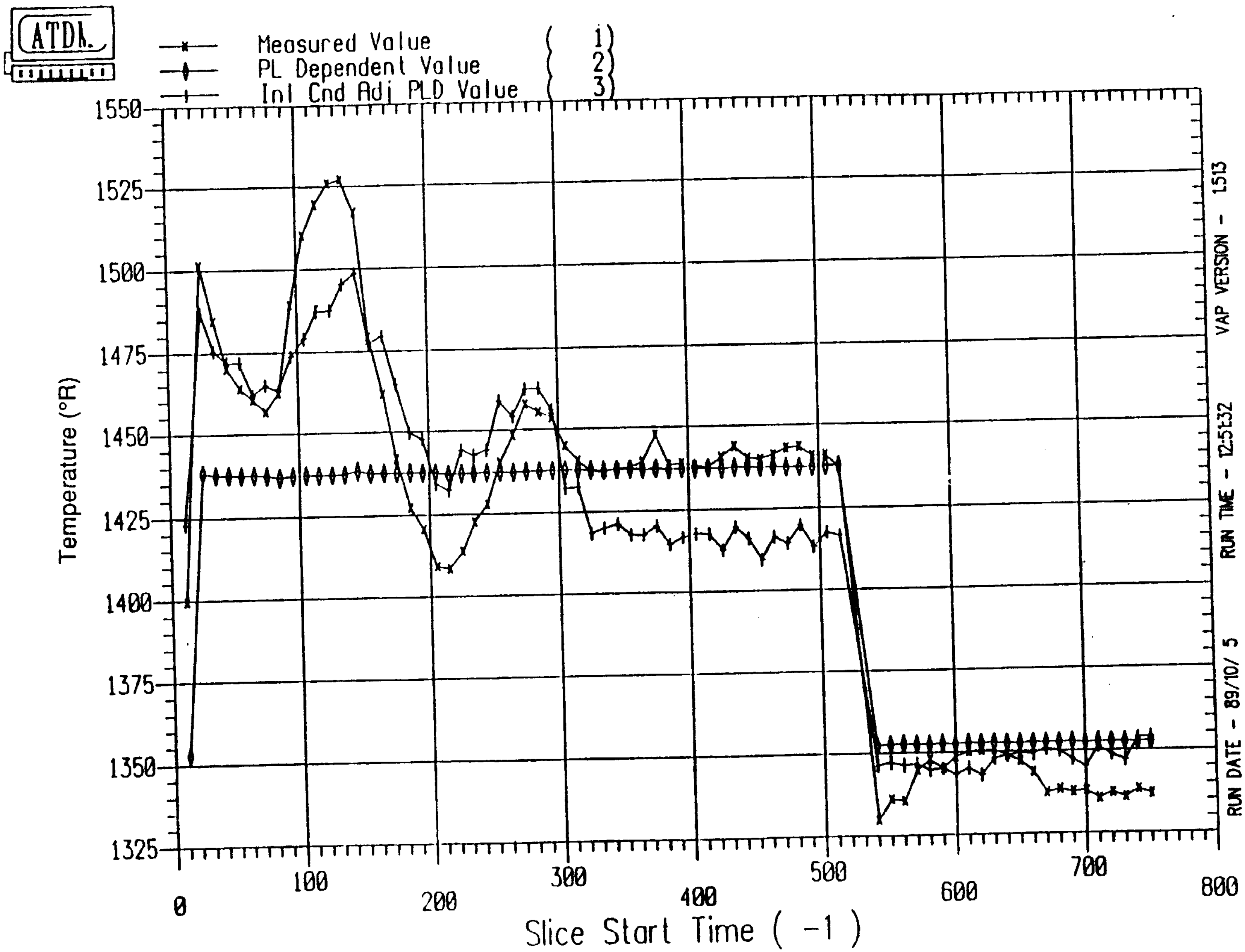

FIGURE 5-19 INFLUENCE FACTOR ESTIMATE CORRECTION - HPOT DS TMP

5.10 VIBRATION MONITORING

Excessive vibration provides independent validation for failures indicated by a performance anomaly and may provide the only early indication for hard component failures in the turbopump. Excessive vibration is an early indication for a number of failure modes, most notably bearing failures, loss of turbopump balancing force, turbine blade fractures, and internal rubbing. The failure modes highlighted in Table 5.8 are expected to include abnormally high vibration levels as part of their failure signature. In addition, of 19 SSME hot-fire failures with redline cutoffs, 4 were cutoff by vibration redlines before the performance redlines were exceeded (Table 5.9). Therefore, monitoring for excessive vibration can be expected to significantly increase the confidence and detectability of turbopump failures.

Currently, vibration is monitored by both the redline and FASCOS systems on the SSME. Both of these systems monitor relatively broadband vibration spectra and operate as simple redline cutoffs. "Cross talk" between components, an excitation caused by vibration of another component, make fault isolation virtually impossible. While some utility is gained by simply knowing the engine level vibration, validation of a failure indicated by performance anomalies is enhanced by identification of an isolated source of vibration.

A certain degree of fault isolation (at least to the level of isolating the responsible turbopump) can be obtained by monitoring a narrow frequency band centered around the synchronous frequency of each turbopump. Justification for this approach lies in the fact that failures indicated by vibration ultimately involve an imbalance in the pump rotating assembly, resulting in a fundamental vibration at the pump synchronous frequency. Real time, dynamic tracking filters (such as those developed by Rocketdyne, under IR&D, for the bearing monitor program) have demonstrated tracking and monitoring of pump synchronous frequencies for real-time SSME data.

Nominal vibration levels can be defined through evaluation of the spectra measured for SSME hot-fire tests. The ADDAM (Automated Digital Data Analysis Machine) system is capable of performing the vibration analysis necessary to characterize these spectra as illustrated by Figures 5-20 and 5-21. Figure 5-20 is the vibration power spectrum indicated by a HPFP radial accelerometer for a specific

TABLE 5-8 FAILURE MODES EXPECTED TO CAUSE EXCESSIVE VIBRATIONS

RANK	LRU-FM	COMPONENT	FAILURE MODE
1	A150-01	HEAT EXCHANGER	COIL FRACTURE/LEAKAGE
2	C200-11	PCA (EMERGENCY PNEUMATIC SHUTDOWN)	FAILURE TO SUPPLY HELIUM PRESSURANT
3	B200-04	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE OF TURBINE BLADES
4	A340-02	NOZZLE ASSEMBLY	EXTERNAL RUPTURE
5	D110-01	MAIN FUEL VALVE	INTERNAL LEAKAGE
6	A600-04	FUEL PREBURNER	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT OCCURS
7	B200-15	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF SUPPORT OR POSITION CONTROL
8	A200-06	MAIN INJECTOR	LOX POST CRACK
9	B600-06	LOW PRESSURE FUEL TURBOPUMP	FUEL LEAKAGE PAST LIFT-OFF SEAL
10	B400-03	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE BLADE STRUCTURAL FAILURE
11	B400-14	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF AXIAL BALANCING FORCE
12	B400-07	HIGH PRESSURE OXIDIZER TURBOPUMP	FAILURE TO TRANSMIT TORQUE
13	A200-09	MAIN INJECTOR	INTERPROPELLANT PLATE CRACKS
14	B400-22	HIGH PRESSURE OXIDIZER TURBOPUMP	PUMP PIECE PART STRUCTURAL FAILURE
15	A330-02	MAIN COMBUSTION CHAMBER	FUEL LEAKS INTO THE CLOSED CAVITY BETWEEN THE LINER AND STRUCTURAL JACKET
16	K103-01	LPFTP TURBIN DISCHARGE DUCT	FAILS TO CONTAIN HYDROGEN
17	D500-06	GOX CONTROL VALVE	MAINTAIN STRUCTURAL INTEGRITY
18	D300-01	ANTI-FLOOD VALVE	LEAKAGE DURING PROPELLANT CONDITIONING
19	K106-02	HIGH PRESSURE FUEL DUCT	FAILS TO CONTAIN HYDROGEN
20	D800-06	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT AND POSITION CONTROL
21	A200-07	MAIN INJECTOR	EXTERNAL RUPTURE
22	E150-14	CHAMBER COOLANT VALVE ACTUATOR	SEQUENCE VALVE LEAKS PASSING EARLY CONTROL PRESSURANT DOWNSTREAM
23	D220-06	OXIDIZER BLEED VALVE	FRETTING OF INTERNAL PARTS
24	B400-23	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE PIECE PART STRUCTURAL FAILURE
25	A330-03	MAIN COMBUSTION CHAMBER	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE
26	B200-26	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE
27	K203-01	OXIDIZER BLEED FLEX LINE	FAILS TO CONTAIN OXIDIZER
28	D120-05	MAIN OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE
29	A050-02	POWERHEAD	SHELL OR PROPELLANT DUCT RUPTURE
30	A600-11	FUEL PREBURNER	EXTERNAL RUPTURE
31	D120-04	MAIN OXIDIZER VALVE	STRUCTURAL FAILURE
32	C200-07	PNEUMATIC CONTROL ASSEMBLY (OXIDIZER SYSTEM	INSUFFICIENT OR NO NITROGEN PURGE FLOW DURING PROPELLANT CONDITIONING
33	A200-05	MAIN INJECTOR	PARTIAL BLOCKAGE OF AN OXIDIZER ORIFICE
34	D130-03	FUEL PREBURNER OXIDIZER VALVE	SHAFT SEAL LEAK
35	D120-06	MAIN OXIDIZER VALVE	FREETING OF INTERNAL PARTS
36	B400-13	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT, POSITION CONTROL, OR ROTORDYNAMIC STABILITY
37	B200-07	HIGH PRESSURE FUEL TURBOPUMP	TURBINE DISCHARGE FLOW BLOCKAGE
38	B400-20	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO FIRST-AND-SECOND-STAGE TURBINE COMPONENTS
39	D300-03	ANTI-FLOOD VALVE	LOW FLOW RESTRICTED OR SHUT OFF
40	A700-02	OXIDIZER PREBURNER	LOSS OF FUEL TO ASI
41	B200-16	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS
42	B200-17	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE DISCS
43	B400-18	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO BEARINGS
44	B200-24	HIGH PRESSURE FUEL TURBOPUMP	FAILURE TO RESTRAIN SHAFT MOVEMENT DURING TURBOPUMP STARTUP
45	B200-23	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF BALANCING CAPABILITY

TABLE 5.9 OBSERVED SSME REDLINE SHUTDOWNS

(1) SHUTDOWN REDLINE	NO. TESTS
HPFT DS temp	8
HPOT DS temp	3
PBP rad accel	2
HPOTP accel	1
HPFTP rad accel	1
HPFP speed	1
HPOTP secondary seal cavity pres	1
HEX DS pres	1
Elevation J minimum pres	1

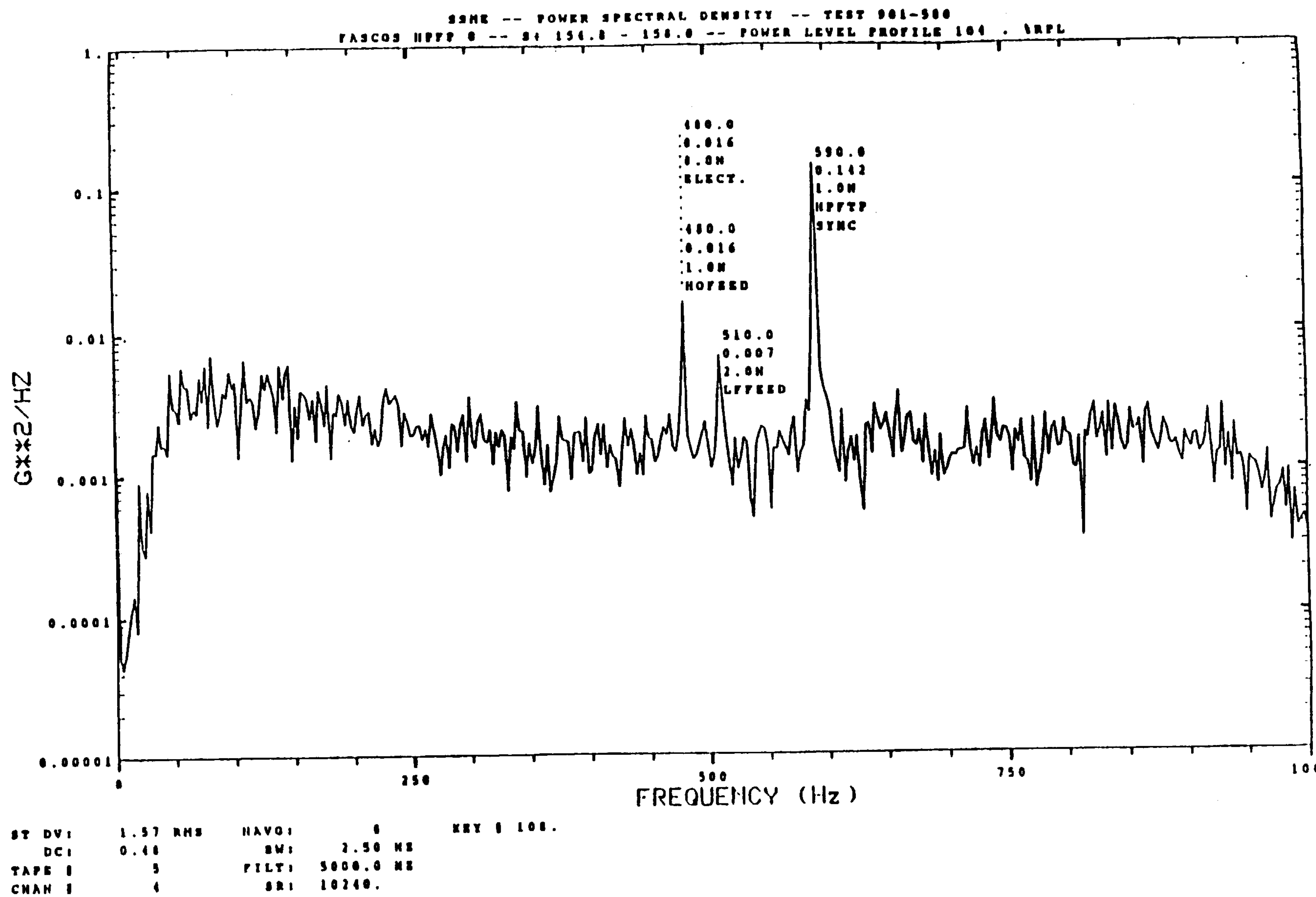

FIGURE 5-20 HPFP ACCELEROMETER POWER SPECTRAL DENSITY

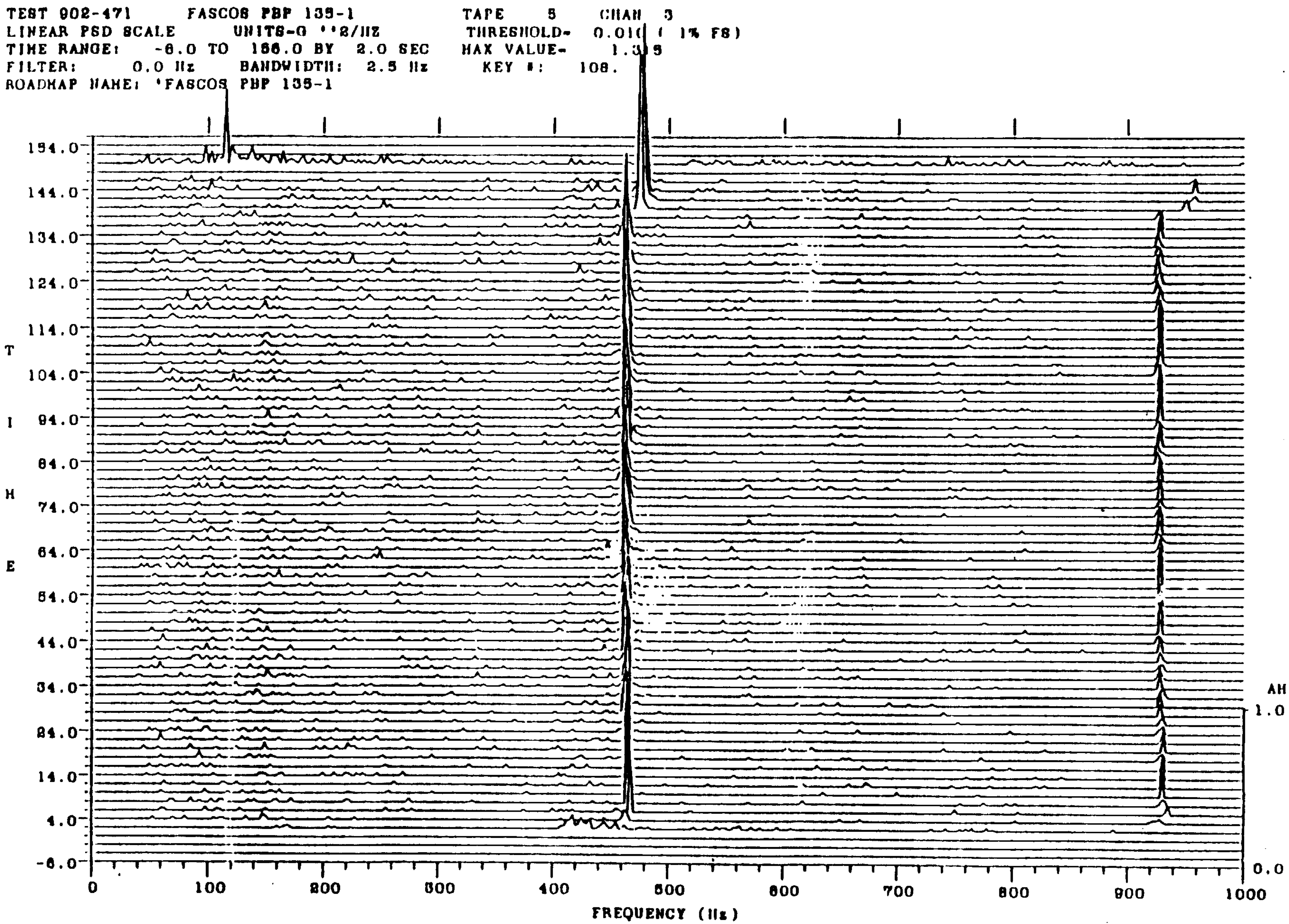

FIGURE 5-21 PBP ACCELEROMETER POWER SPECTRAL DENSITY - TIME DEPENDENT

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time slice. The HPFTP synchronous frequency (about 600 Hz) clearly has the largest amplitude. Figure 5-21 shows the vibration power spectrum for the HPOP with time dependent information shown by using a time scale along the Y-axis and overlaying the vibration data for each time slice. Again the HPOTP synchronous vibration is clearly visible.

5.11 CONCLUSIONS

No single failure detection technique evaluated provides adequate protection for the engine. However, many of the techniques have features that would be expected to significantly improve the existing protection system and a synthesis of applicable features provides the basis of the HMSRE framework described in Section 6.

SECTION 6 - HMSRE FRAMEWORK

Key features of the failure detection methods evaluated in Section 5, (those deemed to have the highest likelihood of success, in a near-term application) were combined to produce the HMSRE framework described in this section. These features include the use of: parameter correlation, operating envelopes, influence coefficients, power-level dependent algorithms, vibration monitoring, and plume spectometry. The framework is compatible with the SSME Block-II controller, is readily adaptable to flight (most of the monitored parameters are existing Block-II measurements), and can be implemented on a test stand within 5 years. Additionally, it is anticipated that the HMSRE framework can be implemented in the processing hardware currently under development for SAFD on the SSME TTBE program.

Two general approaches were considered for the HMSRE framework. One approach addressed a small set of failure modes resulting in fairly exact identification of specific failures before issuing a cutoff command (e.g. bearing signature analysis - Section 5.4). Sensitivity to and identification of specific failure modes has the benefit of providing a high degree of confidence that a failure is occurring, but lacks adequate failure coverage in that only a handful of failure modes are detectable. The alternate approach is to monitor for significant engine level anomalies. This provides far greater failure coverage but does not identify which specific failure mode is occurring.

Detailed failure or degradation information is necessary for an adaptive or maintenance monitoring system, but a safety system needs only to identify that a failure is occurring. In a safety system, detailed failure information serves only to marginally increase confidence in the failure detection. For example, if the HPFT discharge temperature suddenly increases by 150 R and the shaft speed is 1000 rpm above normal, something has probably failed within the engine. Additional monitoring to determine the exact cause of the anomaly only delays the inevitable cutoff command. Therefore, it was decided that monitoring for significant engine anomalies better met the program goal of minimizing engine damage since it provides earlier cutoff and greater coverage of failure modes, including those never before observed and simultaneous, multiple failures. Failure coverage is further increased by defining an HMSRE framework addressing all phases of engine operation (except the cutoff transient). This includes the start transient, mainstage steady state operation at all power levels, and power transients. The cutoff transient is not addressed since an HMSRE cutoff command during this phase would have no effect.

Initially, a general strategy was defined for monitoring significant engine anomalies. The strategy selected is based largely on the parameter correlation schemes shown to have promise in Section 5.3. Combinations of individual, weighted measurement deviations, correlated to provide either an engine level anomaly value or indications of a specific degradation such as a loss of HPFP efficiency, are used as engine failure indicators. Engine anomaly thresholds are set for each parameter to define significant anomaly limits. A key departure from the method described in Section 5.3 is the definition of an overall engine anomaly parameter. This parameter is not related to a known degradation, but instead is intended to indicate general engine status and detect a wide range of engine failures. Special classes of engine failures can be detected earlier by monitoring losses in HPFTP efficiency, losses in HPOTP efficiency, and losses in MCC combustion efficiency. Each of these losses is indirectly observable using the correlations identified in Section 5.3 and are implemented as part of the framework.

This approach is in marked contrast to existing failure detection schemes which rely on definition of anomalies for individual measurements. Since the cutoff decision is based on an engine level parameter, rather than a collection of individual anomalies, confidence that a failure has occurred should be increased. For example, if increases are observed in a set of related measurements (e.g. HPFTP turbine discharge temperature, speed, FPOV position) the confidence that this represents an engine anomaly, and not a collection of spurious sensor indications, is significantly higher than if increases are observed for three "random" measurements. Definition of engine level parameters also allows the HMSRE to detect a wide variety of SSME early failure indications. For example, the first indication of a failure may be a large deviation in only a few measurements or it may be subtle changes in a relatively large number of measurements. Since the HMSRE is not dependent on individual measurement anomalies, a group of subtle changes is just as detectable as a few major deviations, even if some of the measurements never deviate enough to be considered "anomalous". This capability is especially attractive for relatively slow failures in which many measurements generally drift off nominal. Slow failures are of particular interest to this program since early detection of these failures is expected to significantly reduce the ensuing damage. Additionally, since the engine anomaly parameters are determined from contributions of multiple measurements, the system is especially tolerant of failed sensors. This is a critical feature for any SSME failure detection scheme since failed sensors are much more common than other types of engine failures.

Other elements of the framework were defined to support the engine anomaly detection strategy shown in Figure 6-1. Details of this framework are described in three parts below: 1) data acquisition, 2) correlation to engine failures, and 3) normalized measurement deviations.

The framework is easily expanded to include additional sensor inputs and correlated parameters.

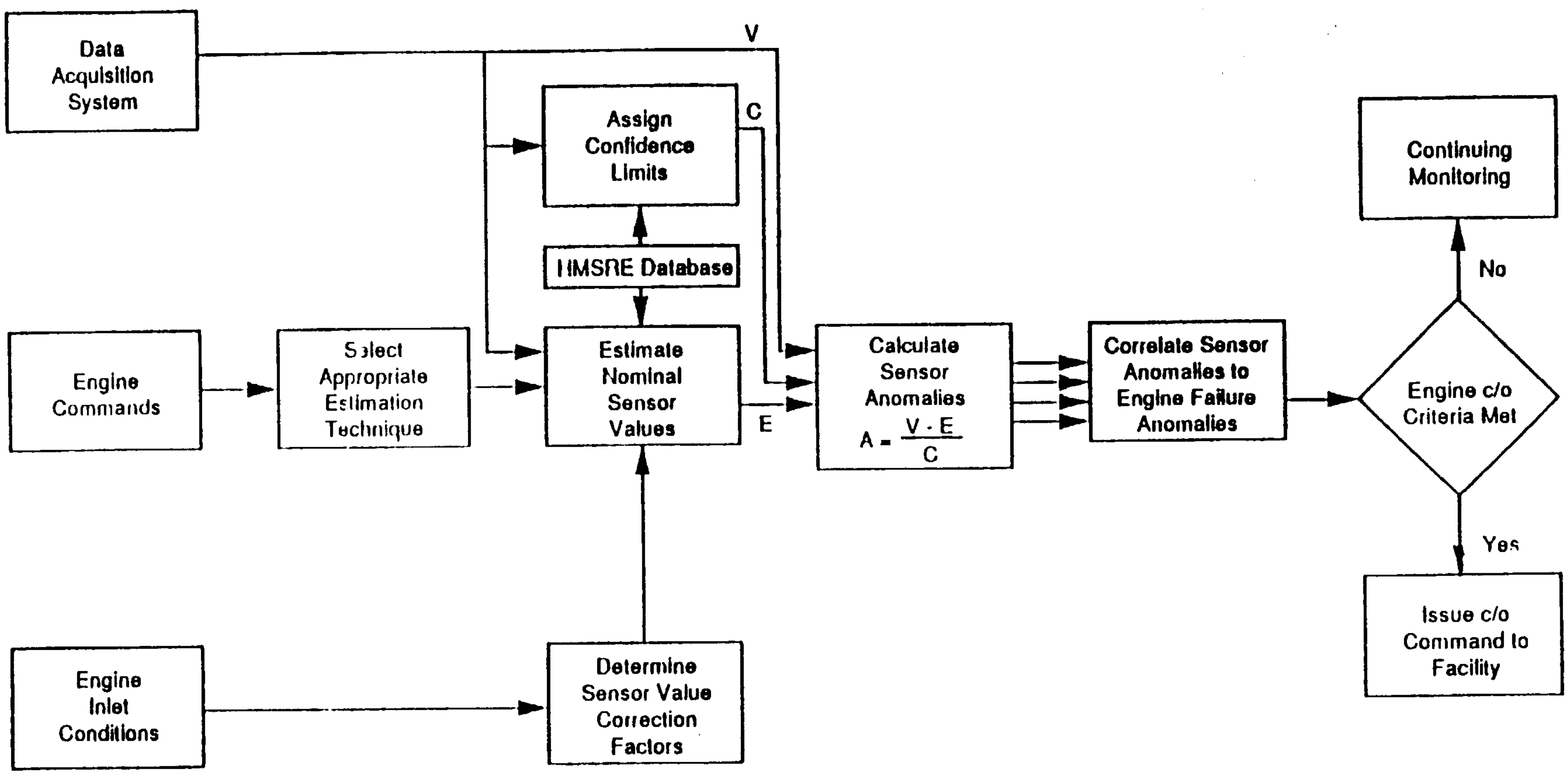


FIGURE 6-1 HMSRE FRAMEWORK OVERVIEW

6.1 DATA AQUISITION

The first step in defining the engine level anomaly strategy for the HMSRE framework was selection of the individual measurements to be monitored and identification of related engine and facility sensors.

A key issue involved in selection of individual measurements is the number monitored. If too few measurements are monitored, the HMSRF system could miss the earliest indications of some failures. If too many measurements are monitored, the robustness and/or sensitivity of the system will be degraded because of the random variations inherent in each of the measurements. Values for correlated parameters would ideally be 0.0 for nominal test cases, but normal variations in individual measurements result in a "background" level for the parameter. As more measurements are monitored, this "background" level is increased. Increasing the "background" level has one of two effects: 1) if the engine anomaly threshold is held constant, the probability of false indications is increased (degraded robustness), or 2) if the threshold is increased to maintain robustness, larger measurement changes are required to indicate an anomaly (degraded sensitivity). Therefore, individual measurements were limited to those with the highest likelihood of early failure indications.

Key selection criteria for the individual measurements were:

1) strong correlation to multiple engine failures
2) early failure indication
3) sensor availability
4) sensor redundancy
5) flight applicability
6) observability

Correlation of measurements to multiple engine failures is determined through Rocketdynes SSME test operations experience and through evaluation of the SSME failure history. A summary of the sensor anomalies recorded for 21 SSME failures is shown in Figure 6-2. As an example, Figure 6-2 indicates that the HPOT Discharge Temperature (seen in 21 of 21 failures) is a better HMSRE candidate than the HPOT Primary Seal Drain Temperature (seen in 2 of 21 failures).

					HPFTP				HPOTP	
TEST	902-249	901-340	901-363	902-118	901-438	901-364	902-209	750-175	901-110	901-136
MEASUREMENT										
HPFP DS T1 A	♦	·	♦	♦	♦	♦	♦	·		
HPFP DS T1 B	♦	♦	·	♦	♦	♦		·		
HPOT DS T1	♦	·	♦	·	♦	·	♦	·	♦	♦
HPOT DS T2	♦	·	♦	·	♦	·	♦	·	♦	♦
FPOV ACT POS	♦	♦	·	♦	♦	♦	♦			
OPOV ACT POS									♦	♦
HPFP SPEED	♦	·	♦	·	·	♦	·	·		
CLNT LNR delta-P		♦	♦	♦	♦	·				
HPFP delta-P		♦	·	♦	♦	♦				
HPOT delta-P		♦	♦	♦	♦	·				
MCC OX INJ PR - MCC PC								·		
MCC CLNT DS T								·		
LPOP DS PR								·		
HPOT PRSL DR T									·	♦
SEC INJ FCPLT delta-P										
HG INJ delta-P										
MCC PC										
PRI INJ FCPLT delta-P										
HPFP DS PR - MCC PC										

			COMB/MAIN INJ						OTHER		
TEST	901-173	901-183	901-331	902-198	750-148	901-225	SF10-01	901-307	901-284	901-485	SF8-01
MEASUREMENT											
HPFP DS T1 A	♦	♦	♦	♦	♦	♦	♦	·	·		♦
HPFP DS T1 B	♦	♦	♦	♦		♦	♦	·			♦
HPOT DS T1	♦	♦	♦	♦	♦	♦	♦	·	·	♦	♦
HPOT DS T2	♦	♦	♦	♦	♦	♦	♦	·		♦	♦
FPOV ACT POS											
OPOV ACT POS							♦	·	·		
HPFP SPEED						♦					
CLNT LNR delta-P								·			
HPFP delta-P	♦		·	♦	·						
HPOT delta-P	·		·	♦	·						
MCC OX INJ PR - MCC PC	·	♦	♦		·	♦		·			
MCC CLNT DS T		♦	♦	♦	♦						
LPOP DS PR	·		♦	·	♦			·	♦		
HPOT PRSL DR T											
SEC INJ FCPLT delta-P	·	·	·	·	·						
HG INJ delta-P	♦	·	♦	·	♦						
MCC PC	·		·	·	·	♦			·		·
PRI INJ FCPLT delta-P	·	·	·	·	·	·					
HPFP DS PR - MCC PC	·	·	·	·	·				·		

FIGURE 6-2 OBSERVED SENSOR INDICATIONS FOR SSME FAILURES

Earliness of failure indications was estimated by Rocketdynes SSME test operations personnel and by evaluation of the SSME failures. Figure 6-3 indicates the time before redline cutoff that each sensor first indicated an anomaly. The data indicates that the turbine discharge temperatures, for example, are among the earliest failure indicators for most of the failures evaluated.

Sensor availability, redundancy, and flight applicability are addressed by emphasizing existing SSME flight and facility measurements (Attachment 10). Additional measurements, such as the plume spectrometer, were individually evaluated by Rocketdynes advanced instrumentation personnel.

Observability of measurements is determined by SSME engine balance model results (shown in Attachment 4), SSME system level evaluation, and the SSME failure history. For example, the direct result of a fuel leak should be a change in the MCC mixture ratio (and temperature) but the SSME control system maintains mixture ratio constant, making this indicator unobservable as shown by the SSME engine balance results for an engine with a fuel leak.

Based on evaluation of these criteria, the following measurements were selected for the HMSRE framework:

1. HPFT Discharge Temperature
2. HPOT Discharge Temperature
3. HPFT Delta Pressure
4. HPOT Delta Pressure
5. MCC Pressure
6. HPFP Speed
7. HPOP Speed
8. FPOV Position
9. OPOV Position
10. HPFTP Vibration
11. HPOTP Vibration
12. Plume Contamination

The measurements selected are mainly existing SSME block-II controller measurements, thereby ensuring that the HMSRE is suitable for flight application. Three measurements that are expected to enhance the overall performance of the HMSRE are not included in the block-II data set: the oxidizer preburner pressure (measured by the facility), the HPOP speed

										A330-03	A340-02									
					B200-17			B200-17		A200-09	A200-09			A340-02		A600-04				
		B400-13			B200-16			B200-16	B200-04	A200-08	A200-08	A200-08	A600-04	A200-08	A200-08	A340-02			A340-02	D110-01
	HPOTP	HPOTP	HPFTP	HPFTP	HPFTP	HPFTP	HPFTP	HPFTP	HPFTP	COMBUST	COMBUST	COMBUST	COMBUST	COMBUST	COMBUST	COMBUST	OTHER	OTHER	OTHER	OTHER
	901-110	901-136	901-340	901-363	901-364	901-436	902-118	902-209	902-249	750-148	901-173	901-189	901-307	901-331	902-198	SF10-01	901-225	901-284	901-485	SF6-01
scndry lcplt dP										0.55	0.48	27.10		0.95	3.00					
primry lcplt dP										0.55	0.48	28.00		0.94	3.00		0.10			
HG Inj. dP										0.58	0.48	28.50		0.94	2.80					
Coolant Liner dP			384.90	165.00	188.20	12.56							20.30							
HPFT dP			118.50	112.70	117.00	0.62	1.34			0.60	0.37			0.85	2.75					
HPOT dP			118.50	114.30	188.20	0.62	1.34			0.63	0.66			0.89	3.00					
MCC ox In. Pr - MCC Pc										0.50	0.10	28.90	28.00	0.84			0.10			
HPFP DS P - MCC Pc										0.80	0.36	27.00		0.89	3.00			6.03		
MCC Pc										0.48	0.48	28.00		0.82	3.00		0.14	6.03		0.12
MCC clnt DS T										0.52		28.50		0.86						
HPFP speed			118.50	114.50	7.20	0.47	0.19	203.10	130.60								0.05			
HPFT DS T1 A			384.00	185.00	7.20	0.51	1.84	203.00	130.60	0.58	0.36	28.00	14.00	0.84	2.90	5.15	0.10	6.01		0.08
HPFT DS T1 B			384.00	113.60	7.20	0.51	1.84	bad sens	130.60	bad sens	0.36	28.00	44.00	0.84	2.90	5.15	0.10			0.08
HPOT DS T1	16.30	25.00	124.90	113.30	184.20	0.16	1.34	203.10	75.50	0.46	0.36	28.00	28.00	0.75	3.00	5.20	0.08	5.88	0.06	0.08
HPOT DS T2	16.30	28.00	123.00	112.60	184.20	0.11	1.34	203.00	75.50	0.46	0.36	28.00	28.00	0.74	3.00	5.20	0.08		0.06	0.08
LPOP DS P										0.60	0.36		31.00	0.88	2.84			5.76		
OPOV act pos	18.50	28.00											37.00			5.20		6.03		
FPOV act pos			120.50	113.80	182.20	0.51	0.72	202.00	101.00											
HPOT prel dr T	17.80	14.00																		

Note: values = seconds before redline cutoff

FIGURE 6-3 SSME FAILURE HISTORY - EARLY INDICATIONS (obtained from the synchronous vibration indicated by HPOTP accelerometers), and plume contaminants (new measurement).

The majority of selected measurements are turbopump measurements. This was a natural consequence of the selection process (which heavily weighted proven observability) since other failure indications tend to be obscured by the SSME closed loop control system. Therefore, the observable failure indications are those that reflect the control system response to a degraded engine, forcing one or both turbopumps to operate at off nominal values. An exception to this rule is the MCC Pressure, whose value is actively controlled by the SSME block-II controller. Observed changes in this parameter would indicate serious problems with the engine or a loss of control functionality.

The HMSRE measurement set is completed by the inclusion of several parameters known to indicate failures that might not effect the performance parameters. Turbopump vibration (in a narrow band centered around the pump synchronous frequencies) is included based on the utility of these measurements shown in Section 5.10. Plume monitoring has less of a historical basis but has the potential for earlier indications of several failure modes (Section 5.5.1) including combustion device failures which provide little or no early warning in SSME performance measurements.

Figure 6-4 shows the source of data for each of the individual measurements and summarizes the data acquisition part of the framework. Table 6.1 indicates the available redundancy for each of the measurements selected.

6.2 CORRELATION TO ENGINE FAILURES

Individual measurements are correlated to engine failures through the definition of engine anomaly parameters as described earlier. Since only the differences in these parameters are used to indicate failures, the deviations of individual measurements, rather than their absolute values, are used to estimate changes in the correlated parameters. The individual measurements are normalized to reflect confidence in the measured deviations.

The method for correlating individual measurements to engine parameters is shown in Figure 6-5. Each normalized measurement is weighted. The sum of the weighted measurements provides estimates of engine anomaly

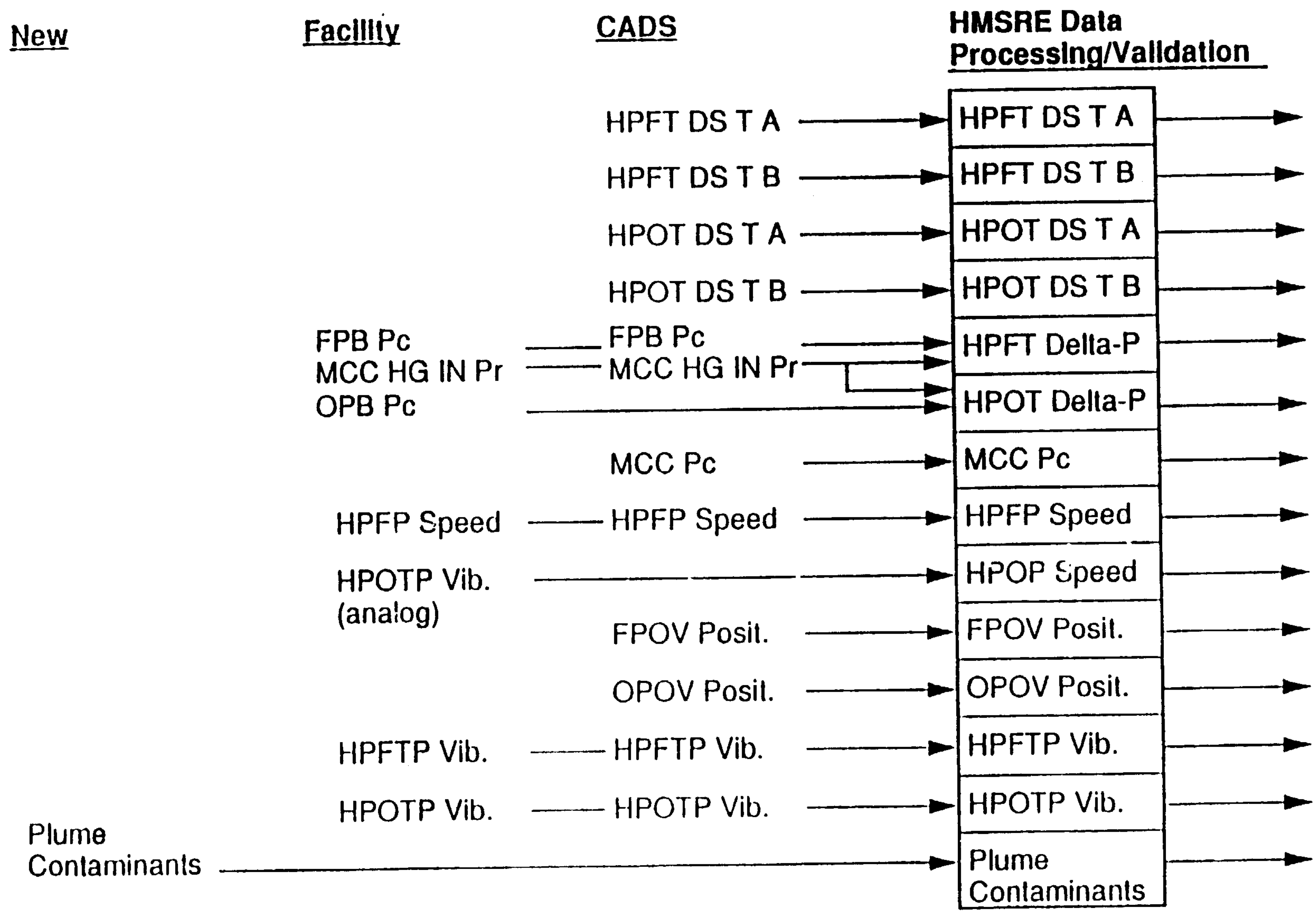


FIGURE 6-4 HMSRE DATA AQUISITION SYSTEM

TABLE 6.1 HMSRE BASELINE MEASUREMENTS

Measurement	Calc.	Blk - II	CADS	Facil.	New
HPFT DS Tmp		2R	2R	--	
HPOT DS Tmp		2R	2R	--	
HPFT dP	X				
FPB Pc		S	S	s	
MCC HG Inlet Pr		S	S	S	
HPOT dP	X				
OPB Pc		--	--	S	
MCC HG Inlet Pr		S	S	S	
MCC Pc		2R	2R	--	
HPFP Speed		S(2)	S(2)	s	
HPOP Speed	X				
HPOP Rad. Accel.		3R*	3R*	7R(a)	
FPOV Position		S(2)	S	--	
OPOV Position		S(2)	S	--	
HPFTP Vibration		3R	3R	9R(a)	
HPOTP Vibration		3R	3R	10R(a)	
Plume Contaminants		--	--	--	S

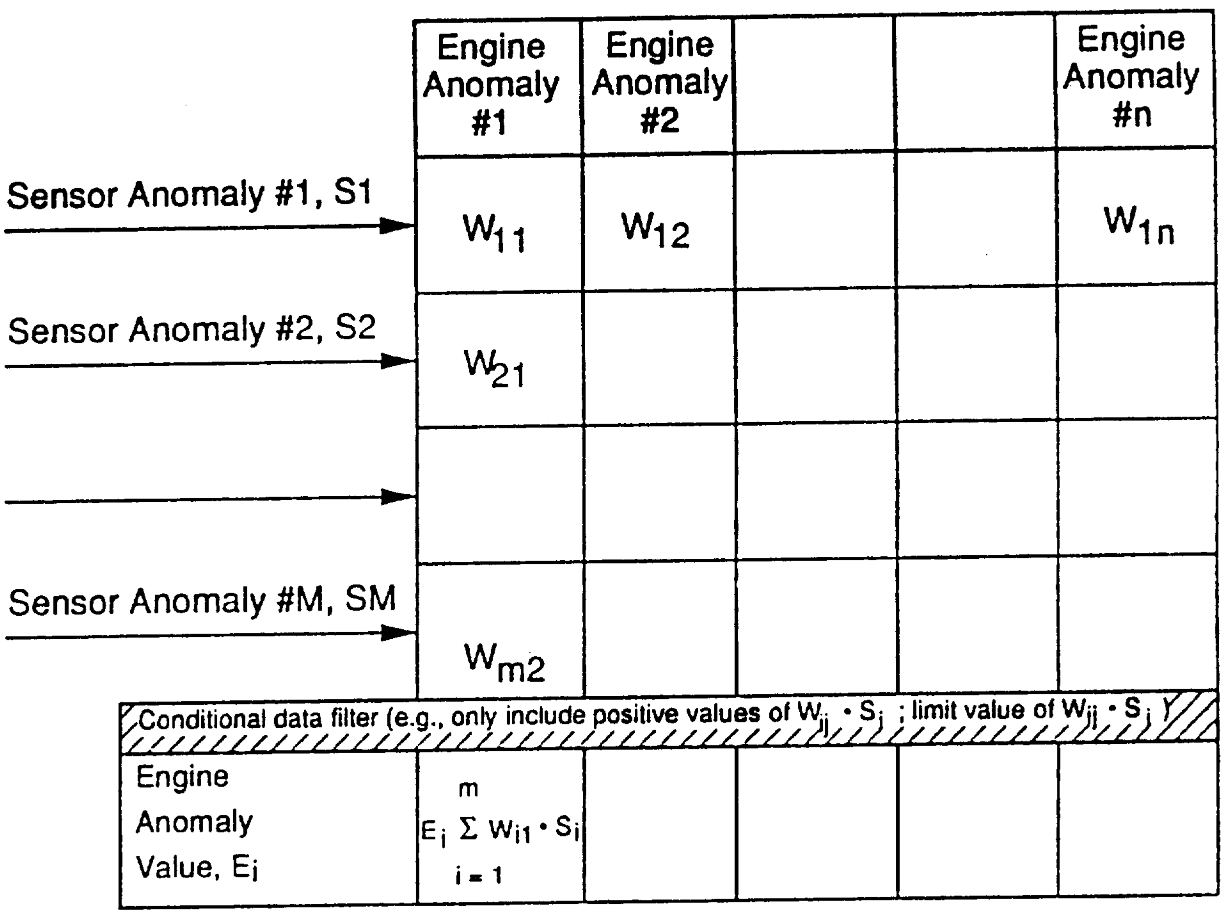


FIGURE 6-5 ENGINE ANOMALY CORRELATION STRATEGY

parameters. A cutoff threshold, above the noise level observed for nominal tests, is set for each parameter. The engine would be sent a cutoff command if any of these thresholds is exceeded. Each measurement is normalized to indicate the number of confidence limits (a limit related to the confidence in the measured deviation - Section 6.3) the measured value deviates from an estimated nominal value. Correlated parameters are defined to be the weighted sum of some or all of these normalized measurements.

The basic failure indicator is a general anomaly parameter defined to indicate overall engine status. The baseline correlation for this parameter is a simple sum of all normalized measurements. This parameter is sensitive to any failures causing deviations in one or more HMSRE measurements. For example, if all the weighting factors are set to 1.0, a correlated value of 5 would indicate that: 1) one sensor is off nominal by 5 times the confidence limit set for that parameter, 2) five sensors are each off nominal by 1 times the confidence limit, or 3) some other combination of sensor values are resulting in a combined off nominal value of 5. In other words, the correlation strategy indicates a level of confidence that an engine failure is occurring. The confidence can be increased by a few individual indicators reading far from nominal, or by many indicators simultaneously drifting off nominal by a lesser amount. This parameter is expected to detect most SSME failures and evaluation of the SSME failure history indicates that 18 of 22 past failures would have been detected by this parameter.

Three additional correlation parameters, especially sensitive to the classes of failures indicated, are included in the baseline HMSRE framework: Loss of HPOTP efficiency, Loss of HPFTP efficiency, and Loss of MCC combustion efficiency. These parameters have a lower noise level than the general anomaly parameter since only specific measurement deviations are included in the weighted sum. This enables a lower threshold and corresponding earlier cutoff.

A preliminary set of weighting factors for these special cases can be determined using the SSME engine balance model. The model was run for each special case. The results are included as Attachment 4 and are summarized in Table 6-2. Table 6-2 indicates the direction and percent change observed for each of the HMSRE parameters. As an example, the Loss of HPFTP Efficiency set of weighting factors are qualitatively shown in Figure 6-6. MCC Pc, OPOV position, and HPOP speed have weighting factors of 0 since very little relative change is expected for these parameters. The anomalies observed for three SSME failures that resulted

TABLE 6.2 NORMALIZED DEVIATIONS FOR FAILURE CORRELATIONS

Engine Parameters	Loss of Combustion Efficiency	Loss of HPOP Efficiency	Loss of HPFP Efficiency
HPFT DS T	-0.20	=0.18	+0.79
HPOT DS T	+1.00	+0.91	-0.53
HPFT Delta P	+0.10	+0.09	+0.68
HPOT Delta p	+0.65	+0.59	+0.21
HPFP-N	+0.10	+0.09	+0.21
HPOP-N	+0.60	+0.00	-0.00
FPOV	-0.50	+0.09	+1.00
OPOV	+0.30	+1.00	-.05
MCC Pc	0.00	0.00	0.00

		Loss of HPFP Efficiency Correlated Anomalies	Test 901-364			Test 902-249			Test 901-410	
			t-185	t-117	t-7	t-130	t-101	t-76	c/o - 490	c/o - 345
HPFT DS T	A	+			+	+			+	
	B				+	+			-	
HPOT DS T	A	-	-					+	-	
	B		-					+	-	+
HPFT Delta-P		+		+						
HPOT Delta-P		+	-							
HPFP-N		+			+	+			+	
HPOP-N										
FPOV		+	+				+			+
OPOV										

901-364: HPFTP turbine end bearings heated by hot gas, eventual failure, loss of engine

902-249: Engine fuel inlet temperature increases causing HPOP cavitation, HPFTP damage occurs, particles rupture nozzle tubes @ T-76, eventual failure, major engine damage

901-410: Test completed (595 seconds), post test inspection indicated turbine damage

FIGURE 6-6 RELATIONSHIP BETWEEN ANALYTICAL CORRELATION FACTORS AND OBSERVED ANOMALIES in a loss of HPFTP efficiency are also shown and correlate well with the expected parameter indications.

6.3 NORMALIZED MEASUREMENT DEVIATIONS

The approach used to normalize individual measurement deviations is shown by Figure 6-7. For each measurement, an expected nominal value is defined. The difference between the actual measurement and the nominal value indicates the magnitude and direction of measured deviations. The normalized value is defined by dividing the difference between measured and nominal values by the associated confidence limit.

Using the approach outlined above, normalizing measurement deviations is reduced to a two part problem: 1) definition of a nominal value, and 2) definition of a confidence level.

Based on the evaluation of detection techniques, three approaches were selected to estimate the nominal value of each measurement: 1) fleetwide operating envelopes, 2) steady state initial values, and 3) power dependent values. Each technique is applicable to a different part of the SSME operating profile and regions of applicability are shown in Figure 6-8. During transients and the initial seconds of the first steady state, fleetwide operational envelopes provide the most useful estimate of nominal measurements (Section 5.8). The first few seconds of subsequent steady states are more accurately estimated by predicting the value based on the values measured during the initial steady state and the scheduled power change (Section 5.9). During the first few seconds of steady state operation, an average is taken and serves as an accurate estimate for the remainder of steady state (Section 5.2). Details about each of these estimation techniques can be found in the referenced sections.

The second requirement is definition of confidence limits. The confidence limit can be thought of as the limit beyond which an engine expert would say that a particular measurement is indicating an anomaly. Therefore, a normalized value of 1.5 would correspond to a high degree of confidence that a measured deviation is significant. On the other hand, a value of 0.5 would indicate only that the measured deviation could be an indication that an engine level parameter is changing.. The confidence limits are different for each parameter and are expected to change during transients. However, the confidence limits are defined such that the numerical values of the anomaly indications are always consistent (i.e. value=1.0 indicates

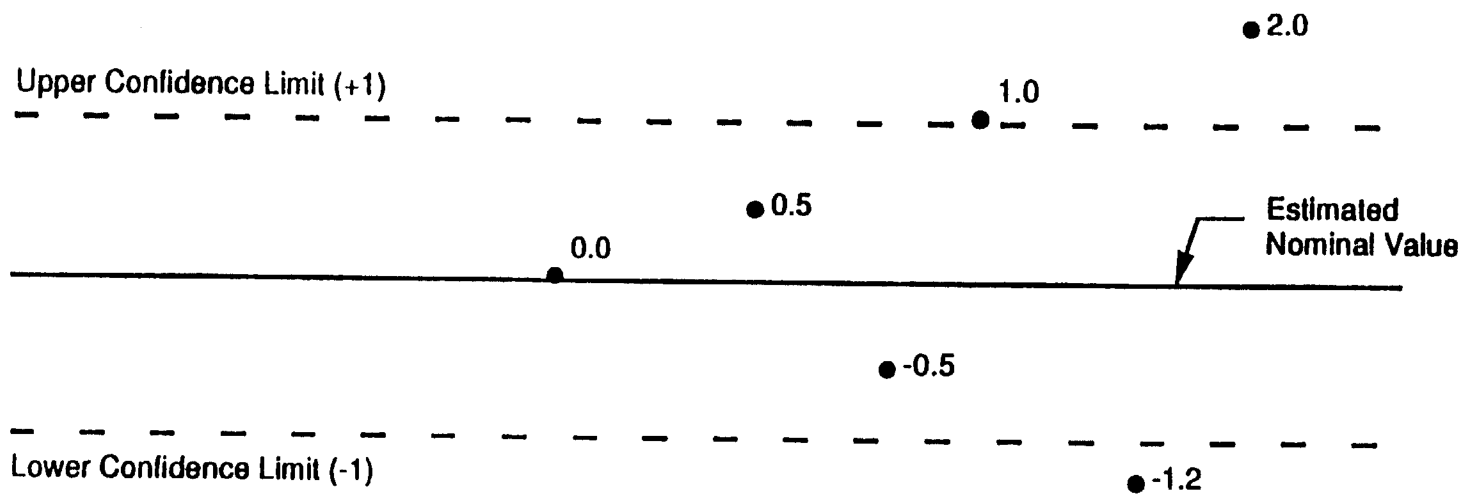
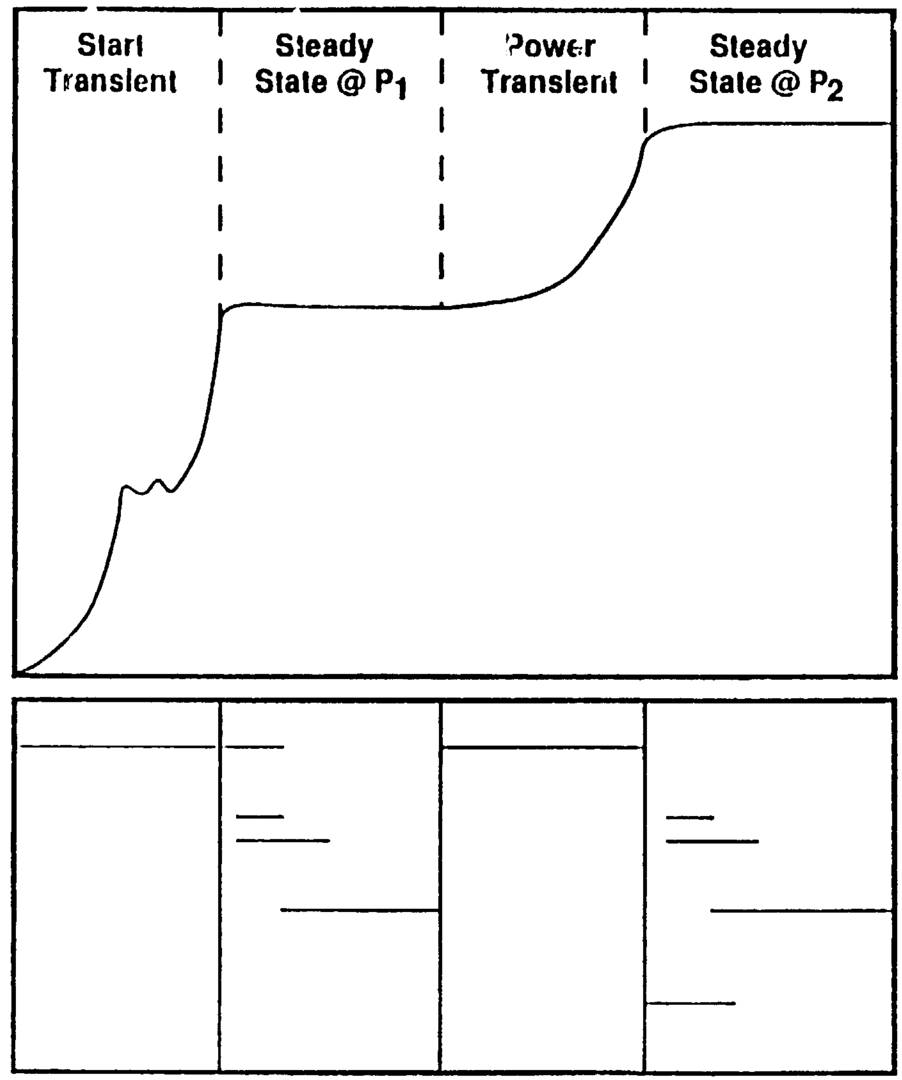


FIGURE 6-7 NORMALIZED MEASUREMENT DEVIATION APPROACH



- Fleetwide nominal envelope
- Determine steady-state value, SS_I
- Estimate = Initial steady state value
- Estimate = power level dependent, $F(\Delta P_C, SS_I)$

FIGURE 6-8 NOMINAL VALUE ESTIMATION SCHEDULE that a deviation is significant). Quantification of the confidence limits will require a thorough sensitivity study based on SSME test histories and models.

6.4 FRAMEWORK CONCLUSIONS

The framework described in this section is composed of well established failure detection elements, applicable to SSME failures, and compatible with implementation in SAFD hardware currently under development (see Attachment 11). This represents a low risk, high payoff strategy for near term implementation.

The framework represents a system that is compatible with the Block-II controller and is easily extended to flight applications. It is sensitive to a wide variety of failure indications, provides early indications of engine failures, is tolerant to sensor failures, and allows a high degree of confidence in engine cutoff commands.

7.0 - EFFECTIVENESS EVALUATION

A measure of the HMSRE effectiveness is obtained by comparing key framework characteristics with those of a baseline detection system, in this case the SAFD system. The effectiveness of the HMSRE framework is evaluated based on four criteria important to rocket engine failure detection systems: l) Failure Coverage, 2) Engine Phase Coverage, 3) Earliness of Indication, and 4) Degradation Due to Sensor Failures. A summary of the effectiveness evaluation is shown in Table 7.1.

Failure Coverage

The failure coverage of the HMSRE was characterized by two different methods: evaluation of 28 SSME incident tests and determination of detectable failure modes.

Twenty eight SSME incident tests were identified and summarized in the SAFD phase II report. The tests covered a wide variety of engine failures and are assumed to be representative of SSME failure indications. These tests were used to estimate the failure coverage of both the SAFD system and the HMSRE framework. For each of the tests listed in Table 7.2, The maximum number of sensors indicating an anomaly was determined to characterize the SAFD system and the maximum value of the HMSRE basic algorithm was calculated to characterize the HMSRE framework.

Of the 28 tests, 4 lasted the program duration and resulted in only minor damage to the engine. These tests are assumed to be near (but slightly below) the threshold of damage sufficient to warrant engine shutdown. Therefore, of the 28 incident tests, 24 required cutoff and 4 did not.

To estimate the cutoff criteria for the HMSRE framework, the incident test data was graphically represented in Figure 7-1. For each test, the maximum HMSRE basic algorithm value is plotted along the Y-direction. The four program duration, minor damage tests (assumed not to warrant engine cutoff) are represented by empty boxes. Based on these data, a HMSRE cutoff threshold of 6.0 was selected for evaluation purposes.

Using a threshold of 6.0, 19 (of 24) tests would have been cutoff early - a demonstrated failure coverage of 79%. Equally important, none of the program duration, minor damage tests would have been cutoff. The failure coverage demonstrated for the HMSRE is comparable to that expected with SAFD (18 of 24 tests cutoff).

TABLE 7.1 HMSRE EFFECTIVENESS SUMMARY

	SAFD	HMSRE
Failure Coverage (based on 28 incident tests)		
Number of tests correctly c/o early:	18/24 (75%)	19/24 (79%)
Number of tests erroneously c/o early:	0/4	0/4
Failure Coverage (based on ranked failure modes)	n/a	55%
Engine Phase Coverage		
Start Transient	no	yes
Steady State	yes	yes
Power Transient	no	yes
Cutoff Transient	no	no
Earliness of Indication (time before Redline c/o)		
Test 901-307	20.0	31.5
Test 902-198	3.1	3.4
Test 902-249	61	121
Degradation due to sensor failure	slight	slight

TABLE 7.2 SSME TEST HISTORY SUMMARY

TEST NUMBER	MAXIMUM SAFD ANOMALIES	MAXIMUM HMSRE MAGNITUDE (est *)	MINOR DAMAGE	PROGRAM DURATION
SF6-01	5	56.2		
SF10-01	5	14.0		
750-148	12	69.1		
750-175	8	133.4		
750-259	12	103.9		
901-110	1	2.2		
901-136	2	4.9		
901-173	11	25.0		
901-183	2	2.2	•	
901-225	8	46.4		
901-284	6	126.2		
901-307	7	9.6		
901-331	13	66.8		
901-340	9	22.2		
901-346	6	11.1		•
901-362	1	5.1	•	•
901-363	2	5.2	•	•
901-364	7	18.3		
901-410	3	9.8		•
901-436	8	52.1		
901-485	2	4.6	•	•
902-095	0	0.0		
902-112	7	60.6		
902-118	8	24.9		
902-120	1	2.6		
902-198	12	82.4	•	
902-209	1	2.9	•	•
902-249	6	27.4		

* estimated using SAFD sigma values and all sensor weights = 1.0

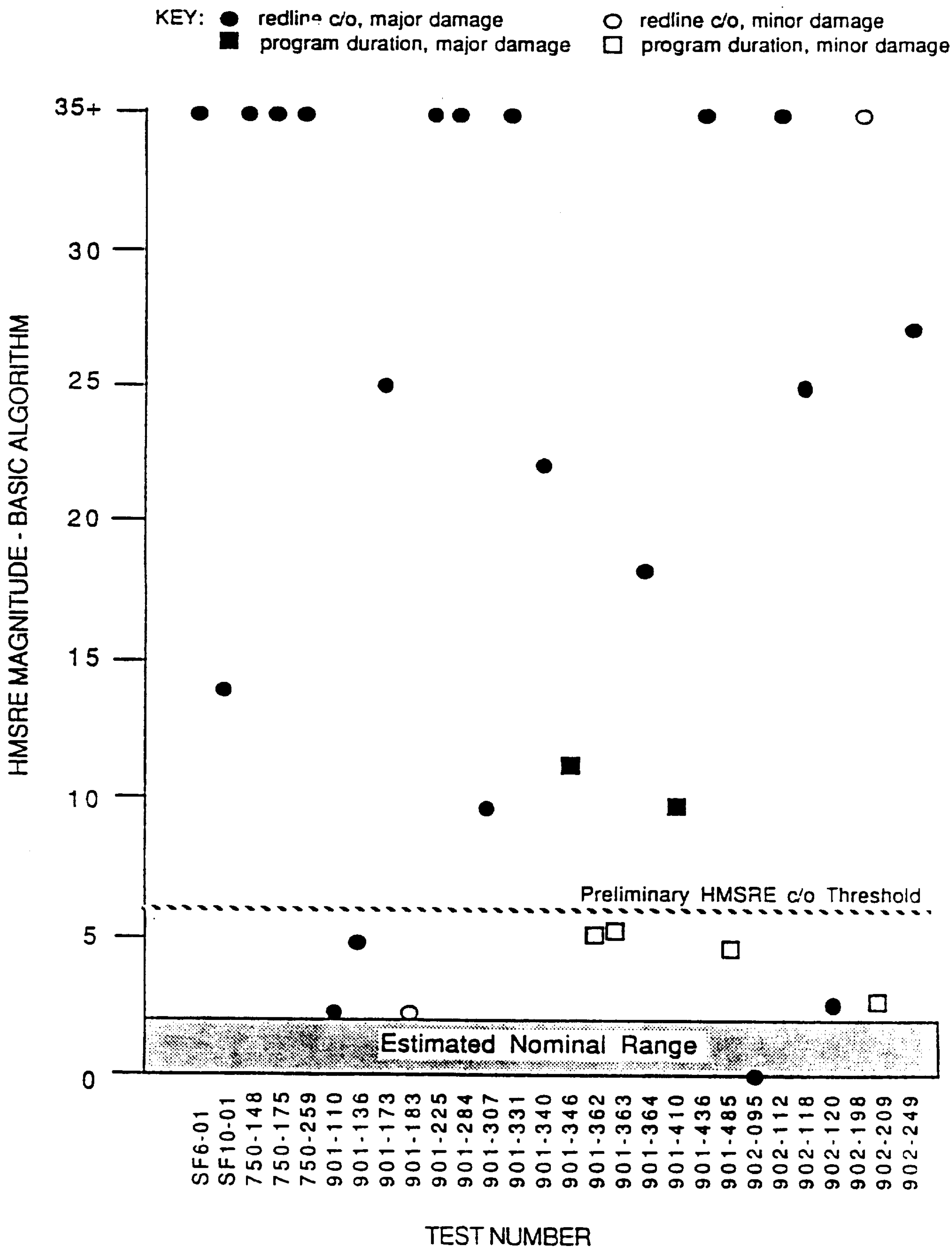


FIGURE 7-1 PRELIMINARY HMSRE SENSITIVITY STUDY

The false alarm rate is expected to be low since the cutoff is 3 times the nominal value and even tests indicating some minor damage remain below the threshold.

Evaluation of the incident tests indicate good failure coverage and a high degree of failure detection robustness.

The second method used to estimate the failure coverage was to identify failure modes among the 45 most likely to occur (according to the Task 1 ranking) detectable by the HMSRE framework. Detectability was assumed for failure modes expected to affect at least two different HMSRE measurements (i.e. HPOT discharge temperature A & B count as 1 measurement). The percentage of failure modes detectable with the HMSRE was estimated by using the figure of merit values as rough estimates for the relative likelihood of each failure mode occurring. This approach indicates that about 55% of all criticality 1 engine failures should be detectable. The assumptions and approximations used in the above failure coverage assessment reflect the tendency towards detectability for each failure mode.

Engine Phase Coverage

The HMSRE framework addresses all phases of engine operations (start transient, mainstage steady state, power transients) except the cutoff phase.

Earliness of Indication

The earliness of failure indication is approximated by evaluating three specific test cases: 901-307, 902-198, and 902-249. The results of these evaluations are shown in Figures 7-2, 7-3, and 7-4. A comparison of cutoff times is shown in Figure 7-5. The HMSRE could have provided an earlier cutoff, as compared to SAFD or Redlines, in all cases.

For test 902-198, the small amount of time gained by using the HMSRE (0.3 sec) probably would not significantly reduce the engine damage as compared to SAFD cutoff.

Test 901-307 shows the HMSRE cutoff 11.5 seconds before the SAFD cutoff. It is likely that significant engine damage occurred during this time interval.

Test 902-249 shows the HMSRE cutoff at t=330 and the SAFD cutoff at t=390 . Examination of the test summary indicates that the engine was slowly degrading until a rub ring failed at t=374. Following failure of this ring, the engine degradation accelerated and spread to other components. Therefore, significant engine damage clearly could have been avoided if the engine were cutoff at the HMSRE threshold.

Degradation Due to Sensor Failure

Insensitivity to sensor failures is crucial to a rocket engine failure detection system. Sensors fail at a much higher rate than any other engine component and a detection system dependent on any single sensor is likely to find itself "blind" when that sensor fails. The HMSRE estimates anomalies and degraded conditions based on the influences of 14 individual measurements. Therefore, the loss of any sensor (or several sensors) slightly degrades the overall failure indication but does not preclude detection.

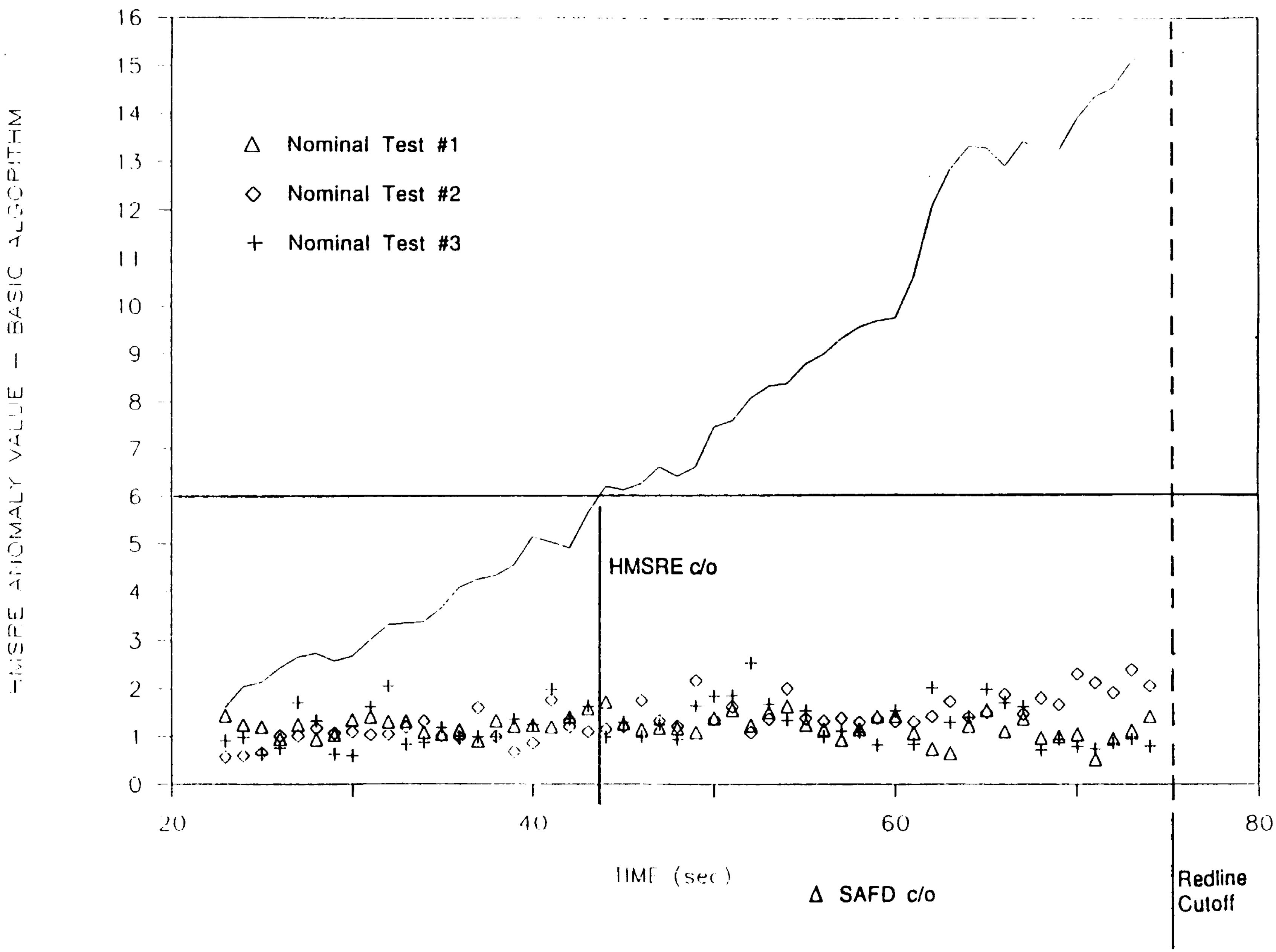


FIGURE 7-2 HMSRE EFFECTIVENESS - TEST 901-307

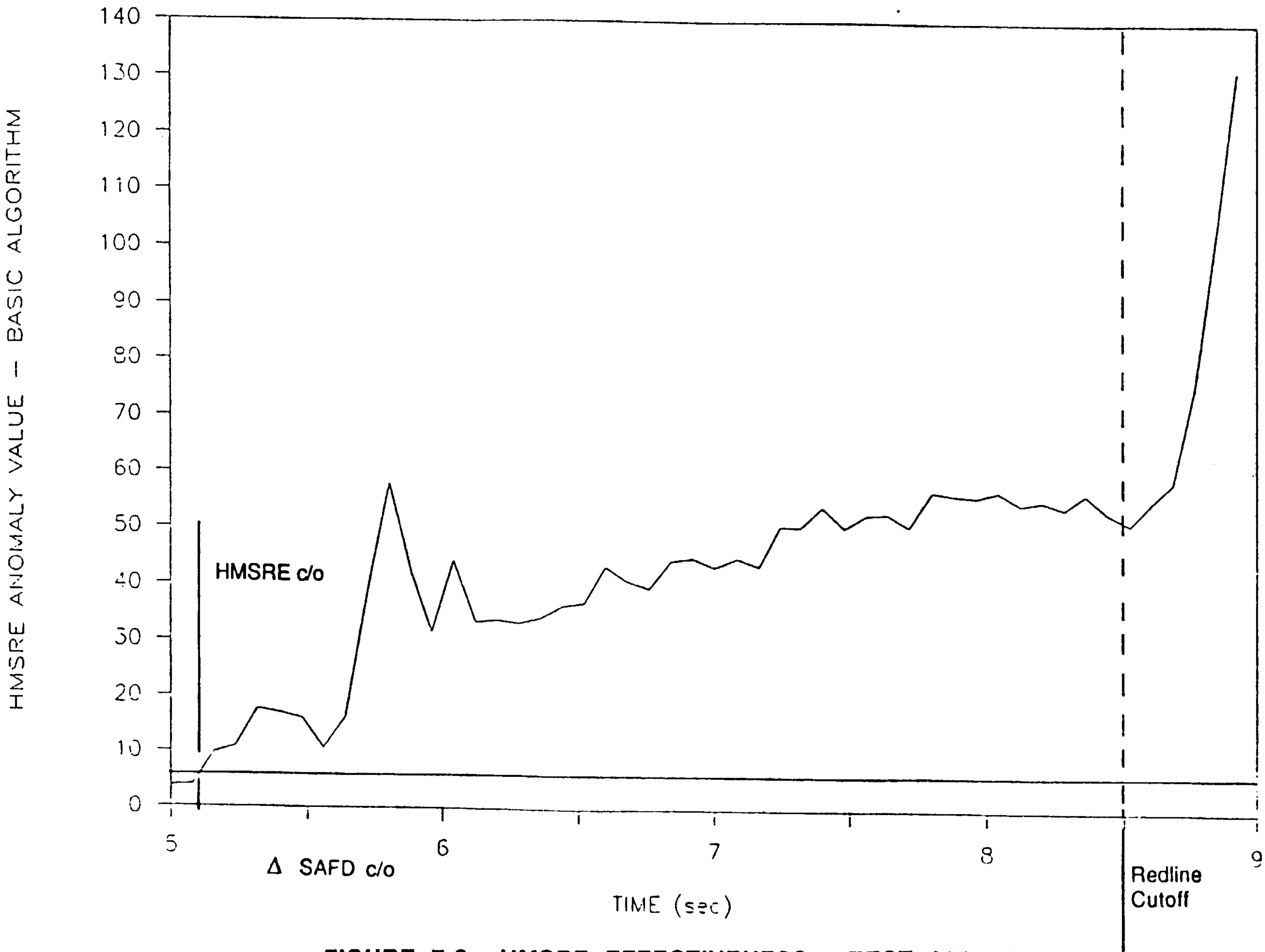


FIGURE 7-3 HMSRE EFFECTIVENESS - TEST 902-198

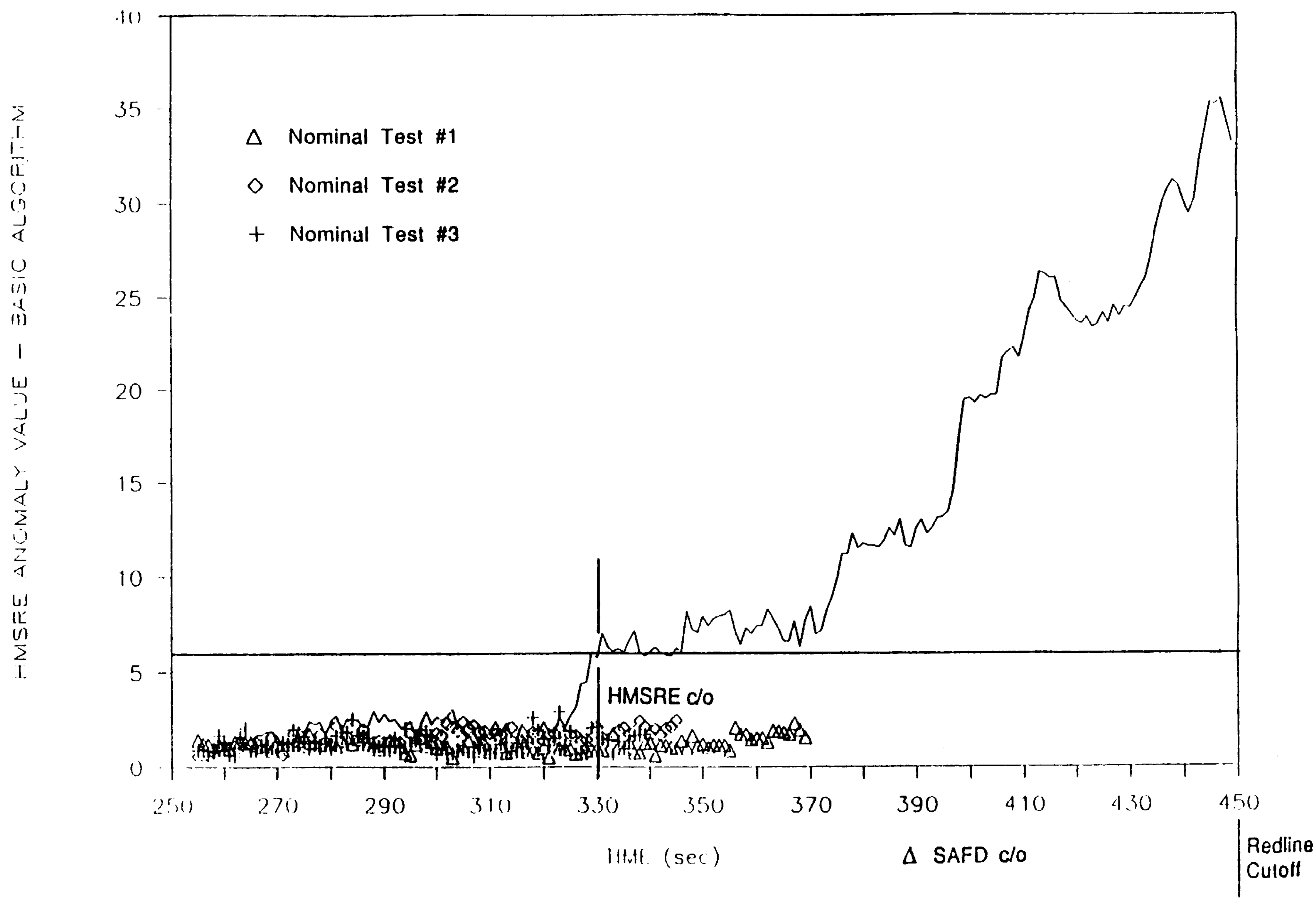


FIGURE 7-4 HMSRE EFFECTIVENESS - TEST 902-249

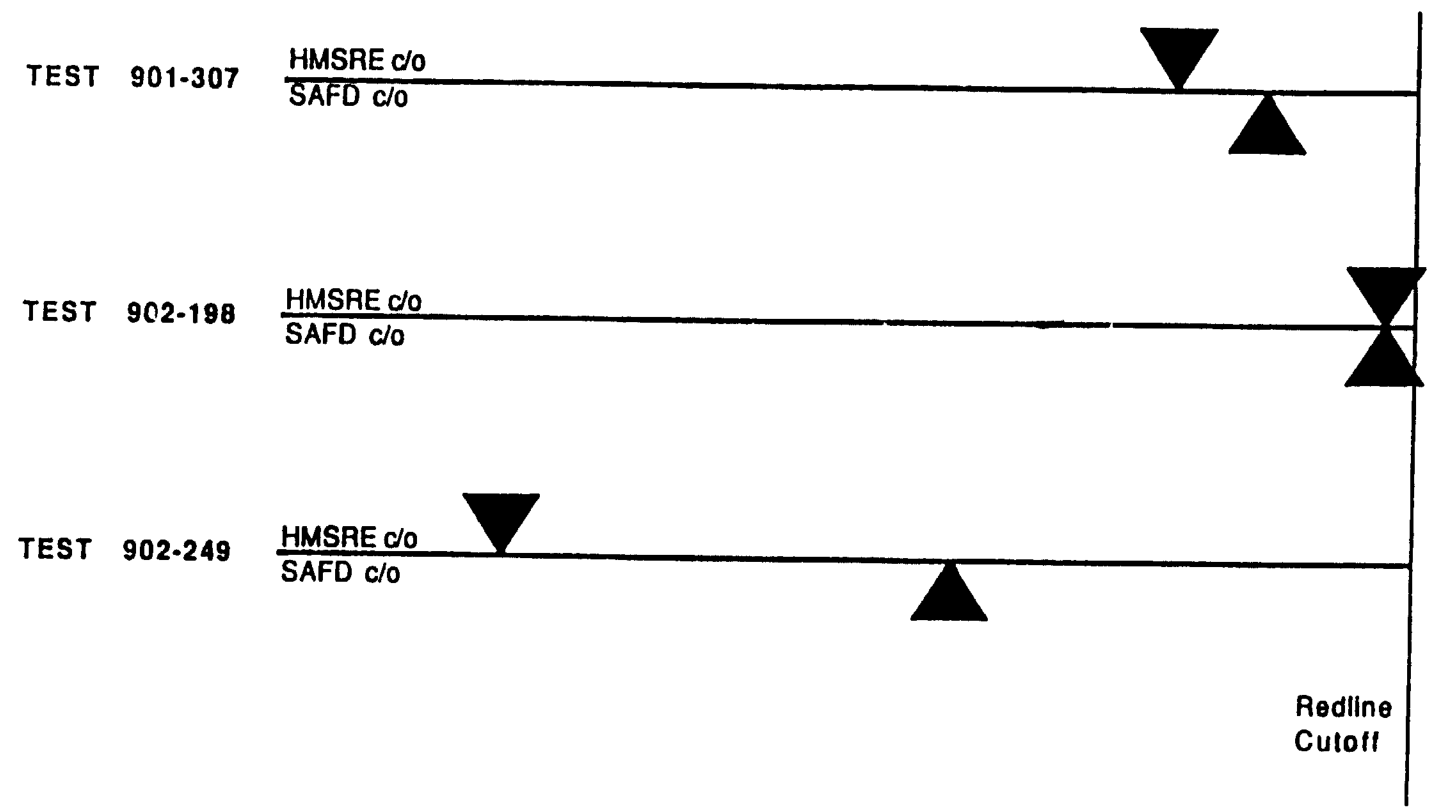


FIGURE 7-5 COMPARISON OF HMSRE AND SAFD CUTOFF TIMES

SECTION 8 - BREADBOARD IMPLEMENTATION PLAN

A 24 month program is recommended for the implementation of a breadboard version of the HMSRE. This will provide an HMSRE ready for use in conjunction with a Space Shuttle Main Engine (SSME) when it is being "hot-fired" on a test stand. It is expected that the HMSRE will provide additional protection to the engine during test firing thereby providing a higher probability of engine and/or major component survival.

This plan provides an overview of how to accomplish the required work. It includes a program logic diagram, a program WBS chart, a program time schedule, a program manloading figure and an implementation plan narrative. This narrative includes estimated manloading, required test facilities, overall plans for testing and a technology program to fill near term technology voids.

8.1 PROGRAM LOGIC

The technical logic flow for the program (Figure 8-1) describes the task sequence and interrelationships for the planned work. Information flow and review points are indicated. This provides a pictorial description of the flow of work that complements the more structured WBS and schedule charts.

Rocketdyne plans to base the HMSRE breadboard implementation in software development and validation efforts, ultimately for implementation on the Space Shuttle Main Engine (SSME) Technology Test Bed (TTBE). The breadboard implementation of the HMSRE will be on computer/workstation hardware which is available at Rocketdyne. The program is divided into three sequential software development and test related tasks, and a parallel technology task.

In Task 1 (Preliminary System Definition), preliminary algorithms for correlating failure data from multiple sensor streams are developed. Nominal value estimation techniques will be defined, and a preliminary database of engine test information which will be used for HMSRE testing will be established. Preliminary confidence limits and weighting factors will be established, and the preliminary algorithms will be coded, with a preliminary system testing period which overlaps the algorithm coding effort to ensure that the HMSRE works successfully in a preliminary state prior to the system development task. The output of this task will be a set of runs (approximately 12) which indicate the length of time before

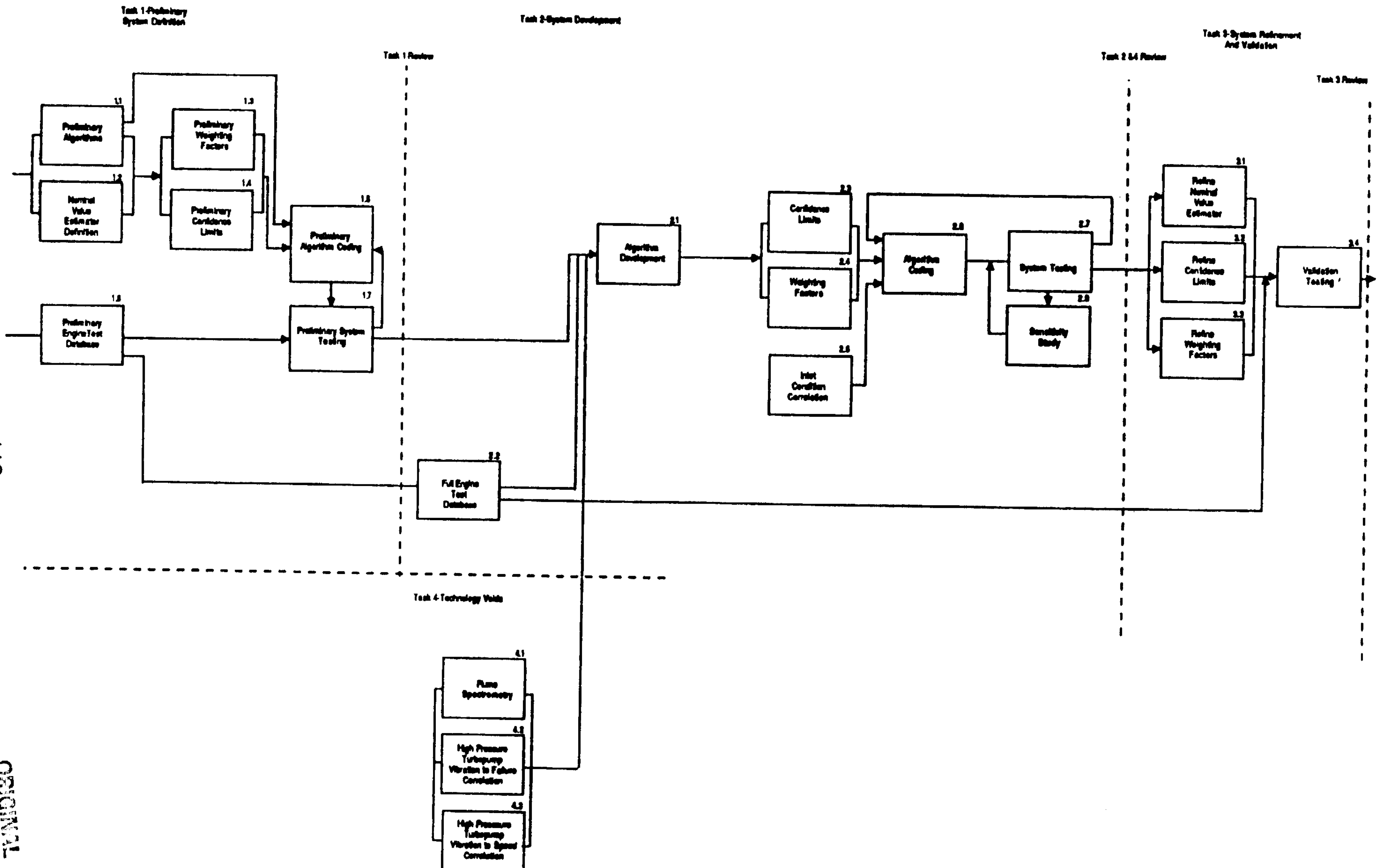


FIGURE 8-1 PROGRAM LOGIC

redline cutoff which the HMSRE would signal for engine shutdown. These results will be presented at LeRC as part of the Task 1 review.

System Development (Task 2), will produce a comprehensive HMSRE, with a full complement of engine test data for HMSRE testing and a full set of algorithms. This task starts with algorithm and full engine test database development. Confidence limits and weighting factors will be defined and implemented in the HMSRE algorithms. Inlet condition correlation techniques will be established and then the algorithms will be coded. The HMSRE will be tested and a sensitivity study will be conducted in parallel with this testing. The hardware for Task 2 activities will be a computer/workstation at the Rocketdyne Canoga Park facility. The system development efforts are expected to incorporate coding techniques which will facilitate code debugging and prove HMSRE functionality. A Task 2 review will be held at LeRC at the conclusion of Task 2.

Task 3, System Refinement and Validation will focus on adding fidelity to the HMSRE through the refinement of the nominal value estimator, confidence limits and weighting factors. Additionally the HMSRE code will be "stripped" of software development "hooks" and messages, to increase speed. At this stage, the HMSRE can be installed on the SAFD development hardware at Rocketdyne's Canoga facility. By this means, any bugs in the system can be worked out on hardware which is configured to behave like the TTBE implementation hardware. Validation testing will be conducted at Rocketdyne and utilize the full engine test database. Successful SSME test data will be used to test for erroneous cutoff. Anomalous test data will be used to "trigger" the HMSRE, and engine simulations will be used to test HMSRE on failure modes that have not occurred or have not been recorded. The HMSRE can then be installed on the SAFD hardware at the TTBE facility. Here it is planned to first implement the HMSRE as a warning device to the test operator where a noise and/or visual indication would be used to quickly signal pending mishaps. Subsequently the HMSRE will be wired to the engine shutdown interface to initiate TTBE shutdown as required.

Three technology voids (elements expected to enhance the overall HMSRE effectiveness but not currently available for the SSME) will be addressed in Task 4. None of these efforts represent major challenges, and development should be low risk. The areas addressed are plume spectrometry failure correlation, Turbopump narrow-band vibration failure correlation, and oxidizer turbopump vibration to speed calculations.

8.1.1 Work Breakdown Structure

The program WBS chart (Figure 8-2) defines work elements to the third level. For the technical tasks (Tasks 1 through 4), subtasks are described. The WBS provides a structured means for allocating program resources, closely monitoring the performance of technical work, and controlling the program expenditures.

8.1.2 Program Schedule

The program schedule is shown in Figure 8-3. Time phasing of the elements to the third (subtask) level, and subtask completion dates are shown. Task timeline allocations are made based on task activities within the 24 month period. The Task 1, (Preliminary System Definition) technical effort will be performed in the first six months and Task 2 (System Development) will start in the seventh month and continue for fourteen months. Task 3 (System Refinement and Validation)will be initiated at the beginning of the twenty-first month with a duration of four months. Task 4 (Technology Voids) will start in the seventh month and continue through the thirteenth month.

Figure 8-4 summarizes the Rocketdyne program manpower loading for the technical effort, and is the basis for cost estimating.

8.2 ESTIMATED MANLOADING

The estimated HMSRE implementation cost is based on a preliminary work breakdown structure (WBS), combined with a preliminary schedule. Hours and durations for each WBS element have been estimated by a team consisting of the current principal investigator, the project manager and functional managers presiding over supporting personnel. The estimate is based on experience on similar programs/ tasks and takes advantage of applicable past and parallel efforts.

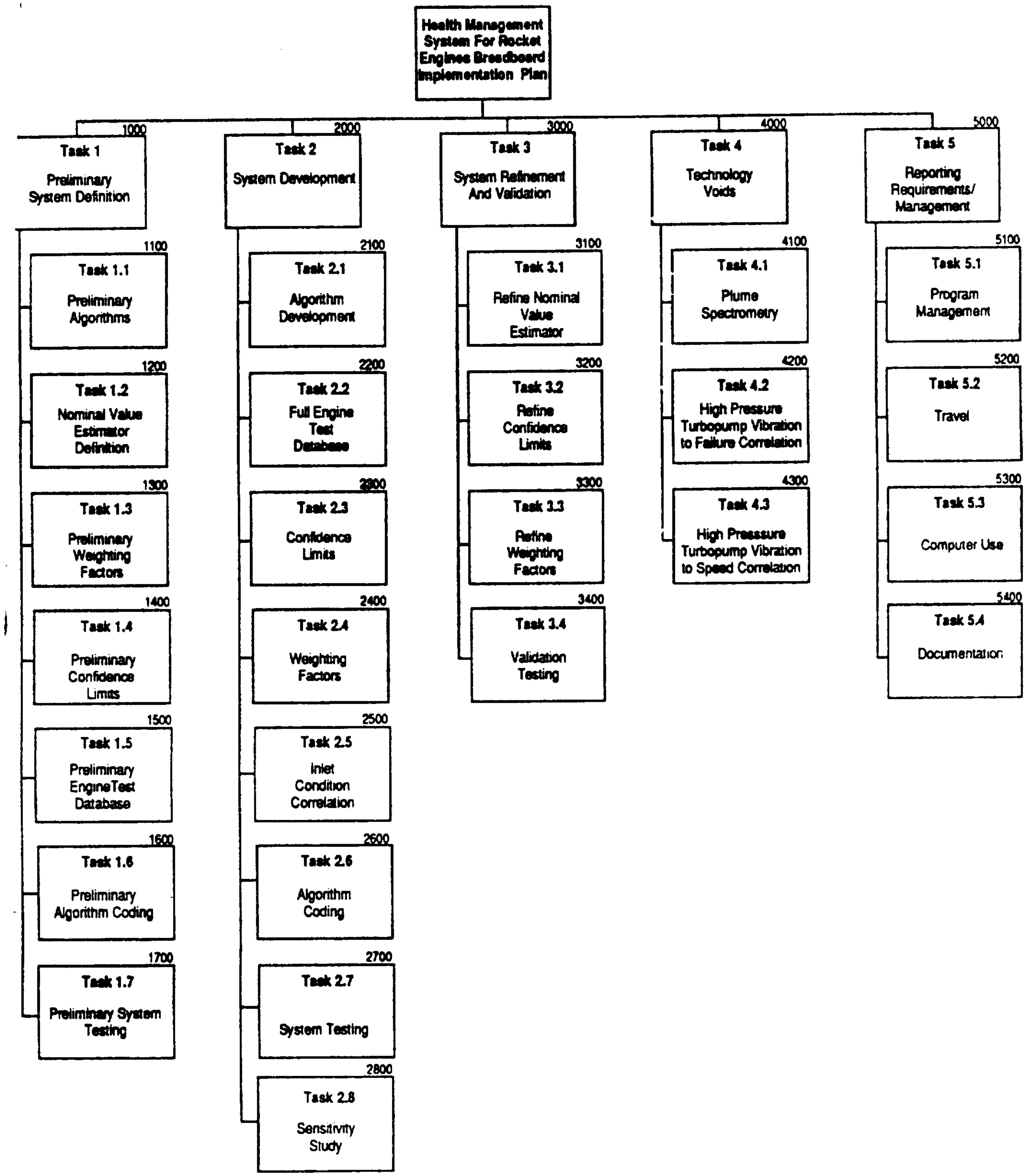


FIGURE 8-2 WORK BREAKDOWN STRUCTURE

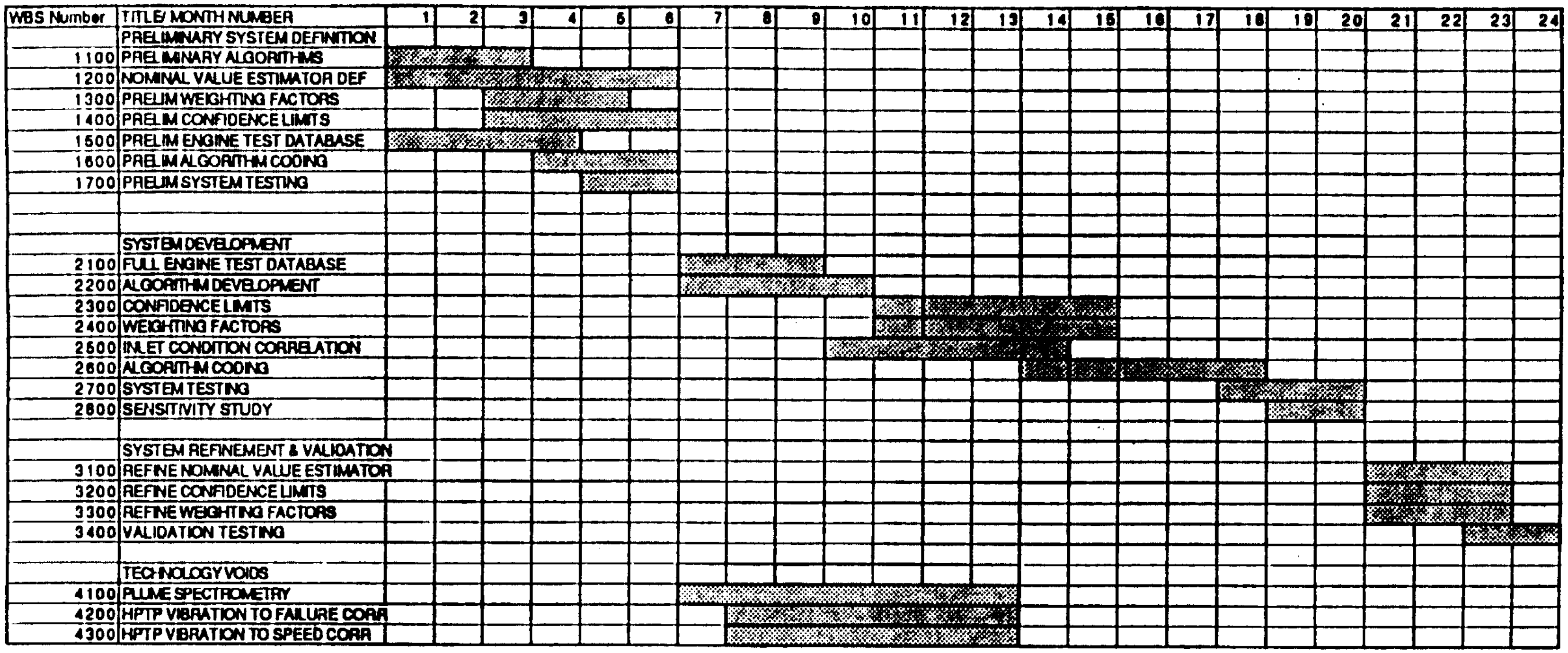


FIGURE 8-3 PROGRAM SCHEDULE

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	WBS Number	Task- Subtask title/ Month Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
2		PRELIMINARY SYSTEM DEFINITION																								
3	1100	PRELIMINARY ALGORITHMS	2	2	2																					
4	1200	NOM VALUE ESTIMATOR DEF	1.5	1.5	1.5	1.5	1.5	1.5																		
5	1300	PREL WEIGHTING FACTORS			1.5	1.5	1.5																			
6	1400	PREL CONFIDENCE LIMITS			1.5	1.5	1.5																			
7	1500	PRELIM ENGINE TEST DATABASE	1.5	1.5	1.5	1.5																				
8	1600	PREL ALGORITHM CODING				1.5	1.5	1.5																		
9	1700	PREL SYSTEM TESTING					1.5	1.5																		
10																										
11																										
12		SYSTEM DEVELOPMENT																								
13	2100	FULL ENGINE TEST DATABASE							1.5	1.5	1.5															
14	2200	ALGORITHM DEVELOPMENT							1.5	1.5	1.5	1.5														
15	2300	CONFIDENCE LIMITS											1.5	1.5	1.5	1.5	1.5									
16	2400	WEIGHTING FACTORS											1.5	1.5	1.5	1.5	1.5									
17	2500	INLET CONDITION CORRELATION										1.5	1.5	1.5	1.5	1.5										
18	2600	ALGORITHM CODING														1.5	1.5	1.5	1.5	1.5						
19	2700	SYSTEM TESTING																		1	1	1				
20	2800	SENSITIVITY STUDY																			0.5	0.5				
21																										
22		SYSTEM REFINE & VALIDATION																								
23	3100	REFINE NOM VALUE ESTIMATOR																					1.5	1.5	1.5	
24	3200	REFINE CONFIDENCE LIMITS																					1.5	1.5	1.5	
25	3300	REFINE WEIGHTING FACTORS																					1.5	1.5	1.5	
26	3400	VALIDATION TESTING																							1	1.5
27																										
28		TECHNOLOGY VOIDS																								
29	4100	PLUME SPECTROMETRY							0.5	0.5	0.5	0.5	0.5	0.5	0.5											
30	4200	HPTP VIB TO FAILURE CORR								0.25	0.25	0.25	0.25	0.25	0.25											
31	4300	HPTP VIB TO SPEED CORR								0.25	0.25	0.25	0.25	0.25	0.25											

FIGURE 8-4 PROGRAM MANLOADING

8.3 TEST FACILITY REQUIREMENTS

Computation Requirements

It has been determined that a commercial/industrial grade computer will have enough capacity and speed to perform the necessary calculations and input/output in the requisite time to provide enhanced engine protection during test firing.
The best suited available test facility for the HMSRE development is a workstation at Rocketdyne-Canoga. This allows ready access to the extensive SSME test data history. Our digital data room can format the test data into ASCII files which can be installed on and accessed from the development station hard disc drive. This will accommodate the HMSRE implementation system development goals. The development station will be self-contained in that it will not seek data from outside the workstation during test runs. The test data to support these runs will come from the engine test database and from Rocketdyne's SSME model outputs. When the HMSRE has been streamlined for real time operation and validated at Rocketdyne in the local SAFD system, the TTBE facility will come into play. The HMSRE real time code will be transferred to the SAFD hardware at TTBE. This supports the ultimate HMSRE implementation goals by providing hot-fire engine test data and potential interaction with the engine via the SSME controller (SSMEC). Test data will come from both the engine instrumentation and facility instrumentation. The use of the System for Anomaly and Failure Detection (SAFD) on the SSME TTBE is integral to HMSRE TTBE implementation. It is planned to use the SAFD capabilities for HMSRE signal conditioning, multiplexing and computing as well as the SAFD algorithms.

The following models are among those available for use in this program:

The SSME DTM Model. A thermodynamic, transient, engine system and component performance prediction model. The SSME DTM is used for engine system design analysis and engine anomaly simulations. The SSME DTM is normally run in batch mode on Rockwell's Cyber 875 computer located at the Information Systems Center in Seal Beach, CA.

The SSME FLYTE Model. A linear, steady-state, engine system and component performance prediction model incorporating influence coefficients. The SSME FLYTE is used for STS flight performance prediction, reconstruction, and anomaly resolution analyses and is normally run in a batch mode on Rocketdyne's ATDM computer.

The SSME OTPP Model. A thermodynamic, steady-state oxidizer turbopump component test data reduction model. The SSME OTPP is normally run interactively on SSME Oxidizer Turbomachinery IBM microcomputers located at the Canoga Facility.

The SSME HPOTP model. A thermodynamic, steady-state oxidizer turbopump component performance prediction model. The SSME HPOTP is used for SSME HPOTP detailed design analysis and performance prediction and is normally run interactively on SSME Hydrodynamics' Apollo workstations located at the Canoga Facility.

A summary of the models is given in Table 8-1. Several of the models accommodate the nonlinear aspects of the system and each is written in the programming language FORTRAN 77. The DRP, FLYTE, OTPP, and HPOTP models perform analysis and anomaly resolution of SSME hot fire data.

8.4 ACQUISITION PLANS

Since it is planned to utilize Rocketdyne-supplied computing hardware for development and initial breadboard HMSRE implementation; and the SAFD hardware at Rocketdyne and MSFC-TTBE for ultimate validation, no acquisition plans are anticipated.

TABLE 8.1 ANALYTICAL MODELS

Model Name	Model Function
SSME Power Balance Model	Non-Linear thermodynamic performance prediction and power balance model (PBM)
LEM: Linear Engine Model	Linearization of PBM. SSME influence coefficient model calculates general trends.
FLYTE	SSME linear flight data prediction and reconstruction model.
FREDA	Inferred flow parameter calculations. Test data driven.
DRP	Non-linear, thermodynamic, steady-state performance prediction.
DTM	Non-linear, thermodynamic, transient performance prediction.
OTPP	Steady-state, component test data reduction.
HPOTP	Steady-state, oxidizer turbopump performance preduction.
Hydrodynamic Models Seal Models	Inferred parameter calculations. Test data driven. Back-calculation of engine parameters.
Aero-Thermal Models	Thermally affected parameters. Component expansion characteristics. Expected operation conditions from equilibrium calculations.
Miscellaneous Models	Smaller models used for the analysis and/or design of specific components, configurations or scenarios.

HMSRE Models

8.5 TECHNOLOGY PROGRAM

Throughout the program, emphasis was placed on compatability with the SSME block-II controller and available facility measurements. Measurements requiring additional development, either in hardware or processing, were not included unless they were felt to offer significant enhancement to the HMSRE. On this basis, only three technology closure areas are conceived for application to the HMSRE. These are the characterization of plume spectrometry for failure mode recognition, the determination of nominal high pressure turbopump vibration values and their correlation to failure modes, and the calculation of high pressure oxidizer turbopump speed from real-time HPOTP vibration data.

8.5.1 Plume Spectrometry

Plume spectrometry provides information, related to internal hardware degradation, that is unavailable with the existing SSME instrumentation. The development effort for this technology consists of two parts: 1) definition of failure related plume anomalies, and 2) plume spectrometry system development.

DEFINITION OF FAILURE RELATED PLUME ANOMALIES

Task 1 - Define critical plume anomaly measurements. Definition of critical measurements includes the selection of monitored materials, identification of anomaly type (e.g. steady plume contamination, spurious plume contamination, increasing plume contamination), and identification of anomaly location (e.g. distributed throughout plume, streaks). Since no significant failure database is available, definition of plume contamination anomalies will rely on expert opinion, detailed modelling, and probabilistic representation of degration modes and engine dynamics.

The general approach:

- Select critical/representative failure modes
- Define general failure scenarios
- Characterize degradations (e.g. continous erosion, large chunks of material released)
- Characterize plume contaminations (e.g. Inconel 718, continously present in plume, steady increase in contamination level, fine particles, evenly distributed throughout plume)

Task 2 - Define nominal values. Nominal SSME operating values will be established for the plume anomaly indications defined in Task 1. Nominal values are defined by evaluating existing Rocketdyne SSME hot-fire data and the data from the Stennis Space Center plume spectrometry hot-fire testing program for each anomaly.

Task 3 - Define acceptable limits. Acceptable deviation limits, for each nominal value defined in task 2, will be established. These limits are based on the statistical distribution of observed values in nominal tests, the expertise of appropriate design and test personnel, and plume contamination calibration tests.

PLUME SPECTROMETRY SYSTEM DEVELOPMENT

Task 1 - System definition. Trade studies will be performed, based on the anomaly definition results described above, to identify required system features. These evaluations are expected to include plume coverage (wide angle, line, single point, etc.), temporal resolution, monitored chemical species, monitoring capabilities (full spectrum, discrete bandwidths), and material quantification requirements.

Task 2 - System development. Hardware and data processing software will be developed to implement capabilities defined in task 1 that are not available with current plume monitoring systems.

Task 3 - System calibration and sensitivity evaluation. The system response to known plume contamination concentrations will be evaluated to correlate the measured plume anomalies to engine hardware degradations defined above.

8.5.2 High Pressure Turbopump Vibration to Failure Mode Correlation

Hardware degradation of the high pressure turbopumps is often accompanied by increased vibration levels. Sensitive vibration monitoring is expected to provide indications of rotating assembly degradations (e.g. bearings, seals) before the degradation becomes severe enough to significantly influence the performance parameters monitored by the block-II controller. Current vibration measurements monitor a fairly wide vibration band and redlines are based on the overall RMS vibration levels. For the HMSRE, isolation of the vibration source to a specific component is desirable to enable effective correlation with other HMSRE parameters that indicate a failure. The accelerometers are available and are currently used by the block-II controller. Therefore, the development required for the HMSRE is limited to the hardware/software necessary to isolate specific component vibration signals and the quantification of the HMSRE nominal values and limits.

Task 1 - Development of vibration isolation hardware and software. Real-time hardware and software will be developed to isolate vibration signals. Several approaches will be evaluated, including tracking filters and software capable of identifying vibration "peaks" indicative of a specific component. The isolation system will be tested and evaluated using SSME taped vibration data.

Task 2 - Quantification of nominal values. Nominal values are established by evaluating the recorded vibration levels, in the bands monitored by the system developed in task 1, for a range of nominal SSME hot-fire tests. Average values will be established at each power level. In addition, the influence of changing inlet conditions will be assessed through evaluation of appropriate test data.

Task 3 - Quantification of limits. Limits will be established, for each band in the system defined in task 1, based on the statistical fluctuations in the data evaluated during task 2 and evaluation of SSME failure tests.

8.5.3 High Pressure Oxidizer Turbopump Vibration to Speed Correlation

The HPOTP speed provides a good indication of HPOTP performance and how hard the pump is being worked. No speed sensor currently exists on the HPOTP, but the speed is calculated (post-test) based on the frequency of the pump sysnchronous frequency. The development effort required for this measurement is to implement the frequency-speed relationship in a real-time system.

SECTION 9 - SUMMARY

The SSME test history indicates that specific early indications of catastrophic engine failure vary widely, even for similar failures. This observation, coupled with the fact that the probability of any one specific failure and propagation scenario is quite small (estimated at about 1% for the most likely failure mode) suggests that an algorithm sensitive to a wide variety of general failure indications is the most appropriate for near term applications. Therefore, the guiding principle behind the HMSRE algorithm is to provide capabilities for early detection of generic SSME failure indications, rather than addressing specific failure modes individually.

Evaluation of the most likely SSME FMEA failure modes, determined by the figure of merit approach, and evaluation of the SSME failure history indicate that several existing measurements generally provide significant, early indications of immenent catastrophic engine failures. These measurements are primarily related to high pressure turbopump performance, but also include vibration and the main injector pressure.

Nine classes of detection schemes were evaluated for extracting early failure indications from the key engine operating parameters identified as generic SSME failure indicators. Of these nine classes, features from five were selected for the HMSRE algorithm: Advanced Redlines, Parameter Correlation, Operational Envelopes, Power Level Dependent Algorithms, and Vibration Monitoring.

The HMSRE failure detection strategy evaluates the difference between measured critical operating conditions and predicted nominal values. The likelihood of catastrophic engine failure is approximated by a weighted, correlated sum of these differences. This strategy enables sensitivity to a wide variety of early failure indications ranging from large excursions in a single, validated parameter to the gradual drifting of a large number of correlated parameters.

Evaluation of the SSME test history indicates that the HMSRE algorithm would have detected 79% of the major incidents. Furthermore, the algorithm provided indications of imminent catastrophic failure well in advance of redline cutoffs for each of three SSME failures representing three distinct failure types.

In addition, the HMSRE algorithm is easily extended to include additional measurements, both conventional and advanced, and the correlation strategy can be refined to include expert system analysis or even neural network type processing.

Finally, in conclusion: the use of available SSME measurements, the generic failure detection utility of the algorithm, the wide failure coverage, the demonstrated early failure indications for three SSME test cases, and the extensibility of the algorithm combine to provide a low risk, high payoff approach for significant improvements in near term SSME failure detection capabilities.

REFERENCES

[1] Failure Control Techniques for the SSME, Phase I, Final Report
Rocketdyne Report Number RI/RD86-165
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
Contract Number NAS8-36305

[2] Failure Control Techniques for the SSME, Phase II, Final Report
Rocketdyne Report Number RI/RD87-198
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
Contract Number NAS8-36305

[3] Critical Item Ordinal Ranking for SSME, Report Number RSS-8790
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
Contract Number NAS8-40000

ATTACHMENT 1

OVERALL FAILURE MODE RANKING

KEY TO ATTACHMENT 1

Column A - Overall Failure Mode Ranking

Column C - SSME FMEA Failure Mode Designation

Field 1 (1 digit) Component Type, example: **B**200-15

A = COMBUSTION DEVICES
B = TURBOMACHINERY
C = PNEUMATICS
D = PROPELLANT VALVES
E = ACTUATORS
F = CONTROLLER/FASCOS
G = IGNITERS
H = ELECTRICAL HARNESSES
J = SENSORS/INSTRUMENTATION
K = LINES AND DUCTS
L = JOINTS
M = GIMBAL
N = ORIFICES

Field 2 (3 digits) Specific Component Designation, example: B**200**-15

Field 3 (2 digits) Failure Mode Designation, example: B200-**15**

Column E - Specific Component (corresponds to field 2 of column C)

Column F - Failure Mode (corresponds to field 3 of column C)

Column BY - Figure of Merit Rating (0-1)

	A	C	E	F	BY
1	RANK	LRU-FM	COMPONENT	FAILURE MODE	
2					F.O.M.
3	1	A150-01	HEAT EXCHANGER	COIL FRACTURE/LEAKAGE.	0.0000
4	2	C200-11	PCA (EMERGENCY PNEUMATIC SHUTDOWN)	FAILURE TO SUPPLY HELIUM PRESSURANT.	0.6955
5	3	B200-04	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE OF TURBINE BLADES.	0.5434
6	4	A340-02	NOZZLE ASSEMBLY	EXTERNAL RUPTURE.	0.43[illegible]2
7	5	D110-01	MAIN FUEL VALVE	INTERNAL LEAKAGE.	0.3660
8	6	A600-04	FUEL PREBURNER	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT OCCURS.	0.3577
9	7	B200-15	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF SUPPORT OR POSITION CONTROL	0.3487
10	8	A200-06	MAIN INJECTOR	LOX POST CRACK.	0.3244
11	9	B600-06	LOW PRESSURE FUEL TURBOPUMP	FUEL LEAKAGE PAST LIFT-OFF SEAL.	0.2778
12	10	B400-03	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE BLADE STRUCTURAL FAILURE.	0.2664
13	11	B400-14	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF AXIAL BALANCING FORCE.	0.2656
14	12	B400-07	HIGH PRESSURE OXIDIZER TURBOPUMP	FAILURE TO TRANSMIT TORQUE.	0.2656
15	13	A200-09	MAIN INJECTOR	INTERPROPELLANT PLATE CRACKS.	0.2493
16	14	B400-22	HIGH PRESSURE OXIDIZER TURBOPUMP	PUMP PIECE PART STRUCTURAL FAILURE.	0.2385
17	15	A330-02	MAIN COMBUSTION CHAMBER	FUEL LEAKS INTO THE CLOSED CAVITY BETWEEN THE LINER AND STRUCTURAL JACKET.	0.2331
18	16	K103-01	LPFTP TURBINE DISCHARGE DUCT	FAILS TO CONTAIN HYDROGEN	0.2249
19	17	D500-06	GOX CONTROL VALVE	MAINTAIN STRUCTURAL INTEGRITY.	0.2249
20	18	D300-01	ANTI-FLOOD VALVE	LEAKAGE DURING PROPELLANT CONDITIONING.	0.2222
21	19	K106-02	HIGH PRESSURE FUEL DUCT	FAILS TO CONTAIN HYDROGEN	0.2208
22	20	B800-06	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT AND POSITION CONTROL.	0.2087
23	21	A200-07	MAIN INJECTOR	EXTERNAL RUPTURE.	0.2085
24	22	E150-14	CHAMBER COOLANT VALVE ACTUATOR	SEQUENCE VALVE LEAKS PASSING EARLY CONTROL PRESSURANT DOWNSTREAM.	0.2024
25	23	D220-06	OXIDIZER BLEED VALVE	FRETTING OF INTERNAL PARTS.	0.1897
26	24	B400-23	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE PIECE PART STRUCTURAL FAILURE	0.1889
27	25	A330-03	MAIN COMBUSTION CHAMBER	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE.	0.1680
28	26	B200-26	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE.	0.1599
29	27	K203-01	OXIDIZER BLEED FLEX LINE	FAILS TO CONTAIN OXIDIZER.	0.1599
30	28	D120-05	MAIN OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.1599
31	29	A050-02	POWERHEAD	SHELL OR PROPELLANT DUCT RUPTURE.	0.1572
32	30	A600-11	FUEL PREBURNER	EXTERNAL RUPTURE.	0.1436
33	31	D120-04	MAIN OXIDIZER VALVE	STRUCTURAL FAILURE.	0.1436
34	32	C200-07	PNEUMATIC CONTROL ASSEMBLY (OXIDIZER SYSTEM PURGE)	INSUFFICIENT OR NO NITROGEN PURGE FLOW DURING PROPELLANT CONDITIONING	0.1436
35	33	A200-05	MAIN INJECTOR	PARTIAL BLOCKAGE OF AN OXIDIZER ORIFICE.	0.1337
36	34	D130-03	FUEL PREBURNER OXIDIZER VALVE	SHAFT SEAL LEAK.	0.1286
37	35	D120-06	MAIN OXIDIZER VALVE	FREETING OF INTERNAL PARTS.	0.1286
38	36	B400-13	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT, POSITION CONTROL, OR ROTORDYNAMIC STABILITY.	0.1076
39	37	B200-07	HIGH PRESSURE FUEL TURBOPUMP	TURBINE DISCHARGE FLOW BLOCKAGE.	0.1057
40	38	B400-20	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO FIRST- AND SECOND-STAGE TURBINE COMPONENTS.	0.0953
41	39	D300-03	ANTI-FLOOD VALVE	LOW FLOW RESTRICTED OR SHUT OFF.	0.0949
42	40	A700-02	OXIDIZER PREBURNER	LOSS OF FUEL TO ASI.	0.0949
43	41	B200-16	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS.	0.0890
44	42	B200-17	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE DISCS.	0.0867
45	43	B400-18	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO BEARINGS.	0.0867
46	44	B200-24	HIGH PRESSURE FUEL TURBOPUMP	FAILURE TO RESTRAIN SHAFT MOVEMENT DURING TURBOPUMP STARTUP.	0.0867
47	45	B200-23	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF BALANCING CAPABILITY.	0.0835
					0.0835

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	A	C	E	F	BY
48	46	A330-04	MAIN COMBUSTION CHAMBER	EXTERNAL RUPTURE.	0.0794
49	47	A600-10	FUEL PREBURNER	EXTERNAL RUPTURE.	0.0794
50	48	B200-18	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO INLET SUPPORT STRUTS AND BEARING SUPPORT BELLOWS.	0.0759
51	49	B200-19	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO MAIN HOUSING, MOUNT RING, BEARING SUPPORT AND BELLOWS.	0.0759
52	50	D220-03	OXIDIZER BLEED VALVE	GROSS LEAKAGE.	0.0759
53	51	D600-07	RECIRCULATION ISOLATION VALVE	FRETTING OF INTERNAL PARTS.	0.0759
54	52	E110-09	MAIN FUEL VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0759
55	53	B400-01	HIGH PRESSURE OXIDIZER TURBOPUMP	LEAKAGE PAST THE OUTBOARD DPB/HPOTP PRESSURE-ASSISTED SEAL.	0.0731
56	54	D140-01	OXIDIZER PREBURNER OXIDIZER VALVE	INTERNAL LEAKGE.	0.0731
57	55	E110-13	MAIN FUEL VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON LEAKAGE.	0.0731
58	56	E110-04	MAIN FUEL VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0731
59	57	E120-12	MAIN OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON LEAKAGE.	0.0731
60	58	E120-04	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
61	59	E130-04	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
62	60	E130-12	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUCNE VALVE LEAKAGE.	0.0731
63	61	E140-12	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUCNE VALVE LEAKAGE.	0.0731
64	62	E140-04	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
65	63	E150-12	CHAMBER COOLANT VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUENCE VALVE LEAKAGE.	0.0731
66	64	A050-01	POWERHEAD	LINER FAILURE.	0.0714
67	65	D140-03	OXIDIZER PREBURNER OXIDIZER VALVE	SHAFT SEAL LEAK.	0.0707
68	66	B200-08	HIGH PRESSURE FUEL TURBOPUMP	FAILS TO TRANSMIT TORQUE.	0.0705
69	67	B600-03	LOW PRESSURE FUEL TURBOPUMP	FAILS TO TRANSMIT TORQUE.	0.0705
70	68	A700-04	OXIDIZER PREBURNER	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT OCCURS.	0.0704
71	69	D500-08	GOX CONTROL VALVE	FRETTING OF INTERNAL PARTS.	0.0704
72	70	C113-01	OXIDIZER DOME FURGE CHECK VALVE	FAILS TO OPEN OR RESTRICTS FLOW DURING PROPELLANT CONDITIONING.	0.0658
73	71	C116-01	FUEL PREBURNER ASI PURGE CHECK VALVE	FAILS TO OPEN OR RESTRICTS FLOW DURING PROPELLANT CONDITIONING.	0.0658
74	72	D210-03	FUEL BLEED VALVE	GROSS LEAKAGE.	0.0658
75	73	A200-08	MAIN INJECTOR	EXTERNAL RUPTURE.	0.0650
76	74	D300-07	ANTI-FLOOD VALVE	PIECE PART STRUCTURAL FAILURE.	0.0623
77	75	A600-06	FUEL PREBURNER	OXIDIZER POST CRACKS.	0.0585
78	76	D120-03	MAIN OXIDIZER VALVE	SEAL LEAKAGE.	0.0583
79	77	E120-09	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0567
80	78	D300-08	ANTI-FLOOD VALVE	FRETTING OF INTERNAL PARTS.	0.0563
81	79	B800-08	LOW PRESSURE OXIDIZER TURBOPUMP	PIECE PART STRUCTURAL FAILURE.	0.0542
82	80	J701-02	FUEL FLOWMETER	PIECE PART FAILURE.	0.0542
83	81	E130-13	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	SEQUENCE VALVE FAILS TO PASS PNEUMATIC PRESSURE TO DOWNSTREAM COMPONENTS.	0.0535
84	82	E140-13	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	SEQUENCE VALVE FAILS TO PASS PENUMATIC PRESSURE TO DOWNSTREAM COMPONENTS.	0.0535
85	83	B800-02	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF TURBINE POWER.	0.0525
86	84	B400-24	HIGH PRESSURE OXIDIZER TURBOPUMP	FRETTING OF INTERNAL PARTS.	0.0523
87	85	B400-21	HIGH PRESSURE OXIDIZER TURBOPUMP	STRUCTURAL FAILURE.	0.0488
88	86	D110-04	MAIN FUEL VALVE	STRUCTURAL FAILURE.	0.0488
89	87	B400-12	HIGH PRESSURE OXIDIZER TURBOPUMP	LEAKAGE UNDER LABYRINTH SEAL, MATING RING OR LEAKAGE OVER THE INTERMED SEAL HOUSING.	0.0461
90	88	B600-07	LOW PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE.	0.0461
91	89	C300-06	HELIUM PRECHARGE VALVE	FAILURE TO CINTAIN HELIUM PRESSURANT.	0.0461
92	90	E130-09	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0461
93	91	K101-02	LPFTP DISCHARGE DUCT (LPFTP DUCT HELIUM BAG)	FAILS TO CONTAIN OXIDIZER.	0.0461
94	92	K102-01	LPFTP TURBINE DRIVE DUCT	FAILS TO CONTAIN OXIDIZER	0.0461

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95	93	K104-02	FUEL BLEED DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
96	94	K201-03	LPOTP DISCHARGE DUCT	FRETTING OF INTERNAL PARTS.	0.0461
97	95	K202-03	LPOTP TURBINE DRIVE DUCT	FRETTING OF INTERNAL PARTS.	0.0461
98	96	K202-01	LPOTP TURBINE DRIVE DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
99	97	K204-03	OXIDIZER TANK PRESSURANT DUCT	FRETTING OF INTERNAL PARTS.	0.0461
100	98	K204-01	OXIDIZER TANK PRESSURANT DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
101	99	K205-01	HIGH PRESSURE OXID DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
102	100	K208-01	PREBURNER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
103	101	K501-01	HELIUM SUPPLY HOSE	FAILS TO CONTAIN HELIUM.	0.0461
104	102	N400-01	POGO SUPPRESSOR ACCUMULATOR	FAILURE TO CONTAIN HELIUM/OXIDIZER.	0.0461
105	103	B200-22	HIGH PRESSURE FUEL TURBOPUMP	FUEL LEAKAGE PAST LIFT-OFF SEAL.	0.0456
106	104	C200-12	PCA (EMERGENCY PNEUMATIC SHUTDOWN)	PURGE SEQUENCE VALVE FAILS TO ACTUATOR DURING PROPELLANT CONDITIONING.	0.0444
107	105	C300-02	HELIUM PRECHARGE VALVE	FAILURE TO TERMINATE HELIUM PRESSURANT FLOW TO POGO ACCUMULATOR DURING PROPELLANT	0.0444
108	106	FOBJ-04	EMERGENCY SHUTDOWN SOLENOID CONTROL	FAILURE TO MAINTAIN SOLENOID DE-ENERGIZED.	0.0444
109	107	K401-01	HYDRAULIC SUPPLY HOSE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0444
110	108	K502-01	NITROGEN SUPPLY HOSE	FAILS TO CONTAIN GN2.	0.0444
111	109	A200-03	MAIN INJECTOR	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0442
112	110	D130-06	FUEL PREBURNER OXIDIZER VALVE	FRETTING OF INTERNAL PARTS.	0.0442
113	111	D140-06	OXIDIZER PREBURNER OXIDIZER VALVE	FRETTING OF INTERNAL PARTS.	0.0442
114	112	A600-09	FUEL PREBURNER	INTERPROPELLANT PLATE OR ELEMENT-TO-PLATE BRAZE JOINT LEAKAGE.	0.0434
115	113	B400-15	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF PURGE PRESSURE BARRIER.	0.0434
116	114	D130-05	FUEL PREBURNER OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
117	115	D140-05	OXIDIZER PREBURNER OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
118	116	D600-06	RECIRCULATION ISOLATION VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
119	117	D220-05	OXIDIZER BLEED VALVE	PIECE PART STRUCTURAL FAILURE.	0.0418
120	118	B800-03	LOW PRESSURE OXIDIZER TURBOPUMP	FAILURE TO TRANSMIT TORQUE.	0.0407
121	119	L101-01	FUEL SYSTEM JOINTS	LEAKAGE.	0.0399
122	120	L102-01	OXIDIZER SYSTEM JOINTS	LEAKAGE.	0.0399
123	121	L103-01	HOT GAS SYSTEM JOINTS	LEAKAGE.	0.0399
124	122	A700-06	OXIDIZER PREBURNER	OXIDIZER POST CRACKS.	0.0390
125	123	H112-01	ELEC HARN (ANTI-FLOOD VALVE POSITION INDICATOR)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0383
126	124	A600-03	FUEL PREBURNER	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0342
127	125	A600-02	FUEL PREBURNER	LOSS OF FUEL TO ASI.	0.0342
128	126	A700-03	OXIDIZER PREBURNER	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0342
129	127	A700-08	OXIDIZER PREBURNER	PARTIAL BLOCKAGE OF FUEL TO BAFFLES.	0.0342
130	128	N717-01	MCC ASI FUEL ORFICE (F5.2)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
131	129	N718-01	OPB ASI FUEL ORIFICE (F25)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
132	130	N719-01	FPB ASI FUEL ORFICE (F21)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
133	131	C300-01	HELIUM PRECHARGE VALVE	INSUFFICIENT OR NO HELIUM PRESSURANT TO POGO ACCUMULATOR.	0.0325
134	132	A600-12	FUEL PREBURNER	OMEGA JOINT FAILURE.	0.0298
135	133	A700-12	OXIDIZER PREBURNER	OMEGA JOINT FAILURE.	0.0298
136	134	A700-11	OXIDIZER PREBURNER	EXTERNAL RUPTURE.	0.0298
137	135	A700-10	OXIDIZER PREBURNER	EXTERNAL RUPTURE.	0.0298
138	136	A700-09	OXIDIZER PREBURNER	INTERPROPELLANT PLATE OR ELEMENT-TO-PLATE BRAZE JOINT LEAKAGE.	0.0298
139	137	B200-14	HIGH PRESSURE FUEL TURBOPUMP	FRAGMENTATION OF VOLUTE LINER.	0.0298
140	138	B200-03	HIGH PRESSURE FUEL TURBOPUMP	TURBINE BEARING SUPPORT BELLOWS FAILURE.	0.0298
141	139	B800-07	LOW PRESSURE OXIDIZER TURBOPUMP	STRUCTURAL FAILURE.	0.0298

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142	140	C300-07	HELIUM PRECHARGE VALVE	FAILURE TO CONTAIN OXIDIZER.	0.0298
143	141	D130-04	FUEL PREBURNER OXIDIZER VALVE	STRUCTURAL FAILURE.	0.0298
144	142	D140-04	OXIDIZER PREBURNER OXIDIZER VALVE	STRUCTURAL FAILURE.	0.0298
145	143	D150-03	CHAMBER COOLANT VALVE	STRUCTURAL FAILURE.	0.0298
146	144	D300-06	ANTI-FLOOD VALVE	STRUCTURAL FAILURE.	0.0298
147	145	D500-05	GOX CONTROL VALVE	STRUCTURAL FAILURE.	0.0298
148	146	D600-05	RECIRCULATION ISOLATION VALVE	STRUCTURAL FAILURE.	0.0298
149	147	E110-12	MAIN FUEL VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
150	148	E110-11	MAIN FUEL VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
151	149	E120-10	MAIN OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
152	150	E130-11	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
153	151	E130-10	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
154	152	E140-11	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
155	153	E140-10	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
156	154	E150-11	CHAMBER COOLANT VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
157	155	J201-02	MCC Pc PRESSURE TRANSDUCER (G8.7)	LEAKAGE INTO SENSOR HOUSING.	0.0298
158	156	J202-02	MCC Pc PRESSURE TRANSDUCER (G8.8)	LEAKAGE INTO SENSOR HOUSING.	0.0298
159	157	J205-02	FUEL PREBURNER CHAMBER PRESSURE TRANSDUCER (G4.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
160	158	J207-02	OXIDIZER TANK PRESSURANT TRANSDUCER (020.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
161	159	J208-02	HPFTP DISCHARGE PRESSURE TRANSDUCER (F4.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
162	160	J209-02	HPOTP BOOST PUMP DISCH PRESS TRANSDUCER (011.1.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
163	161	J210-02	FUEL INJECTION PRESSURE TRANSDUCER(G7.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
164	162	J220-02	HPOTP DISCHARGE PRESSURE TRANSDUCER (06.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
165	163	J221-02	MCC COOLANT OUTLET PRESSURE TRANSDUCER (F7.1a)	LEAKAGE INTO SENSOR HOUSING.	0.0298
166	164	J222-02	POGO PRECHARGE PRESSURE TRANSDUCER (026.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
167	165	J225-02	EMERGENCY SHUTDOWN PRESSURE TRANSDUCER (P2.3)	LEAKAGE INTO SENSOR HOUSING.	0.0298
168	166	J230-02	HPOTP COOLANT LINER PRESSURE TRANSDUCER (N11.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
169	167	J306-02	LPFTP DISCHARGE TEMPERATURE TRANSDUCER (F2.3)	STRUCTURAL FAILURE OF PROBE.	0.0298
170	168	J309-03	MCC COOLANT OUTLET TEMPERATURE TRANSDUCER (F7.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
171	169	J312-03	HPOTP BOOST STAGE DISCHARGE TEMPERATURE (011.1.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
172	170	J313-02	MCC OXIDIZER INJECTION TEMP TRANSDUCER (08.3)	STRUCTURAL FAILURE OF PROBE.	0.0298
173	171	J609-02	LPOTP SHAFT SPEED TRANSDUCER (01.1)	STRUCTURAL FAILURE.	0.0298
174	172	K101-03	LPFTP DISCHARGE DUCT (LPFTP DUCT HELIUM BAG)	PIECE PART STRUCTURAL FAILURE.	0.0298
175	173	K104-01	FUEL BLEED DUCT	LOSS OF INSULATION CAPABILITY	0.0298
176	174	K107-01	FUEL TANK PRESSURANT LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
177	175	K110-02	FUEL BLEED DUCT	FAILS TO CONTAIN HYDROGEN.	0.0298
178	176	K111-01	PREBURNER FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
179	177	K112-01	OPB ASI FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
180	178	K113-01	FPB ASI FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
181	179	K120-01	LPFTP DISCHARGE PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
182	180	K121-01	HPFTP DISCHARGE PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
183	181	K201-02	LPOTP DISCHARGE DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
184	182	K201-01	LPOTP DISCHARGE DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
185	183	K202-02	LPOTP TURBINE DRIVE DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
186	184	K204-02	OXIDIZER TANK PRESSURANT DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
187	185	K206-01	FPB OXIDIZER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
188	186	K207-01	HEAT EXCHANGER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298

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189	187	K211-01	OPB ASI OXIDIZER SUPPLY	FAILS TO CONTAIN GN2.	0.0298
190	188	K212-01	OPB OXIDIZER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
191	189	K213-01	OXID BLEED LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
192	190	K214-01	OXID RECIRC BLEED LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
193	191	K215-01	POGO GOX SUPPLY LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
194	192	K216-01	RIV OVERRIDE LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
195	193	K217-01	ACCUMULATOR SUPPLY LINE	FAILS TO CONTAIN OXIDIZER/HELIUM.	0.0298
196	194	K218-01	POGO PRECHARGE LINE	FAILS TO CONTAIN OXIDIZER/HELIUM.	0.0298
197	195	K219-01	HPOTP DISC PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
198	196	K220-01	PB DISCH PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN OXYGEN.	0.0298
199	197	K222-01	HEAT EXCH OUTLET PRESS TRANS LINE	FAILURE TO CONTAIN GASEOUS OXYGEN.	0.0298
200	198	K223-01	LPOTP DISCH PRESS TRANSDUCER LINE	FAILURE TO CONTAIN OXYGEN.	0.0298
201	199	K318-01	HPOTP TURBINE PRIMARY SEAL DRAIN	FAILURE TO CONTAIN HOT GAS.	0.0298
202	200	K319-01	HPOTP 2ND SEAL DRAIN LINE	FAILS TO CONTAIN HOT GAS.	0.0298
203	201	K320-01	HPOTP OXID SEAL DRAIN MANIFOLD	FAILURE TO CONTAIN OXIDIZER.	0.0298
204	202	K403-02	HYDRAULIC RETURN HOSE	QUICK-DISCONNECT FAILS (DISCONNECTS).	0.0298
205	203	K505-01	HPOTP INTERMEDIATE SEAL PURGE LINE	FAILS TO CONTAIN HELIUM.	0.0298
206	204	K515-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
207	205	K519-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
208	206	K532-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
209	207	K540-01	MCC DRYING PURGE LINE	FAILS TO CONTAIN GN2.	0.0298
210	208	K541-01	HPFTP BEARING PURGE LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
211	209	K546-01	REMOVE MOUNT MCC FUEL PRES LINE	FAILS TO CONTAIN HOT GAS.	0.0298
212	210	K547-01	MCC PC PRESSURE LINE	FAILURE TO CONTAIN HOT GAS.	0.0298
213	211	K548-01	HPFTP COOLANT LINER PRES TRANS LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
214	212	K549-01	OFFSET MOUNT MCC Pc PRESSURE LINE	FAILURE TO CONTAIN HOT GAS.	0.0298
215	213	N400-02	POGO SUPRESSOR ACCUMULATOR	INTERNAL STRUCTURAL FAILURE.	0.0298
216	214	N500-01	POGO RECIRCULATION LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
217	215	N700-02	ADAPTER STANDPIPE	INTERNAL STRUCTURAL FAILURE.	0.0298
218	216	N700-01	ADAPTER STANDPIPE	EXTERNAL STRUCTURAL FAILURE.	0.0298
219	217	E120-11	MAIN OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0287
220	218	J223-02	FPB PURGE PRESSURE TRANSDUCERS (P2.5)	LEAKAGE INTO SENSOR HOUSING.	0.0287
221	219	J224-02	OPB PURGE PRESSURE TRANSDUCERS (P2.4)	LEAKAGE INTO SENSOR HOUSING.	0.0287
222	220	K401-02	HYDRAULIC SUPPLY HOSE	QUICK-DISCONNECT FAILS (DISCONNECTS).	0.0287
223	221	K405-01	MFVA HYDRAULIC SUPPLY LINE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
224	222	K406-01	MOVA HYDRAULIC SUPPLY LINE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
225	223	K407-01	HYDRAULIC SUPPLY MANIFOLD	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
226	224	K503-01	OXIDIZER SYSTEM LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
227	225	K508-01	OPOVA EMER SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
228	226	K509-01	MCC DOME PURGE LINE	FAILS TO CONTAIN GN2.	0.0287
229	227	K510-01	EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
230	228	K511-01	EMERGENCY SHUTDOWN CONTROL LINES	FAILS TO CONTAIN HELIUM.	0.0287
231	229	K512-01	MFV EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
232	230	K513-01	CCV EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
233	231	K516-01	NITROGEN SUPPLY LINES	FAILS TO CONTAIN GN2.	0.0287
234	232	K518-01	FPB PURGE LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
235	233	K530-01	HPV WARMANT LINES	FAILS TO CONTAIN GN2.	0.0287

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236	234	K535-01	NITROGEN SUPPLY LINE	FAILS TO CONTAIN GN2.	0.0287
237	235	K544-01	FPB ASI PURGE LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
238	236	N900-01	GCV CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
239	237	A150-02	HEAT EXCHANGER	INLET, BYPASS LINE, OUTLET RUPTURE.	0.0268
240	238	B800-01	LOW PRESSURE OXIDIZER TURBOPUMP	SEAL LEAKAGE-TURBINE INLET.	0.0227
241	239	A200-02	MAIN INJECTOR	LOSS OF FUEL TO ASI.	0.0217
242	240	B800-09	LOW PRESSURE OXIDIZER TURBOPUMP	FRETTING OF INTERNAL PARTS.	0.0211
243	241	B200-10	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF IMPELLER HEAD RIZE.	0.0192
244	242	J312-02	HPOTP BOOST STAGE DISCHARGE TEMPERATURE (011.1.2)	STRUCTURAL FAILURE OF PROBE.	0.0163
245	243	B400-05	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE INTERSTAGE SEAL LEAKAGE.	0.0159
246	244	B200-06	HIGH PRESSSURE FUEL TURBOPUMP	PLATFORM SEAL LEAKAGE.	0.0121
247	245	A150-03	HEAT EXCHANGER	BYPASS LINE ORIFICE RESTRICTION.	0.0121
248	246	K536-01	EMERGENCY SHUTDOWN POGO POST CHANGE	FAILS TO CONTAIN HELIUM.	[illegible]
249	247	N709-01	GCV GOX OUTLET ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0121
250	248	N704-01	FPB ASI PURGE ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0115
251	249	N707-01	MAIN INJECTOR OXID PURGE ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0115
252	250	N724-01	GOX CONTROL VALVE INLET ORIFICE (024)	ORIFICE RESTRICTED OR BLOCKED.	0.0115
253	251	B200-09	HIGH PRESSSURE FUEL TURBOPUMP	PRESSURE DROP OR FLOW DISTORTION AT IMPELLER INLET.	0.0107
254	252	B200-05	HIGH PRESSURE FUEL TURBOPUMP	SEAL FRACTURE, DISTORTION OR RUBBING.	0.0070
255	253	B200-02	HIGH PRESSURE FUEL TURBOPUMP	ENERGY LOSS AT TURBINE INLET.	0.0022
256	254	G100-01	SPARK IGNITER	REDUNDANT MAIN INJECTOR IGNITERS FAIL TO SPARK/WEAK OR LOW SPARK RATE.	0.0019
257	255	B200-20	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE COOLANT FLOW.	0.0007
258	256	B600-04	LOW PRESSURE FUEL TURBOPUMP	LOSS OF HEAD RISE.	0.0007
259	257	E110-01	MIAN FUEL VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0007
260	258	E130-01	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0007
261	259	B400-04	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE BLADE TIP SEAL LEAKAGE.	0.0005
262	260	C200-16	PNEUMATIC CONTROL ASSEMBLY	FAILURE TO CONTAIN HELIUM.	0.0004
263	261	H111-01	ELEC HARN (EMERG SHUTDOWN CONTROL SOLENOID VAVLE)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0003
264	262	B200-11	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE IMPELLER BYPASS LEAKAGE.	0.0002
265	263	A200-01	MAIN INJECTOR	ASI FAILS TO IGNITE.	0.0002
266	264	C116-02	FUEL PREBURNER ASI PURGE CHECK VALVE	CHECK VALVE LEAKS.	0.0002
267	265	C200-09	PCA (HPOTP INTERMEDIATE SEAL PURGE)	INSUFFICENT OR NO HELIUM PURGE FLOW.	0.0002
268	266	B400-19	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO TURBINE SEALS.	0.0002
269	267	D110-02	MAIN FUEL VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
270	268	D130-02	FUEL PREBURNER OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
271	269	D140-02	OXIDIZER PREBURNER OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
272	270	D500-04	GOX CONTROL VALVE	FAILS TO OPEN.	0.0002
273	271	B600-05	LOW PRESSURE FUEL TURBOPUMP	LOSS OF SUPPORT OR POSITION CONTROL OF ROTATING ASSEMBLY.	0.0002
274	272	B200-12	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE PUMP INTERSTAGE SEAL LEAKAGE.	0.0002
275	273	B200-13	HIGH PRESSURE FUEL TURBOPUMP	ENERGY LOSS IN DIFFUSERS AND HOUSING.	0.0002
276	274	B400-09	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF INDUCER/IMPELLER HEAD RISE.	0.0002
277	275	B600-02	LOW PRESSURE FUEL TURBOPUMP	POWER LOSS IN ROTOR.	0.0002
278	276	B800-04	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF INDUCER HEAD RISE.	0.0002
279	277	E140-01	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0002
280	278	B400-06	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE DISCHARGE FLOW BLOCKAGE.	0.0002
281	279	D120-02	MAIN OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
282	280	D220-02	OXIDIZER BLEED VALVE	VALVE FAILS TO CLOSE.	0.0002

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283	281	B400-08	HIGH PRESSURE OXIDIZER TURBOPUMP	FLOW DISTORTION AT MAIN PUMP INLET.	0.0001
284	282	H108-01	ELEC HARN (BLEED VALVE SOLENOID CONTROL)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0001
285	283	J201-01	MCC Pc PRESSURE TRANSDUCER (68.7)	NO OUTPUT OR ERRONEOUS SIGNAL.	0.0001
286	284	J202-01	MCC Pc PRESSURE TRANSDUCER (68.8)	NO OUTPUT OR ERRONEOUS SIGNAL.	0.0001
287	285	H103-01	ELEC HARN (VEHICLE RECORDER DATA)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0001
288	286	B600-01	LOW PRESSURE FUEL TURBOPUMP	ENERGY LOSS AT TURBINE INLET.	0.0001
289	287	C200-18	PNEUMATIC CONTROL ASSEMBLY	FAILS TO ACTUATOR FULLY (FUEL SYSTEM PURGE PAV, OXIDIZER BLEED PAV).	0.0001
290	288	C200-17	PNEUMATIC CONTROL ASSEMBLY	FAILS TO ACTUATOR FULLY (EMERGENCY SHUTDOWN PAV, HPOTP INTERMEDIATE SEAL PURGE PAV,	0.0001
291	289	B200-21	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE HOT-GAS LEAKAGE INTO COOLANT CIRCUIT.	0.0001
292	290	FOAG-01	PRESSURE SENSOR INTERFACE P9	FAILURE OF MCC Pc PRESSURE SENSOR INTERFACE.	0.0001
293	291	FOBN-01	VEHICLE RECORDER INTERFACE	DATA PATH FAILURE.	0.0001
294	292	B400-10	HIGH PRESSURE OXIDIZER TURBOPUMP	ENERGY LOSS IN MAIN PUMP DIFFUSER.	0.0001
295	293	B800-05	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF DYNAMIC HEAD RECOVERY/GUIDANCE.	0.0001
296	294	B600-08	LOW PRESSURE FUEL TURBOPUMP	TURBINE SEAL LEAKAGE.	0.0001
297	295	E120-01	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0001
298	296	L101-01	FUEL SYSTEM JOINTS	LEAKAGE.	0.0001
299	297	L102-01	OXIDIZER SYSTEM JOINTS	LEAKAGE.	0.0001
300	298	FOBJ-03	EMERGENCY SHUTDOWN SOLENOID CONTROL	FAILURE TO REMOVE THE CURRENT OT DE-ENERGIZE SOLENOID.	0.0000
301	299	FOBG-02	POGO PRECHARGE SOLENOID CONTROL	FAILURE TO PROVIDE HOLDING CURRENT TO MAINTAIN SOLENOID ENERGIZED.	0.0000
302	300	FOBG-01	POGO PRECHARGE SOLENOID CONTROL	FAILURE TO PROVIDE THE CURRENT OT ENERGIZE THE SOLENOID.	0.0000
303	301	H104-01	ELEC HARN (VEHICLE RECORDER DATA)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0000
304	302	H105-01	ELEC HARN (VEHICLE COMMAND)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0000
305	303	C200-08	PCA (HPOTP INTERMEDIATE SEAL PURGE)	INSUFFICIENT OR NO HELIUM PURGE P OW.	0.0000
306	304	D300-02	ANTI-FLOOD VALVE	VALVE FAILS TO OPEN.	0.0000
307	305	A600-01	FUEL PREBURNER	ASI FAILS TO IGNITE.	0.0000
308	306	B400-16	HIGH PRESSURE OXIDIZER TURBOPUMP	EXCESSIVE PRIMARY/SECONDARY SEAL LEAKAGE.	0.0000
309	307	D600-03	RECIRCULATION ISOLATION VALVE	FAILS TO OPEN.	0.0000
310	308	B200-01	HIGH PRESSURE FUEL TURBOPUMP	LEAKAGE PAST PREBURNER G5 STATIC SEAL INTO HOT GAS MANIFOLD.	0.0000
311	309	B400-02	HIGH PRESSURE OXIDIZER TURBOPUMP	EXCESSIVE TURBINE INLET FLOW DISTORTION.	0.0000
312	310	D500-02	GOX CONTROL VALVE	CHECK VALVE FAILS TO OPEN.	

ATTACHMENT 2

FAILURE MODE RANKING BY LRU

KEY TO ATTACHMENT 2

Column A - Overall Failure Mode Ranking

Column C - SSME FMEA Failure Mode Designation

Field 1 (1 digit) Component Type, example: **B**200-15

A = COMBUSTION DEVICES
B = TURBOMACHINERY
C = PNEUMATICS
D = PROPELLANT VALVES
E = ACTUATORS
F = CONTROLLER/FASCOS
G = IGNITERS
H = ELECTRICAL HARNESSES
J = SENSORS/INSTRUMENTATION
K = LINES AND DUCTS
L = JOINTS
M = GIMBAL
N = ORIFICES

Field 2 (3 digits) Specific Component Designation, example: B**200**-15

Field 3 (2 digits) Failure Mode Designation, example: B200-**15**

Column E - Specific Component (corresponds to field 2 of column C)

Column F - Failure Mode (corresponds to field 3 of column C)

Column BY - Figure of Merit Rating (0-1)

	A	C	E	F	BY
1	RANK	LRU-FM	COMPONENT		BY
2				FAILURE MODE	F.O.M.
3	29	A050-02	POWERHEAD	SHELL OR PROPELLANT DUCT RUPTURE.	0.0000
4	64	A050-01	POWERHEAD	LINER FAILURE.	0.1436
5					0.0714
6	1	A150-01	HEAT EXCHANGER	COIL FRACTURE/LEAKAGE.	
7	237	A150-02	HEAT EXCHANGER	INLET, BYPASS LINE, OUTLET RUPTURE.	0.6955
8	245	A150-03	HEAT EXCHANGER	BYPASS LINE ORIFICE RESTRICTION.	0.0268
9					0.0121
10	8	A200-06	MAIN INJECTOR	LOX POST CRACK.	
11	13	A200-09	MAIN INJECTOR	INTERPROPELLANT PLATE CRACKS.	0.2778
12	21	A200-07	MAIN INJECTOR	EXTERNAL RUPTURE.	0.2385
13	33	A200-05	MAIN INJECTOR	PARTIAL BLOCKAGE OF AN OXIDIZER ORIFICE.	0.2024
14	73	A200-08	MAIN INJECTOR	EXTERNAL RUPTURE.	0.1286
15	109	A200-03	MAIN INJECTOR	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0650
16	239	A200-02	MAIN INJECTOR	LOSS OF FUEL TO ASI.	0.0442
17	263	A200-01	MAIN INJECTOR	ASI FAILS TO IGNITE.	0.0217
18					0.0002
19	15	A330-02	MAIN COMBUSTION CHAMBER	FUEL LEAKS INTO THE CLOSED CAVITY BETWEEN THE LINER AND STRUCTURAL JACKET.	
20	25	A330-03	MAIN COMBUSTION CHAMBER	INTERNAL RUPTURE AT THE MCC NOZZLE INTERFACE.	0.2249
21	46	A330-04	MAIN COMBUSTION CHAMBER	EXTERNAL RUPTURE.	0.1599
22					0.0794
23	4	A340-02	NOZZLE ASSEMBLY	EXTERNAL RUPTURE.	
24					0.3660
25	6	A600-04	FUEL PREBURNER	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT OCCURS.	
26	30	A600-11	FUEL PREBURNER	EXTERNAL RUPTURE.	0.3487
27	47	A600-10	FUEL PREBURNER	EXTERNAL RUPTURE.	0.1436
28	75	A600-06	FUEL PREBURNER	OXIDIZER POST CRACKS.	0.0794
29	112	A600-09	FUEL PREBURNER	INTERPROPELLANT PLATE OR ELEMENT-TO-PLATE BRAZE JOINT LEAKAGE.	0.0585
30	124	A600-03	FUEL PREBURNER	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0434
31	125	A600-02	FUEL PREBURNER	LOSS OF FUEL TO ASI.	0.0342
32	132	A600-12	FUEL PREBURNER	OMEGA JOINT FAILURE.	0.0342
33	305	A600-01	FUEL PREBURNER	ASI FAILS TO IGNITE.	0.0298
34					0.0000
35	40	A700-02	OXIDIZER PREBURNER	LOSS OF FUEL TO ASI.	
36	68	A700-04	OXIDIZER PREBURNER	NON-UNIFORMITY OF FUEL FLOW IN THE INJECTION ELEMENT OCCURS.	0.0890
37	122	A700-06	OXIDIZER PREBURNER	OXIDIZER POST CRACKS.	0.0704
38	126	A700-03	OXIDIZER PREBURNER	BLOCKAGE OF ONE LOX ASI PASSAGE.	0.0390
39	127	A700-08	OXIDIZER PREBURNER	PARTIAL BLOCKAGE OF FUEL TO BAFFLES.	0.0342
40	133	A700-12	OXIDIZER PREBURNER	OMEGA JOINT FAILURE.	0.0342
41	134	A700-11	OXIDIZER PREBURNER	EXTERNAL RUPTURE.	0.0298
42	135	A700-10	OXIDIZER PREBURNER	EXTERNAL RUPTURE.	0.0298
43	136	A700-09	OXIDIZER PREBURNER	INTERPROPELLANT PLATE OR ELEMENT-TO-PLATE BRAZE JOINT LEAKAGE.	0.0298
44					0.0298
45					
46					
47					

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	A	C	E	F	BY
48	3	B200-04	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE OF TURBINE BLADES.	0.·322
49	7	B200-15	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF SUPPORT OR POSITION CONTROL.	0.3244
50	26	B200-26	HIGH PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE.	0.1599
51	37	B200-07	HIGH PRESSURE FUEL TURBOPUMP	TURBINE DISCHARGE FLOW BLOCKAGE.	0.0953
52	41	B200-16	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE BEARINGS.	0.0867
53	42	B200-17	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO TURBINE DISCS.	0.0867
54	44	B200-24	HIGH PRESSURE FUEL TURBOPUMP	FAILURE TO RESTRAIN SHAFT MOVEMENT DURING TURBOPUMP STARTUP.	0.0835
55	45	B200-23	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF BALANCING CAPABILITY.	0.0835
56	48	B200-18	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO INLET SUPPORT STRUTS AND BEARING SUPPORT BELLOWS.	0.0759
57	49	B200-19	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF COOLANT FLOW TO MAIN HOUSING, MOUNT RING, BEARING SUPPORT AND BELLOWS.	0.0759
58	66	B200-08	HIGH PRESSURE FUEL TURBOPUMP	FAILS TO TRANSMIT TORQUE.	0.0705
59	103	B200-22	HIGH PRESSURE FUEL TURBOPUMP	FUEL LEAKAGE PAST LIFT-OFF SEAL.	0.0456
60	137	B200-14	HIGH PRESSURE FUEL TURBOPUMP	FRAGMENTATION OF VOLUTE LINER.	0.0298
61	138	B200-03	HIGH PRESSURE FUEL TURBOPUMP	TURBINE BEARING SUPPORT BELLOWS FAILURE.	0.0298
62	241	B200-10	HIGH PRESSURE FUEL TURBOPUMP	LOSS OF IMPELLER HEAD RIZE.	0.0192
63	244	B200-06	HIGH PRESSURE FUEL TURBOPUMP	PLATFORM SEAL LEAKAGE.	0.0121
64	251	B200-09	HIGH PRESSURE FUEL TURBOPUMP	PRESSURE DROP OR FLOW DISTORTION AT IMPELLER INLET.	0.0107
65	252	B200-05	HIGH PRESSURE FUEL TURBOPUMP	SEAL FRACTURE, DISTORTION OR RUBBING.	0.0070
66	253	B200-02	HIGH PRESSURE FUEL TURBOPUMP	ENERGY LOSS AT TURBINE INLET.	0.0022
67	255	B200-20	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE COOLANT FLOW.	0.0007
68	262	B200-11	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE IMPELLER BYPASS LEAKAGE.	0.0002
69	272	B200-12	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE PUMP INTERSTAGE SEAL LEAKAGE.	0.0002
70	273	B200-13	HIGH PRESSURE FUEL TURBOPUMP	ENERGY LOSS IN DIFFUSERS AND HOUSING.	0.0002
71	289	B200-21	HIGH PRESSURE FUEL TURBOPUMP	EXCESSIVE HOT-GAS LEAKAGE INTO COOLANT CIRCUIT.	0.0001
72	308	B200-01	HIGH PRESSURE FUEL TURBOPUMP	LEAKAGE PAST PREBURNER G5 STATIC SEAL INTO HOT GAS MANIFOLD.	0.0000
73					
74	10	B400-03	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE BLADE STRUCTURAL FAILURE.	0.2656
75	11	B400-14	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF AXIAL BALANCING FORCE.	0.2656
76	12	B400-07	HIGH PRESSURE OXIDIZER TURBOPUMP	FAILURE TO TRANSMIT TORQUE.	0.2493
77	14	B400-22	HIGH PRESSURE OXIDIZER TURBOPUMP	PUMP PIECE PART STRUCTURAL FAILURE.	0.2331
78	24	B400-23	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE PIECE PART STRUCTURAL FAILURE	0.1680
79	36	B400-13	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT, POSITION CONTROL, OR ROTORDYNAMIC STABILITY.	0.1057
80	38	B400-20	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO FIRST- AND SECOND-STAGE TURBINE COMPONENTS.	0.0949
81	43	B400-18	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO BEARINGS.	0.0867
82	53	B400-01	HIGH PRESSURE OXIDIZER TURBOPUMP	LEAKAGE PAST THE OUTBOARD DPB/HPOTP PRESSURE-ASSISTED SEAL.	0.0731
83	84	B400-24	HIGH PRESSURE OXIDIZER TURBOPUMP	FRETTING OF INTERNAL PARTS.	0.0523
84	85	B400-21	HIGH PRESSURE OXIDIZER TURBOPUMP	STRUCTURAL FAILURE.	0.0488
85	87	B400-12	HIGH PRESSURE OXIDIZER TURBOPUMP	LEAKAGE UNDER LABYRINTH SEAL, MATING RING OR LEAKAGE OVER THE INTERMED.SEAL HOUSING.	0.0461
86	113	B400-15	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF PURGE PRESSURE BARRIER.	0.0434
87	243	B400-05	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE INTERSTAGE SEAL LEAKAGE.	0.0159
88	259	B400-04	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE BLADE TIP SEAL LEAKAGE.	0.0005
89	266	B400-19	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF COOLANT TO TURBINE SEALS.	0.0002
90	274	B400-09	HIGH PRESSURE OXIDIZER TURBOPUMP	LOSS OF INDUCER/IMPELLER HEAD RISE.	0.0002
91	278	B400-06	HIGH PRESSURE OXIDIZER TURBOPUMP	TURBINE DISCHARGE FLOW BLOCKAGE.	0.0002
92	281	B400-08	HIGH PRESSURE OXIDIZER TURBOPUMP	FLOW DISTORTION AT MAIN PUMP INLET.	0.0001
93	292	B400-10	HIGH PRESSURE OXIDIZER TURBOPUMP	ENERGY LOSS IN MAIN PUMP DIFFUSER.	0.0001
94	306	B400-16	HIGH PRESSURE OXIDIZER TURBOPUMP	EXCESSIVE PRIMARY/SECONDARY SEAL LEAKAGE.	0.0000

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95	309	B400-02	HIGH PRESSURE OXIDIZER TURBOPUMP	EXCESSIVE TURBINE INLET FLOW DISTORTION.	0.0000
96					
97	9	B600-06	LOW PRESSURE FUEL TURBOPUMP	FUEL LEAKAGE PAST LIFT-OFF SEAL.	0.2664
98	67	B600-03	LOW PRESSURE FUEL TURBOPUMP	FAILS TO TRANSMIT TORQUE.	0.0705
99	88	B600-07	LOW PRESSURE FUEL TURBOPUMP	STRUCTURAL FAILURE.	0.0461
100	256	B600-04	LOW PRESSURE FUEL TURBOPUMP	LOSS OF HEAD RISE.	0.0007
101	271	B600-05	LOW PRESSURE FUEL TURBOPUMP	LOSS OF SUPPORT OR POSITION CONTROL OF ROTATING ASSEMBLY.	0.0002
102	275	B600-02	LOW PRESSURE FUEL TURBOPUMP	POWER LOSS IN ROTOR.	0.0002
103	286	B600-01	LOW PRESSURE FUEL TURBOPUMP	ENERGY LOSS AT TURBINE INLET.	0.0001
104	294	B600-08	LOW PRESSURE FUEL TURBOPUMP	TURBINE SEAL LEAKAGE.	0.0001
105					
106	20	B800-06	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF SUPPORT AND POSITION CONTROL.	0.2085
107	79	B800-08	LOW PRESSURE OXIDIZER TURBOPUMP	PIECE PART STRUCTURAL FAILURE.	0.0542
108	83	B800-02	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF TURBINE POWER.	0.0525
109	118	B800-03	LOW PRESSURE OXIDIZER TURBOPUMP	FAILURE TO TRANSMIT TORQUE.	0.0407
110	139	B800-07	LOW PRESSURE OXIDIZER TURBOPUMP	STRUCTURAL FAILURE.	0.0298
111	238	B800-01	LOW PRESSURE OXIDIZER TURBOPUMP	SEAL LEAKAGE-TURBINE INLET.	0.0227
112	240	B800-09	LOW PRESSURE OXIDIZER TURBOPUMP	FRETTING OF INTERNAL PARTS.	0.0211
113	276	B800-04	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF INDUCER HEAD RISE.	0.0002
114	293	B800-05	LOW PRESSURE OXIDIZER TURBOPUMP	LOSS OF DYNAMIC HEAD RECOVERY/GUIDANCE.	0.0001
115					
116	70	C113-01	OXIDIZER DOME PURGE CHECK VALVE	FAILS TO OPEN OR RESTRICTS FLOW DURING PROPELLANT CONDITIONING.	0.0658
117					
118	71	C116-01	FUEL PREBURNER ASI PURGE CHECK VALVE	FAILS TO OPEN OR RESTRICTS FLOW DURING PROPELLANT CONDITIONING.	0.0658
119	264	C116-02	FUEL PREBURNER ASI PURGE CHECK VALVE	CHECK VALVE LEAKS.	0.0002
120					
121	2	C200-11	PCA (EMERGENCY PNEUMATIC SHUTDOWN)	FAILURE TO SUPPLY HELIUM PRESSURANT.	0.5434
122	32	C200-07	PNEUMATIC CONTROL ASSEMBLY (OXIDIZER SYS PURGE)	INSUFFICIENT OR NO NITROGEN PURGE FLOW DURING PROPELLANT CONDITIONING	0.1337
123	104	C200-12	PCA (EMERGENCY PNEUMATIC SHUTDOWN)	PURGE SEQUENCE VALVE FAILS TO ACTUATOR DURING PROPELLANT CONDITIONING.	0.0444
124	260	C200-16	PNEUMATIC CONTROL ASSEMBLY	FAILURE TO CONTAIN HELIUM.	0.0004
125	265	C200-09	PCA (HPOTP INTERMEDIATE SEAL PURGE)	INSUFFICENT OR NO HELIUM PURGE FLOW.	0.0002
126	287	C200-18	PNEUMATIC CONTROL ASSEMBLY	FAILS TO ACTUATOR FULLY (FUEL SYSTEM PURGE PAV, OXIDIZER BLEED PAV).	0.0001
127	288	C200-17	PNEUMATIC CONTROL ASSEMBLY	FAILS TO ACTUATOR FULLY (EMERGENCY SHUTDOWN PAV, HPOTP INTERMEDIATE SEAL PURGE PAV	0.0001
128	303	C200-08	PCA (HPOTP INTERMEDIATE SEAL PURGE)	INSUFFICIENT OR NO HELIUM PURGE FLOW.	0.0000
129					
130	89	C300-06	HELIUM PRECHARGE VALVE	FAILURE TO CINTAIN HELIUM PRESSURANT.	0.0461
131	105	C300-02	HELIUM PRECHARGE VALVE	FAILURE TO TERMINATE HELIUM PRESSURANT FLOW TO POGO ACCUMULATOR DURING PROPELLANT	0.0444
132	131	C300-01	HELIUM PRECHARGE VALVE	INSUFFICIENT OR NO HELIUM PRESSURANT TO POGO ACCUMULATOR.	0.0325
133	140	C300-07	HELIUM PRECHARGE VALVE	FAILURE TO CONTAIN OXIDIZER.	0.0298
134					
135	5	D110-01	MAIN FUEL VALVE	INTERNAL LEAKAGE.	0.3577
136	86	D110-04	MAIN FUEL VALVE	STRUCTURAL FAILURE.	0.0488
137	267	D110-02	MAIN FUEL VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
138					
139	28	D120-05	MAIN OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.1572
140	31	D120-04	MAIN OXIDIZER VALVE	STRUCTURAL FAILURE.	0.1436
141	35	D120-06	MAIN OXIDIZER VALVE	FRETTING OF INTERNAL PARTS.	0.1076

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142	76	D120-03	MAIN OXIDIZER VALVE	SEAL LEAKAGE.	0.0583
143	279	D120-02	MAIN OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
144					
145	34	D130-03	FUEL PREBURNER OXIDIZER VALVE	SHAFT SEAL LEAK.	0.1286
146	110	D130-06	FUEL PREBURNER OXIDIZER VALVE	FRETTING OF INTERNAL PARTS.	0.0442
147	114	D130-05	FUEL PREBURNER OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
148	141	D130-04	FUEL PREBURNER OXIDIZER VALVE	STRUCTURAL FAILURE.	0.0298
149	268	D130-02	FUEL PREBURNER OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
150					
151	54	D140-01	OXIDIZER PREBURNER OXIDIZER VALVE	INTERNAL LEAKGE.	0.0731
152	65	D140-03	OXIDIZER PREBURNER OXIDIZER VALVE	SHAFT SEAL LEAK.	0.0707
153	111	D140-06	OXIDIZER PREBURNER OXIDIZER VALVE	FRETTING OF INTERNAL PARTS.	0.0442
154	115	D140-05	OXIDIZER PREBURNER OXIDIZER VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
155	142	D140-04	OXIDIZER PREBURNER OXIDIZER VALVE	STRUCTURAL FAILURE.	0.0298
156	269	D140-02	OXIDIZER PREBURNER OXIDIZER VALVE	FAILS TO MOVE OR MOVES SLOWLY.	0.0002
157					
158	143	D150-03	CHAMBER COOLANT VALVE	STRUCTURAL FAILURE.	0.0298
159					
160	72	D210-03	FUEL BLEED VALVE	GROSS LEAKAGE.	0.0658
161					
162	23	D220-06	OXIDIZER BLEED VALVE	FRETTING OF INTERNAL PARTS.	0.1889
163	50	D220-03	OXIDIZER BLEED VALVE	GROSS LEAKAGE.	0.0759
164	117	D220-05	OXIDIZER BLEED VALVE	PIECE PART STRUCTURAL FAILURE.	0.0418
165	280	D220-02	OXIDIZER BLEED VALVE	VALVE FAILS TO CLOSE.	0.0002
166					
167	18	D300-01	ANTI-FLOOD VALVE	LEAKAGE DURING PROPELLANT CONDITIONING.	0.2208
168	39	D300-03	ANTI-FLOOD VALVE	LOW FLOW RESTRICTED OR SHUT OFF.	0.0949
169	74	D300-07	ANTI-FLOOD VALVE	PIECE PART STRUCTURAL FAILURE.	0.0623
170	78	D300-08	ANTI-FLOOD VALVE	FRETTING OF INTERNAL PARTS.	0.0563
171	144	D300-06	ANTI-FLOOD VALVE	STRUCTURAL FAILURE.	0.0298
172	304	D300-02	ANTI-FLOOD VALVE	VALVE FAILS TO OPEN.	0.0000
173					
174	17	D500-06	GOX CONTROL VALVE	MAINTAIN STRUCTURAL INTEGRITY.	0.2222
175	69	D500-08	GOX CONTROL VALVE	FRETTING OF INTERNAL PARTS.	0.0704
176	145	D500-05	GOX CONTROL VALVE	STRUCTURAL FAILURE.	0.0298
177	270	D500-04	GOX CONTROL VALVE	FAILS TO OPEN.	0.0002
178	1	D500-02	GOX CONTROL VALVE	CHECK VALVE FAILS TO OPEN.	
179					
180	51	D600-07	RECIRCULATION ISOLATION VALVE	FRETTING OF INTERNAL PARTS.	0.0759
181	116	D600-06	RECIRCULATION ISOLATION VALVE	PIECE PART STRUCTURAL FAILURE.	0.0434
182	146	D600-05	RECIRCULATION ISOLATION VALVE	STRUCTURAL FAILURE.	0.0298
183	307	D600-03	RECIRCULATION ISOLATION VALVE	FAILS TO OPEN.	0.0000
184					
185	52	E110-09	MAIN FUEL VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0759
186	55	E110-13	MAIN FUEL VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON LEAKAGE.	0.0731
187	56	E110-04	MAIN FUEL VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0731
188	147	E110-12	MAIN FUEL VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298

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189	148	E110-11	MAIN FUEL VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
190	257	E110-01	MIAN FUEL VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0007
191					
192	57	E120-12	MAIN OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON LEAKAGE.	0.0731
193	58	E120-04	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
194	77	E120-09	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0567
195	149	E120-10	MAIN OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
196	217	E120-11	MAIN OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0287
197	295	E120-01	MAIN OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0001
198					
199	59	E130-04	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
200	60	E130-12	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUCNE VALVE LEAKAGE.	0.0731
201	81	E130-13	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	SEQUENCE VALVE FAILS TO PASS PNEUMATIC PRESSURE TO DOWNSTREAM COMPONENTS.	0.0535
202	90	E130-09	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO GO INTO HYDRAULIC LOCKUP.	0.0461
203	150	E130-11	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
204	151	E130-10	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
205	258	E130-01	FUEL PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0007
206					
207	61	E140-12	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUCNE VALVE LEAKAGE.	0.0731
208	62	E140-04	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO CLOSE PNEUMATICALLY.	0.0731
209	82	E140-13	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	SEQUENCE VALVE FAILS TO PASS PENUMATIC PRESSURE TO DOWNSTREAM COMPONENTS.	0.0535
210	152	E140-11	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
211	153	E140-10	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
212	277	E140-01	OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR	FAILS TO RESPOND TO POSITION COMMANDS.	0.0002
213					
214	22	E150-14	CHAMBER COOLANT VALVE ACTUATOR	SEQUENCE VALVE LEAKS PASSING EARLY CONTROL PRESSURANT DOWNSTREAM.	0.1897
215	63	E150-12	CHAMBER COOLANT VALVE ACTUATOR	PNEUMATIC SHUTDOWN PISTON OR SEQUENCE VALVE LEAKAGE.	0.0731
216	154	E150-11	CHAMBER COOLANT VALVE ACTUATOR	STRUCTURAL FAILURE.	0.0298
217					
218	290	FOAG-01	PRESSURE SENSOR INTERFACE P9	FAILURE OF MCC Pc PRESSURE SENSOR INTERFACE.	0.0001
219	299	FOBG-02	POGO PRECHARGE SOLENOID CONTROL	FAILURE TO PROVIDE HOLDING CURRENT TO MAINTAIN SOLENOID ENERGIZED.	0.0000
220	300	FOBG-01	POGO PRECHARGE SOLENOID CONTROL	FAILURE TO PROVIDE THE CURRENT OT ENERGIZE THE SOLENOID.	0.0000
221	106	FOBJ-04	EMERGENCY SHUTDOWN SOLENOID CONTROL	FAILURE TO MAINTAIN SOLENOID DE-ENERGIZED.	0.0444
222	298	FOBJ-03	EMERGENCY SHUTDOWN SOLENOID CONTROL	FAILURE TO REMOVE THE CURRENT OT DE-ENERGIZE SOLENOID.	0.0000
223	291	FOBN-01	VEHICLE RECORDER INTERFACE	DATA PATH FAILURE.	0.0001
224					
225	254	G100-01	SPARK IGNITER	REDUNDANT MAIN INJECTOR IGNITERS FAIL TO SPARK/WEAK OR LOW SPARK RATE.	0.0019
226					
227	283	H103-01	ELEC HARN (VEHICLE RECORDER DATA)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0001
228	301	H104-01	ELEC HARN (VEHICLE RECORDER DATA)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0000
229	302	H105-01	ELEC HARN (VEHICLE COMMAND)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0000
230	282	H108-01	ELEC HARN (BLEED VALVE SOLENOID CONTROL)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0001
231	261	H111-01	ELEC HARN (EMERG SHUTDOWN CONTROL SOLENOID VAVL	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0003
232	123	H112-01	ELEC HARN (ANTI-FLOOD VALVE POSITION INDICATOR)	OPEN OR SHORT CIRCUIT IN HARNESS. LOSS OF CONNECTOR.	0.0383
233					
234	155	J201-02	MCC Pc PRESSURE TRANSDUCER (G8.7)	LEAKAGE INTO SENSOR HOUSING.	0.0298
235	284	J201-01	MCC Pc PRESSURE TRANSDUCER (G8.7)	NO OUTPUT OR ERRONEOUS SIGNAL.	0.0001

	A	C	E	F	BY
236	156	J202-02	MCC Pc PRESSURE TRANSDUCER (G8.8)	LEAKAGE INTO SENSOR HOUSING.	0.0298
237	285	J202-01	MCC Pc PRESSURE TRANSDUCER (68.8)	NO OUTPUT OR ERRONEOUS SIGNAL	0.0001
238					
239	157	J205-02	FUEL PREBURNER CHAMBER PRESSURE TRANSDUCER (G	LEAKAGE INTO SENSOR HOUSING.	0.0298
240	15b	J207-02	OXIDIZER TANK PRESSURANT TRANSDUCER (020.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
241	159	J208-02	HPFTP DISCHARGE PRESSURE TRANSDUCER (F4.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
242	160	J209-02	HPOTP BOOST PUMP DISCH PRESS TRANSDUCER (011.1	LEAKAGE INTO SENSOR HOUSING.	0.0298
243	161	J210-02	FUEL INJECTION PRESSURE TRANSDUCER(G7.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
244	162	J220-02	HPOTP DISCHARGE PRESSURE TRANSDUCER (06.1)	LEAKAGE INTO SENSOR HOUSING.	0.0298
245	163	J221-02	MCC COOLANT OUTLET PRESSURE TRANSDUCER (F7.1a)	LEAKAGE INTO SENSOR HOUSING.	0.0298
246	164	J222-02	POGO PRECHARGE PRESSURE TRANSDUCER (026.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
247	218	J223-02	FPB PURGE PRESSURE TRANSDUCERS (P2.5)	LEAKAGE INTO SENSOR HOUSING.	0.0287
248	219	J224-02	OPB PURGE PRESSURE TRANSDUCERS (P2.4)	LEAKAGE INTO SENSOR HOUSING.	0.0287
249	165	J225-02	EMERGENCY SHUTDOWN PRESSURE TRANSDUCER (P2.3)	LEAKAGE INTO SENSOR HOUSING.	0.0298
250	166	J230-02	HPOTP COOLANT LINER PRESSURE TRANSDUCER (N11.2)	LEAKAGE INTO SENSOR HOUSING.	0.0298
251	167	J306-02	LPFTP DISCHARGE TEMPERATURE TRANSDUCER (F2.3)	STRUCTURAL FAILURE OF PROBE.	0.0298
252	168	J309-03	MCC COOLANT OUTLET TEMPERATURE TRANSDUCER (F7	LEAKAGE INTO SENSOR HOUSING.	0.0298
253					
254	169	J312-03	HPOTP BOOST STAGE DISCHARGE TEMPERATURE (011.1	LEAKAGE INTO SENSOR HOUSING.	0.0298
255	242	J312-02	HPOTP BOOST STAGE DISCHARGE TEMPERATURE (011.1	STRUCTURAL FAILURE OF PROBE.	0.0163
256					
257	170	J313-02	MCC OXIDIZER INJECTION TEMP TRANSDUCER (08.3)	STRUCTURAL FAILURE OF PROBE.	0.0298
258	171	J609-02	LPOTP SHAFT SPEED TRANSDUCER (01.1)	STRUCTURAL FAILURE.	0.0298
259	80	J701-02	FUEL FLOWMETER	PIECE PART FAILURE.	0.0542
260					
261	91	K101-02	LPFTP DISCHARGE DUCT (LPFTP DUCT HELIUM BAG)	FAILS TO CONTAIN OXIDIZER.	0.0461
262	172	K101-03	LPFTP DISCHARGE DUCT (LPFTP DUCT HELIUM BAG)	PIECE PART STRUCTURAL FAILURE.	0.0298
263					
264	92	K102-01	LPFTP TURBINE DRIVE DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
265	16	K103-01	LPFTP TURBINE DISCHARGE DUCT	FAILS TO CONTAIN HYDROGEN	0.2249
266	93	K104-02	FUEL BLEED DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
267	173	K104-01	FUEL BLEED DUCT	LOSS OF INSULATION CAPABILITY	0.0298
268	19	K106-02	HIGH PRESSURE FUEL DUCT	FAILS TO CONTAIN HYDROGEN	0.2087
269	174	K107-01	FUEL TANK PRESSURANT LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
270	175	K110-02	FUEL BLEED DUCT	FAILS TO CONTAIN HYDROGEN.	0.0298
271	176	K111-01	PREBURNER FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
272	177	K112-01	OPB ASI FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
273	178	K113-01	FPB ASI FUEL SUPPLY LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
274	179	K120-01	LPFTP DISCHARGE PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
275	180	K121-01	HPFTP DISCHARGE PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
276	94	K201-03	LPOTP DISCHARGE DUCT	FRETTING OF INTERNAL PARTS.	0.0461
277	181	K201-02	LPOTP DISCHARGE DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
278	182	K201-01	LPOTP DISCHARGE DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
279	95	K202-03	LPOTP TURBINE DRIVE DUCT	FRETTING OF INTERNAL PARTS.	0.0461
280	96	K202-01	LPOTP TURBINE DRIVE DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
281	183	K202-02	LPOTP TURBINE DRIVE DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
282	27	K203-01	OXIDIZER BLEED FLEX LINE	FAILS TO CONTAIN OXIDIZER.	0.1599

	A	C	E	F	BY
283	97	K204-03	OXIDIZER TANK PRESSURANT DUCT	FRETTING OF INTERNAL PARTS.	0.0461
284	98	K204-01	OXIDIZER TANK PRESSURANT DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
285	184	K204-02	OXIDIZER TANK PRESSURANT DUCT	INTERNAL STRUCTURAL FAILURE.	0.0298
286	99	K205-01	HIGH PRESSURE OXID DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
287	185	K206-01	FPB OXIDIZER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
288	186	K207-01	HEAT EXCHANGER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
289	100	K208-01	PREBURNER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0461
290	187	K211-01	OPB ASI OXIDIZER SUPPLY	FAILS TO CONTAIN GN2.	0.0298
291	188	K212-01	OPB OXIDIZER SUPPLY DUCT	FAILS TO CONTAIN OXIDIZER.	0.0298
292	189	K213-01	OXID BLEED LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
293	190	K214-01	OXID RECIRC BLEED LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
294	191	K215-01	POGO GOX SUPPLY LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
295	192	K216-01	RIV OVERRIDE LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
296	193	K217-01	ACCUMULATOR SUPPLY LINE	FAILS TO CONTAIN OXIDIZER/HELIUM.	0.0298
297	194	K218-01	POGO PRECHARGE LINE	FAILS TO CONTAIN OXIDIZER/HELIUM.	0.0298
298	195	K219-01	HPOTP DISC PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
299	196	K220-01	PB DISCH PRESSURE TRANSDUCER LINE	FAILS TO CONTAIN OXYGEN.	0.0298
300	197	K222-01	HEAT EXCH OUTLET PRESS TRANS LINE	FAILURE TO CONTAIN GASEOUS OXYGEN.	0.0298
301	198	K223-01	LPOTP DISCH PRESS TRANSDUCER LINE	FAILURE TO CONTAIN OXYGEN.	0.0298
302	199	K318-01	HPOTP TURBINE PRIMARY SEAL DRAIN	FAILURE TO CONTAIN HOT GAS.	0.0298
303	200	K319-01	HPOTP 2ND SEAL DRAIN LINE	FAILS TO CONTAIN HOT GAS.	0.0298
304	201	K320-01	HPOTP OXID SEAL DRAIN MANIFOLD	FAILURE TO CONTAIN OXIDIZER.	0.0298
305	107	K401-01	HYDRAULIC SUPPLY HOSE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0444
306	220	K401-02	HYDRAULIC SUPPLY HOSE	QUICK-DISCONNECT FAILS (DISCONNECTS).	0.0287
307	202	K403-02	HYDRAULIC RETURN HOSE	QUICK-DISCONNECT FAILS (DISCONNECTS).	0.0298
308	221	K405-01	MFVA HYDRAULIC SUPPLY LINE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
309	222	K406-01	MOVA HYDRAULIC SUPPLY LINE	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
310	223	K407-01	HYDRAULIC SUPPLY MANIFOLD	FAILURE TO CONTAIN HYDRAULIC FLUID.	0.0287
311	101	K501-01	HELIUM SUPPLY HOSE	FAILS TO CONTAIN HELIUM.	0.0461
312	108	K502-01	NITROGEN SUPPLY HOSE	FAILS TO CONTAIN GN2.	0.0444
313	224	K503-01	OXIDIZER SYSTEM LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
314	203	K505-01	HPOTP INTERMEDIATE SEAL PURGE LINE	FAILS TO CONTAIN HELIUM.	0.0298
315	225	K508-01	OPOVA EMER SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
316	226	K509-01	MCC DOME PURGE LINE	FAILS TO CONTAIN GN2.	0.0287
317	227	K510-01	EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
318	228	K511-01	EMERGENCY SHUTDOWN CONTROL LINES	FAILS TO CONTAIN HELIUM.	0.0287
319	229	K512-01	MFV EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
320	230	K513-01	CCV EMERGENCY SHUTDOWN CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
321	204	K515-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
322	231	K516-01	NITROGEN SUPPLY LINES	FAILS TO CONTAIN GN2.	0.0287
323	232	K518-01	FPB PURGE LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
324	205	K519-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
325	233	K530-01	HPV WARMANT LINES	FAILS TO CONTAIN GN2.	0.0287
326	206	K532-01	HELIUM SUPPLY LINE	FAILS TO CONTAIN HELIUM.	0.0298
327	234	K535-01	NITROGEN SUPPLY LINE	FAILS TO CONTAIN GN2.	0.0287
328	246	K536-01	EMERGENCY SHUTDOWN POGO POST CHANGE	FAILS TO CONTAIN HELIUM.	0.0121
329	207	K540-01	MCC DRYING PURGE LINE	FAILS TO CONTAIN GN2.	0.0298

	A	C	E	F	BY
330	208	K541-01	HPFTP BEARING PURGE LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
331	235	K544-01	FPB ASI PURGE LINE	FAILS TO CONTAIN PURGE GAS.	0.0287
332	209	K546-01	REMOVE MOUNT MCC FUEL PRES LINE	FAILS TO CONTAIN HOT GAS.	0.0298
333	210	K547-01	MCC PC PRESSURE LINE	FAILURE TO CONTAIN HOT GAS.	0.0298
334	211	K548-01	HPFTP COOLANT LINER PRES TRANS LINE	FAILS TO CONTAIN HYDROGEN.	0.0298
335	212	K549-01	OFFSET MOUNT MCC Pc PRESSURE LINE	FAILURE TO CONTAIN HOT GAS.	0.0298
336					
337	119	L101-01	FUEL SYSTEM JOINTS	LEAKAGE.	0.0399
338	296	L101-01	FUEL SYSTEM JOINTS	LEAKAGE.	0.0001
339	120	L102-01	OXIDIZER SYSTEM JOINTS	LEAKAGE.	0.0399
340	297	L102-01	OXIDIZER SYSTEM JOINTS	LEAKAGE.	0.0001
341	121	L103-01	HOT GAS SYSTEM JOINTS	LEAKAGE.	0.0399
342					
343	102	N400-01	POGO SUPPRESSOR ACCUMULATOR	FAILURE TO CONTAIN HELIUM/OXIDIZER.	0.0461
344	213	N400-02	POGO SUPRESSOR ACCUMULATOR	INTERNAL STRUCTURAL FAILURE.	0.0298
345	214	N500-01	POGO RECIRCULATION LINE	FAILS TO CONTAIN OXIDIZER.	0.0298
346	215	N700-02	ADAPTER STANDPIPE	INTERNAL STRUCTURAL FAILURE.	0.0298
347	216	N700-01	ADAPTER STANDPIPE	EXTERNAL STRUCTURAL FAILURE.	0.0298
348	248	N704-01	FPB ASI PURGE ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0115
349	249	N707-01	MAIN INJECTOR OXID PURGE ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0115
350	247	N709-01	GCV GOX OUTLET ORIFICE	ORIFICE RESTRICTED OR BLOCKED.	0.0121
351	128	N717-01	MCC ASI FUEL ORFICE (F5.2)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
352	129	N718-01	OPB ASI FUEL ORFICE (F25)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
353	130	N719-01	FPB ASI FUEL ORFICE (F21)	ORIFICE RESTRICTED OR BLOCKED.	0.0325
354	250	N724-01	GOX CONTROL VALVE INLET ORIFICE (024)	ORIFICE RESTRICTED OR BLOCKED.	0.0115
355	236	N900-01	GCV CONTROL LINE	FAILS TO CONTAIN HELIUM.	0.0287
356	END				

ATTACHMENT 3

FAILURE MODE SUMMARIES

ABBREVIATIONS AND ACRONYMS

AFV	Anti-Flood Valve
ASI	Augmented Spark Igniter
CCV	Chamber Coolant Valve
CCVA	Chamber Coolant Valve Actuator
F	Flight
FBV	Fuel Bleed Valve
FPB	Fuel Preburner
FPL	Full Power Level
FPOV	Fuel Preburner Oxidizer Valve
GCV	Gaseous Oxygen Control Valve
HEX	Heat Exchanger
HF	High Frequency
HGM	Hot Gas Manifold
HPFTP	High-Pressure Fuel Turbopump
HPOTP	High-Pressure Oxidizer Turbopump
HPV	Helium Precharge Valve
LPFTP	Low-Pressure Fuel Turbopump
LPOTP	Low-Pressure Oxidizer Turbopump
LRU	Line Replaceable Unit
LVDT	Linear Variable Differential Transformer
MCC	Main Combustion Chamber
MFV	Main Fuel Valve
MOV	Main Oxidizer Valve
MPL	Minimum Power Level
MR	Mixture Ratio
MVA	Main Valve Actuator
OBV	Oxidizer Bleed Valve
OPB	Oxidizer Preburner
OPOV	Oxidizer Preburner Oxidizer Valve
OX	Oxidizer
PB	Preburner
PBP	Preburner Boost Pump
PBVA	Preburner Valve Actuator
PCA	Pneumatic Control Assembly
RIV	Recirculation Isolation Valve
RPL	Rated Power Level
RVDT	Rotary Variable Differential Transformer
SRB	Solid Rocket Booster
TB	Test Bed
VEEI	Vehicle Engine Electronics Interface

Rank No.: 1
Component: Heat Exchanger (HEX)
Failure Mode: Coil fracture/leakage
Line Replaceable Unit - Failure Mode No.: **A150-01**

Possible causes: (1) Coil weld or parent material fracture due to fatigue, (2) loss of channel/bracket supports, (3) damage due to impact from fragmented liner, turning vanes, or channels, (4) tube wall wear at support points, (5) tube damage during HPOTP removal and installation, and (6) coil collapse.

Possible effects: Mixing of GOX with fuel-rich hot gas stream could result in ignition, detonation, and burning. Burning would result in coil, HGM liner or HPOTP turbine, or main injector burn-through causing loss of engine. Fuel-rich hot gas could enter the downstream side of the coil and combine with oxygen from the bypass system, causing a fire in the discharge line that supplies the POGO accumulator and the vehicle oxygen pressurization system.

Available sensors: (1) HEX discharge pressure (F, TB), and (2) HEX interface temperature (F, TB). Detection is difficult to accommodate.

Test correlation with failure mode: 901-222

Rank No.: 2
Component: Pneumatic Control Assembly (PCA) - Emergency Pneumatic Shutdown
Failure Mode: Failure to supply Helium pressurant
Line Replaceable Unit - Failure Mode No.: **C200-11**

Possible causes: (1) PCA component failure (PCA inlet Helium filter blocked, emergency pneumatic orifice blocked), (2) emergency shutdown solenoid valve failure (armature jammed closed, push rod jammed closed, broken spring), (3) vent port poppet/seat leakage (contamination, damaged/defective sealing surface), and (4) control cavity seal leakage (contamination, damaged/defective seal).

Possible effects: If Helium pressurant is not applied to the closing piston of the main fuel valve (MFV) actuator, the MFV could drift, causing propellant leakage which could in turn result in fire, open air detonation, and overpressure condition.

Available sensors: None, no sensor information would be effective since, without a working PCA, the system can not be shutdown.

Test correlation with failure mode: 750-163

Rank No.: 3
Component: High Pressure Fuel Turbopump (HPFTP)
Failure Mode. Structural Failure of Turbine Blades
Line Replaceable Unit - Failure Mode No.: **B200-04**

Possible causes: (1) Rotor blade cracks, (2) loss of blade dampers, (3) excessive tip rubbing, (4) tip seal failure, (5) housing pilot lip failure (6) housing retaining lug failure, (7) nozzle failure, (8) impact from macroscopic contaminant, (9) disk fir-tree yielding or fracture, and (10) excessive rubbing of platform seals.

Possible effects: Multiple blade failures resulting in immediate loss of turbine power and rotor imbalance. Rotor imbalance results in excessive vibration which would cause more rubbing and additional component failures. Extensive turbine damage could result from impact and overtemperature. Possible burst of pump inlet due to pressure surge. Possible HPFTP seizure could result in LOX-rich shutdown with subsequent main injector or fuel preburner injector post damage/erosion.

Available sensors: (1) HPFTP speed (F, TB), (2) LPFTP speed (F, TB), (3) HPFP discharge pressure (F, TB), (4) HPFT discharge temperature (F, TB), (5) LPFT discharge pressure (F, TB), (6) LPFT discharge temperature (F, TB), and (7) FPB chamber pressure (F, TB), (8) FPOV position (F, TB), (9) OPOV position (F, TB), and (10) HPFTP housing strain (TB).

Test correlation with failure mode: 902-249.

Rank No.: 4
Component: Nozzle Assembly
Failure Mode: External Rupture
Line Replaceable Unit - Failure Mode No.: **A340-02**

Possible causes: (1) Structural failure of the steerhorn, feedlines, mixer, diffuser, forward and aft manifold, and (2) tube failure and jacket fatigue.

Possible effects: Overpressurization due to leakage external to the nozzle and into the aft compartment. Fragmentation may cause damage to adjacent engines. Sudden loss of fuel causes LOX-rich operation.

Available sensors: (1) HPFT discharge temperature (F, TB), (2) HPFT discharge pressure (F, TB), (3) HPOT discharge temperature (F, TB), (4) HPOT discharge pressure (F, TB), (5) FPOV position (F, TB), and OPOV position (F, TB).

Test correlation with failure mode: 901-485, 902-162, 750-041, 750-285, SF6-03,. SF10-01.

Rank No.: 5
Component: Fuel Valve
Failure Mode: Internal Leakage
Line Replaceable Unit - Failure Mode No.: **D110-01**

Possible causes: (1) Damage/failure of seal, ball, or bellows, and (2) contamination.

Possible effects: (1) Fire due to leakage, and (2) open air detonation and overpressure condition.

Available sensors: (1) HPFT discharge temperature (F, TB), (2) HPOT discharge temperature (F, TB), (3) HPFT discharge pressure (F, TB), (4) HPOT discharge pressure (F, TB), (5) FPOV position (F, TB), (6) OPOV position (F, TB), (7) MCC coolant discharge temperature (F, TB), (8) MCC coolant discharge pressure (F, TB), and (9) MCC pressure (F, TB).

Test correlation with failure mode: SF6-01

Rank No.: 6
Component: Fuel Preburner
Failure Mode: Non-uniformity of Fuel Flow in the Injector Element.
Line Replaceable Unit - Failure Mode No.: **A600-04**

Possible causes: (1) contamination in the fuel annulus, and (2) slippage of LOX post support pins.

Possible effects: Local high mixtures and recirculation of gases around the elements periphery due to non-uniformity which, in turn, causes local erosion of the injection element tip, the injector faceplate, the combustion zone liner or injector baffle. Erosion through the liner may result in burn-through of the structural wall.

Available sensors: HPFT discharge temperature (F, TB), (2) FPB pressure (F, TB), (3) FPB fuel manifold pressure (TB), and (4) FPB oxidizer manifold pressure (TB).

Test correlation with failure mode: SF10-01, 901-307, 902-244.

Rank No.: 7
Component: High Pressure Fuel Turbopump (HPFTP)
Failure Mode: Loss of support or position control.
Line Replaceable Unit - Failure Mode No.: **B200-15**

Possible causes: (1) Bearing failure (ball/cage failure, loss of coolant, corrosion, contamination, race failures, (2) fracture/distortion of bearing carrier or excessive loss of bolt preload, (3) excessive loss of bearing retaining nut preload, (4) excessive clearance at pump interstage seals, (5) failure or excessive wear of bearing preload spring, (6) pump slinger pin failure, and (7) stud failure or loss of preload.

Possible effects: Reduced speed, flow and pump output pressure, and increased vibration levels. Possible turbine blade failure or disintegration of rotating assembly.

Available sensors: (1) HPFTP speed (F, TB), (2) HPFTP discharge pressure (F, TB), (3) fuel flowrate (F, TB), (4) HPFTP radial and axial accelerometers (F, TB), (5) HPFP balance cavity pressure (TB), and (6) HPFP thrust bearing speed (TB).

Test correlation with failure mode: none

Rank No.: 8
Component: Main Injector
Failure Mode: LOX post crack
Line Replaceable Unit - Failure Mode No.: **A200-6**

Possible causes: (1) Impact damage, (2) weld or material flaws, (3) fatigue, (4) scrub liner failure, (5) heat shield retainer failure, (6) secondary faceplate retainer failure, and (7) loss of flow shield function.

Possible effects: Post and injector burnout as a result of hot gas flowing into the posts and igniting with the oxidizer. Injector debris can rupture nozzle tubes, causing preburner fuel starvation, turbine and main injector burnout, and aft compartment overpressurization and fire.

Available sensors: (1) HPOT discharge temperature (F, TB), (2) HPFT discharge temperature (F, TB), (3) HPOT discharge pressure (F, TB), (4) HPFT discharge pressure (F, TB), (5) HPOP speed (F, TB), (6) HPFP speed (F, TB), (7) OPOV position (F, TB), (8) FPOV position (F, TB), and (9) MCC pressure (F, TB).

Test correlation with failure mode: 901-173, 901-183, 901-331, 902-198, 750-148.

Rank No.: 9
Component: Low Pressure Fuel Turbopump (LPFTP)
Failure Mode: Fuel leakage fast liftoff seal.
Line Replaceable Unit - Failure Mode No.: **B600-06**

Possible causes: (1) Contamination, (2) damaged sealing surfaces on liftoff seal or shaft, (3) binding within liftoff seal, (4) leakage past static seal at liftoff seal to manifold interface, and (5) damage due to failure to liftoff..

Possible effects: Fuel flow into the turbine and through the MCC and nozzle with the possible result of open air fire/detonation.

Available sensors: (1) LPFTP discharge pressured, (2) LPFTP shaft speed, (3) LPFTP discharge HF pressure, (4) LPFTP turbine inlet pressure, (5) LPFTP turbine pressure drop, and (6) LPFTP radial accelerometer.

Test correlation with failure mode: None.

Rank No.: 10
Component: High Pressure Oxidizer Turbopump (HPOTP)
Failure Mode: Turbine Blade structural failure.
Line Replaceable Unit - Failure Mode No.: **B400-03**

Possible causes: (1) Blade cracks, (2) rotor blade tip rubbing, (3) honeycomb retainer failure, (4) impact, (5) inadequate cooling flow, (6) loss of damper function, (7) operation t resonance, (8) disc fir-tree yielding and fracture, and (9) nozzle failure.

Possible effects: Loss of turbine blades, leading to multiple blade failure and rotor unbalance, with subsequent rubbing and ultimate rotating assembly disintegration.

Available sensors: (1) Strain gages near shaft, and (2) accelerometer.

Test correlation with failure mode: None.

Rank No.: 11
Component: High Pressure Oxidizer Turbopump (HPOTP)
Failure Mode: Loss of Axial Balancing Force
Line Replaceable Unit - Failure Mode No.: **B400-14**

Possible causes: (1) Damage to balance piston orifices from contamination, and (2) Loss of bolt preload causing rubbing in the balance piston region.

Possible effects: Excessive shaft axial displacement resulting in internal rubbing of rotating components. Disintegration of rotating parts will occur at high speeds.

Available sensors: (1) Strain gage near shaft, and (2) HPOTP preburner accelerometer.

Test correlation with failure mode: none

Rank No.: 12
Component: High Pressure Oxidizer Turbopump (HPOTP)
Failure Mode: Failure to Transient Torque
Line Replaceable Unit - Failure Mode No.: **B400-07**

Possible causes: (1) Failure of shaft or impeller splines, (2) Curvic coupling failure, (3) Loss of turbine tie - bolt preload, (4) Loss of preburner tie-bolt preload, (5) Main impeller retainer nut/lock failure, (6) Turbine disc failure, and (7) Shaft failure.

Possible effects: Turbine unload and overspeed with probable blade failure and/or disk burst, rubbing, and rotor unbalance. Turbine burst may cause shrapnel damage to other parts of the engine, resulting in ultimate rotating assembly disintegration, fire, or explosion.

Available sensors: (1) HPOTP pump speed, (2) HPOTP discharge pressure, (3) HPOTP discharge temperature, (4) Strain gages, and (5) Accelerometer.

Test correlation with failure mode: 750-175.

Rank No.: 13
Component: Main Injector
Failure Mode: Interpropellant Plate Cracks
Line Replaceable Unit - Failure Mode No.: **A200-09**

Possible causes: (1) Weld or parent material failure, and (2) Heat shield failure.

Possible effects: Ignition occurring in the main injector resulting in injector/powerhead burnout, and aft compartment overpressurization and fire. LOX/post damage, MCC erosion, and nozzle tube rupture may result.

Available sensors: (1) HPFTP discharge temperature, and (2) HPOT discharge temperature.

Test correlation with failure mode: 901-173, 750-148.

Rank No.: 14
Component: High Pressure Oxidizer Turbopump
Failure Mode: Pump Piece Part Structural Failure
Line Replaceable Unit - Failure Mode No.: **B400-22**

Possible causes: Internal structural failure of shaft, main housing, preburner pump housing, intermediate seal, mating ring, and other hardware (springs, nuts, washers, bolts, seals), etc.

Possible effects: Fire from LOX impact or rubbing, hot gas leakage into primary OX seal cavity.

Available sensors: (1) HPOTP turbine discharge pressure, (2) HPOTP turbine discharge HF pressure, (3) HPOTP discharge temperature, and (4) HPOTP radial and axial accelerometers.

Test correlation with failure mode: 901-110.

Rank No.: 15
Component: Main Combustion Chamber
Failure Mode: Fuel Leaks into the Closed Cavity Between the Liner and Structural Jacket
Line Replaceable Unit - Failure Mode No.: **A330-02**

Possible causes: (1) Failure in EDNi liner closeout structure caused by long liner inner wall cracks; (2) Jacket EB closeout weld over penetration into EDNi liner; and (3) Fracture of manifold to liner welds.

Possible effects: Burst diaphragm rupture due to leakage into the closed cavity, venting the cavity into the engine fuel drain system. Excessive leakage causes deformation of the liner in the divergent section. Significant changes in the exhaust gases flow produce a strong shock at the downstream nozzle wall. Tube failures cause loss of fuel to the preburners and high turbine temperatures. Cavity overpressurization causes ripping of welds, sudden loss of fuel, engine turbine, and aft compartment overpressurization and fire.

Available sensors: (1) MCC liner cavity delta-pressure, (2) FPB fuel manifold pressure, (3) OPB LOX manifold pressure, (4) MCC coolant delta pressure, (5) FPOV actuator position, (6) OPOV actuator position, (7) HPFTP turbine discharge temperature, (8) HPOTP turbine discharge temperature, (9) HPFTP pump discharge pressure, (10) HPFTP boost pump discharge pressure, (11) LPFTF shaft speed, (12) LPFTP pump discharge pressure, and (13) HPOTP pump discharge pressure.

Test correlation with failure mode: None

Rank No.: 16
Component: LPFTP Turbine Discharge Duct
Failure Mode: Fails to Contain Hydrogen
Line Replaceable Unit - Failure Mode No.: **K103-01**

Possible causes: (1) Parent material failure or weld failure; and (2) Flex joint assemblies structural failure of retainer assembly, internal support assembly, inner bellows, or welds.

Possible effects: Fuel leakage into aft compartment resulting in overpressurization and possible fire or detonation.

Available sensors: (1) HPFTP inlet HF pressure, (2) Fuel flow, (3) LPFTP discharge HF pressure, (4) HPFTP axial accelerometer, (5) HPFTP radial accelerometer, and (6) HPFTP shaft speed.

Test correlation with failure mode: None

Rank No.: 17
Component: GOX Control Valve
Failure Mode: Maintain Structural Integrity
Line Replaceable Unit - Failure Mode No.: **D500-06**

Possible causes: (1) Fracture of housing; and (2) Internal structural failure of poppet, check valve poppet, GCV or check valve retainer, seat, stem, guide, poppet spring or check valve snapspring, guide retainer ring, and check valve seal.

Possible effects: (1) Loss of pogo suppression flow and overpressurization of aft compartment; and (2) Fire from GOX impact or rubbing.

Available sensors: (1) LPOTP pump discharge HF pressure, (2) LPOTP pump discharge pressure, (3) LPOTP pump discharge temperature, (4) HPOTP inlet HF pressure.

Test correlation with failure mode: None

Rank No.: 18
Component: Anti-Flood Valve
Failure Mode: Leakage During Propellant Conditioning
Line Replaceable Unit - Failure Mode No.: **D300-01**

Possible causes: (1) Poppet or seat damage, (2) Contamination, and (3) Fractured poppet or piston springs.

Possible effects: LOX flow to heat exchanger. Heat from start will cause GOX to overpressurize and rupture the heat exchanger coils. LOX and hot-gas will mix resulting in uncontained fire/explosion.

Available sensors: (1) HEX vent inlet pressure, (2) HEX vent delta-pressure, (3) HEX inlet temperature, and (4) HEX inlet pressure.

Test correlation with failure mode: None

Rank No.: 19
Component: High Pressure Fuel Duct
Failure Mode: Fails to Contain Hydrogen
Line Replaceable Unit - Failure Mode No.: **K106-02**

Possible causes: Parent material or weld failure.

Possible effects: Fuel leakage into aft compartment resulting in overpressurization and possible fire or detonation.

Available sensors: (1) HPFTP discharge pressure, and (2) HPFTP discharge temp.

Test correlation with failure mode: None

Rank No.: 20
Component: Low Pressure Oxidizer Turbopump
Failure Mode: Loss of Support and Position Control
Line Replaceable Unit - Failure Mode No.: **B800-06**

Possible causes: (1) High rotor axial thrust loads; (2) Pump/turbine end bearing failure due to wear, spalling, pitting, cage wear/failure, corrosion, loss of coolant or contamination; (3) Loss of support bolt preload; (4) Loss of pump/turbine end bearing inner and outer race retaining nut preload due to nut failure, lock failure, or vibration; (5) Turbine end bearing preload spring wear/failure; (6) Excessive fretting at bearing journals; and (7) Excessive rotor radial loads.

Possible effects: Potential contact between rotor and stationary components due to excessive rotor movement; rubbing in oxygen environment can cause LPOTP fire or explosion.

Available sensors: (1) LPOTP radial accelerometer, and (2) LPOTP pump discharge temperature.

Test correlation with failure mode: None

Rank No.: 21
Component: Main Injector
Failure Mode: External Rupture
Line Replaceable Unit - Failure Mode No.: **A200-07**

Possible causes: (1) Weld or parent material failure; (2) Splitter failure; and (3) Liquid metal embrittlement at braze areas.

Possible effects: LOX and hot-gas leakage into the aft compartment resulting in overpressurization and fire.

Available sensors: (1) MCC pressure, (2) Main injector secondary face plate delta-pressure, (3) MCC liner cavity delta-pressure, (4) MCC fuel injection pressure, (5) FPB fuel manifold pressure, (6) OPB LOX manifold pressure, (7) FPOV actuator position, (8) OPOV actuator position, (9) HPFTP turbine discharge temperature, (10) HPOTP turbine discharge temperature, (11) HPFTP pump discharge pressure, (12) HPFTP boost pump discharge pressure, (13) LPFTP shaft speed, (14) LPFTP pump discharge pressure, and (15) HPOTP pump discharge pressure.

Test correlation with failure mode: None

Rank No.: 22
Component: Chamber Coolant Valve Actuator
Failure Mode: Sequence Valve Leaks Passing Early Control Pressurant Downstream
Line Replaceable Unit - Failure Mode No.: **E150-14**

Possible causes: Damaged sequence valve and valve seals.

Possible effects: The control pressurant closes the purge sequence PAV early with the result of terminating preburner shutdown purges; HPOTP intermediate seal purge, and pogo shutdown charge. Loss of pogo shutdown charge during MECO, at zero 6 condition and minimum NPSP, will result in cavitation/overspeed of HPOTP and/or LPOTP.

Available sensors: (1) HPOTP inlet HF pressure, (2) LPOTP inlet pressure, (3) LPOTP shaft speed, (4) HPOTP turbine radial accelerometer, (5) FPB purge pressure, (6) OPB purge pressure, and (7) HPOTP intermediate seal purge pressure.

Test correlation with failure mode: None

Rank No.: 23
Component: Oxidizer Bleed Valve
Failure Mode: Fretting of Internal Parts
Line Replaceable Unit - Failure Mode No.: **D220-06**

Possible causes: Relative motion of poppet/piston and poppet/spring/poppet.

Possible effects: Fire from ignition of internal parts.

Available sensors: Not detectable.

Test correlation with failure mode: None

Rank No.: 24
Component: High Pressure Oxidizer Turbopump
Failure Mode: Turbine Piece Part Structural Failure
Line Replaceable Unit - Failure Mode No.: **B400-23**

Possible causes: Internal structural failure of turbine housing, discharge strut/strut retainer, shaft, disc, first-stage turbine blades and dampers, first-stage tip seal and retainer, first stage nozzle, second-stage turbine blade and dampers, second-stage tip seal, second-stage nozzle, interstage seal, jet ring, bellows shield, turbine seal coolant shield, discharge strut retainer disc bolt and washer, turbine blade lock, first-stage nozzle retainer bolts and lock, first-stage nozzle retainer bolts and washers, jet ring retainer bolts and washers, turbine seal retainer bolts and locks, and first stage nozzle plug.

Possible effects: Migration downstream of part fragment resulting in puncture of heat exchanger tube.

Available sensors: (1) HPOTP turbine discharge pressure, (2) HPOTP turbine discharge HF pressure, (3) HPOTP discharge temperature, and (4) HPOTP radial and axial accelerometers.

Test correlation with failure mode: None

Rank No.: 25
Component: Main Combustion Chamber
Failure Mode: Internal Rupture at the MCC Nozzle Interface
Line Replaceable Unit - Failure Mode No.: **A330-03**

Possible causes: (1) Delamination of the nickel plating at the aft end of the MCC; (2) Weld failures at the turnaround manifold of the liner, and (3) Weld or parent material failure.

Possible effects: Fuel leakage at the internal interface to be dumped into the main exhaust gases. Loss of fuel to the LPFTP will result in HPFTP cavitation, LOX-rich operation, and engine failure.

Available sensors: (1) HPOT discharge temperature.

Test correlation with failure mode: 750-148

Rank No.: 26
Component: High Pressure Fuel Turbopump
Failure Mode: Structural Failure
Line Replaceable Unit - Failure Mode No.: **B200-26**

Possible causes: (1) Failure of parent metal or welds in main housing, inlet housing, thrust bearing housing; and (2) Diffuser cracking causing overpressurization of pump housing.

Possible effects: (1) Immediate loss of turbopump output; and (2) External damage to engine from hydrogen fire or explosion and aft compartment overpressurization.

Available sensors: (1) HPFP discharge pressure, (2) Housing strain measurements, and (3) Housing accelerometer.

Test correlation with failure mode: None

Rank No.: 27
Component: Oxidizer Bleed Flex Line
Failure Mode: Fails to Contain Oxidizer
Line Replaceable Unit - Failure Mode No.: **K203-01**

Possible causes: (1) Parent material failure or weld failure; and (2) Damage/defective bellows assembly.

Possible effects: (1) Oxidizer leakage into and overpressurization of aft compartment.

Available sensors: No engine sensors.

Test correlation with failure mode: None

Rank No.: 28
Component: Main Oxidizer Valve
Failure Mode: Piece Part Structural Failure
Line Replaceable Unit - Failure Mode No.: **D120-05**

Possible causes: Internal structural failure of bellows, cam follower, inlet/outlet sleeve, shaft bearing retainer, cam/shaft bearing, ball/shaft seal, shaft assembly, and fasteners and cupwashers.

Possible effects: Fire from LOX impact or rubbing.

Available sensors: (1) MOV discharge HF pressure, and (2) MOV hydraulic temperature.

Test correlation with failure mode: None

Rank No.: 29
Component: Powerhead
Failure Mode: Shell or Propellant Duct Rupture
Line Replaceable Unit - Failure Mode No.: **A050-02**

Possible causes: Weld or parent metal failure.

Possible effects: (1) External fuel or hot-gas leak; and (2) Overpressurization of aft compartment.

Available sensors: (1) MCC pressure, (2) Main injector secondary face plate delta-pressure, (3) MCC liner cavity delta-pressure, (4) MCC fuel injection pressure, (5) FPB fuel manifold pressure, (6) OPB LOX manifold pressure, (7) FPOV actuator position, (8) OPOV actuator position, (9) HPFTP turbine discharge temperature, (10) HPOTP turbine discharge temperature, (11) HPFTP pump discharge pressure, (12) HPFTP boost pump discharge pressure, (13) LPFTP shaft speed, (14) LPFTP pump discharge pressure, and (15) HPOTP pump discharge pressure.

Test correlation with failure mode: None

Rank No.: 30
Component: Fuel Preburner
Failure Mode: External Rupture
Line Replaceable Unit - Failure Mode No.: **A600-11**

Possible causes: Failure of parent material or weld.

Possible effects: Leakage into the aft compartment causing overpressurization and/or fire.

Available sensors: (1) FPB injector delta-pressure, (2) FPB temperature, (3) FPB fuel manifold temperature, (4) FPB ASI fuel temperature, (5) FPB orifice inlet temperature, (6) FPB accelerometer, (7) FPB liner axial temperature, (8) FPB manifold pressure, (9) FPB chamber HF pressure, and (10) FPB chamber HP delta-pressure.

Test correlation with failure mode: None

Rank No.: 31
Component: Main Oxidizer Valve
Failure Mode: Structural Failure
Line Replaceable Unit - Failure Mode No.: **D120-04**

Possible causes: Fracture of housing or end cap.

Possible effects: (1) Reduced oxidizer flow to engine; and (2) High pressure oxidizer leakage into aft compartment.

Available sensors: (1) MOV discharge HF pressure, and (2) MOV hydraulic temperature.

Test correlation with failure mode: None

Rank No.: 32
Component: Pneumatic Control Assembly (PCA) - Oxidizer System Purge
Failure Mode: Insufficient or No Nitrogen Purge Flow During Propellant Conditioning
Line Replaceable Unit - Failure Mode No.: **C200-07**

Possible causes: (1) PCA component failure due to blocked/restricted PCA inlet nitrogen filter, ruptured PCA oxidizer system burst diaphragm, blocked/restricted HPOTP intermediate seal purge control orifice, or blocked/restricted MCC oxidizer dome purge control orifice; (2) Oxidizer system purge pressure activated valve failure; (3) Control cavity seal leakage due to contamination, damaged/defective seal, or blocked flow passage; and (4) Vent port poppet/seat leakage due to contamination, damaged/defective sealing surface, or damaged guide.

Possible effects: (1) Reduced nitrogen flow causing loss of oxidizer dome purge resulting in uncleared moisture and ice formation; LOX orifices block can cause combustion within the post, post burn through, and extensive erosion during start; uncontained engine damage; (2) Reduced flow causing loss of intermediate seal purge resulting in uncleared moisture and ice formation during propellant drop; ice damages HPOTP intermediate seal causing failure; LOX and hot-turbine gases mix resulting in uncontained engine damage during start; and (3) Loss of purge reduces the purge flow below acceptable limits for inerting propellant leakage at ICD limits with the potential result of open air fire.

Available sensors: Preburner purge monitor patch (OPB and FPB purge pressure redlines)

Test correlation with failure mode: 901-129, 902-330

Rank No.: 33
Component: Main Injector
Failure Mode: Partial Blockage of an Oxidizer Orifice
Line Replaceable Unit - Failure Mode No.: **A200-05**

Possible causes: Local contamination in oxidizer manifold.

Possible effects: Combustion gas backflow into the post causing combustion within the post and post burn - through as a result of blockage. Extensive subsequent erosion results in aft compartment overpressurization and fire.

Available sensors: (1) Main injector secondary face plate delta-pressure, (2) HGM fuel transfer duct HF pressure, (3) Main injector LOX injection pressure, and (4) Main injector LOX injection temperature.

Test correlation with failure mode: None

Rank No.: 34
Component: Fuel Preburner Oxidizer Valve
Failure Mode: Shaft Seal Leak
Line Replaceable Unit - Failure Mode No.: **D130-03**

Possible causes: (1) Contamination generated from coupling.

Possible effects: (1) Leakage past both the primary and secondary seals results in burst diaphragm rupture; and (2) IF hydraulic fluid leakage from the actuator primary and secondary seals exist concurrently, commingling of oxidizer and hydraulic fluid will result in fire.

Available sensors: (1) FPB ASI LOX orifice pressure, (2) FPB ASI LOX orifice delta-pressure, (3) FPB ASI LOX temperature, and (4) FPB actuator position.

Test correlation with failure mode: None

Rank No.: 35
Component: Main Oxidizer Valve
Failure Mode: Fretting of Internal Parts
Line Replaceable Unit - Failure Mode No.: **D120-06**

Possible causes: (1) Relative motion of (i) bellows/housing, (ii) sleeve/bellows/shim, (iii) cam follower/guide/housing, (iv) bellows/guide/cam follower, (v) shaft bearings/retainer, (vi) retainer/shaft, (vii) retainer/wave washers/cap, and (viii) outlet sleeve/housing/shim.

Possible effects: (1) Fire from ignition of internal parts.

Available sensors: (1) MOV discharge HF pressure, and (2) MOV hydraulic temperature.

Test correlation with failure mode: 901-225.

Rank No.: 36
Component: High Pressure Oxidizer Turbopump
Failure Mode: Loss of Support, Position Control, or Rotordynamic Stability
Line Replaceable Unit - Failure Mode No.: **B400-13**

Possible causes: (1) Bearing failure due to spalling, pitting, wear or corrosion of balls/races; loss of radial clearance; cage failure; loss of coolant; or contamination in bearings; (2) Excessive PBP damping seal clearance; (3) Loss of bearing retaining bolt preload; (4) Cartridge wet failure or loss of support; (5) Loss of bearing retainer nut preload; (6) Bearing preload spring failure; (7) Excessive turbine interstage seal clearance; (8) Excessive primary and secondary turbine seal clearance; (9) Fretting of bearing/cartridge or isolator; and (10) Loss or increase of deadband.

Possible effects: (1) Bearing failure results in excessive axial or radial displacements which leads to rubbing of turbine or pump components; disintegration of rotating parts, possibly resulting in an oxidizer fire or explosion.

Available sensors: (1) HPOT speed (F, TB), (2) HPOT discharge pressure (F, TB), (3) HPOT discharge temperature (F, TB), and (4) HPOTP radial and axial accelerometers (F, TB).

Test correlation with failure mode: 901-136

Rank No.: 37
Component: High Pressure Fuel Turbopump
Failure Mode: Turbine Discharge Flow Blockage
Line Replaceable Unit - Failure Mode No.: **B200-07**

Possible causes: (1) Turnaround duct distortion/buckling; (2) Sheet metal cracking resulting in loss of pieces; (3) stiffener vane cracking resulting in loss of pieces or disengagement of slip joint; and (4) Failure of coolant liner.

Possible effects: (1) Flow blockage decreases turbine pressure ratio, reduces turbopump speed, flow and discharge pressure. Decreased flow is sensed by controller which increases fuel preburner oxidizer flow; (2) A rapid buckling may result in extensive turbine damage from overtemperature; and (3) Possible burst of pump inlet due tc pressure surge.

Available sensors: (1) HPFTP discharge temperature, (2) HPFTP pump speed. (3) Flowrate, (4) HPFTP discharge pressure, and (5) Strain gage for turn around duct metal.

Test correlation with failure mode: 901-340, 901-363, 902-118, 901-436.

Rank No.: 38
Component: High Pressure Oxidizer Turbopump
Failure Mode: Loss of Coolant to First- and Second-Stage Turbine Components
Line Replaceable Unit - Failure Mode No.: **B400-20**

Possible causes: (1) Fracture or blockage of coolant circuits; (2) Coolant passage cracks into main housing, (3) Jet ring failure, (4) Failure of second-stage nozzle/interstage seal, and (5) OPB/HPOTP pressure-assisted seal leakage.

Possible effects: (1) Overheating of inlet strut, disks and blades, nozzle box structures, and turbine interstage seal lead to flow distortion and rubbing; and (2) Structural component failure results in disintegration of rotating components.

Available sensors: (1) HPOTP primary seal drain temperature, (2) HPOTP primary seal drain pressure, (3) HPOTP turbine seal cavity pressure, (4) HPOTP turbine radial accelerometer, (5) HPOTP turbine discharge pressure, and (6) HPOTP turbine discharge HF pressure.

Test correlation with failure mode: None

Rank No.: 39
Component: Anti-Flood Valve
Failure Mode: LOX Flow Restricted or Shutoff
Line Replaceable Unit - Failure Mode No.: **D300-03**

Possible causes: (1) Blocked inlet filter; (2) Vent passage blocked and cracked piston/piston seal leakage; and (3) Fractured poppet/seat.

Possible effects: (1) Loss of pressurant flow to accumulator and vehicle; (2) Collapse and possible cracking of heat exchanger coil; (3) Hot-gas flow to vehicle oxidizer tank and pogo accumulator; and (4) Loss of pogo suppression.

Available sensors: (1) HEX vent inlet pressure, (2) HEX vent delta-pressure, (3) HEX inlet temperature, (4) HEX inlet pressure, (5) Oxidizer tank pressure, and (6) LPOTP pump discharge pressure.

Test correlation with failure mode: None

Rank No.: 40
Component: Oxidizer Preburner
Failure Mode: Loss of Fuel to ASI
Line Replaceable Unit - Failure Mode No.: **A700-02**

Possible causes: Contamination of the ASI fuel orifices/passageways

Possible effects: High mixture ratio erosion of the ASI combustion chamber walls, injector burnout, loss of turbine, and engine failure due to loss of fuel.

Available sensors: (1) FPOV valve position, (2) OPOV valve position, and (3) HPOT discharge temperature.

Test correlation with failure mode: None

Rank No.: 41
Component: High Pressure Fuel Turbopump
Failure Mode: Loss of Coolant Flow to Turbine Bearings
Line Replaceable Unit - Failure Mode No.: **B200-16**

Possible causes: (1) Lift-off sealing binding/closure; (2) Coolant flow passage blockage; (3) Failure of turbine hub labyrinth seal; (4) Failure of vortex control paddle or its torque pin on shaft-end; and (5) Hot-gas leakage past Kaiser cap to turbine bearing carrier interface due to static seal failure; thermal shield failure, nut failure, or Kaiser cap failure.

Possible effects: (1) Bearings overheat and fail, causing rubbing, increased vibration and possible turbine blade failure or disintegration of rotating assembly.

Available sensors: (1) HPOTP turbine radial accelerometer, (2) HPOTP turbine axial accelerometer, (3) HPOTP turbine discharge temperature, (4) HPOTP turbine discharge pressure, (5) HPOTP primary seal drain pressure, and (6) HPOTP primary seal drain temperature.

Test correlation with failure mode: 901-364, 902-209, 750-165

Rank No.: 42
Component: High Pressure Fuel Turbopump
Failure Mode: Loss of Coolant Flow to Turbine Discs
Line Replaceable Unit - Failure Mode No.: **B200-17**

Possible causes: (1) Lift-off sealing binding/closure; (2) Coolant flow passage blockage; (3) Failure of turbine hub labyrinth seal; (4) Failure of vortex control paddle or its torque pin on shaft-end; and (5) Failure of interstage seal.

Possible effects: (1) Loss of coolant to one side of disc can allow disc deflection and platform seal rubbing; and (2) Excessive coolant loss can allow turbine first-stage or second-stage disc to overheat and burst.

Available sensors: (1) HPOTP turbine radial accelerometer, (2) HPOTP turbine axial accelerometer, (3) HPOTP turbine discharge temperature, (4) HPOTP turbine discharge pressure, (5) HPOTP primary seal drain pressure, and (6) HPOTP primary seal drain temperature.

Test correlation with failure mode: 901-364, 902-209, 750-165

Rank No.: 43
Component: High Pressure Oxidizer Turbopump
Failure Mode: Loss of Coolant to Bearings
Line Replaceable Unit - Failure Mode No.: **B400-18**

Possible causes: (1) Blockage of turbine and bearing coolant circuits; and (2) leakage past aft preburner pump pressure - assisted seal.

Possible effects: (1) Bearings degrade causing rubbing and disintegration of rotating components.

Available sensors: (1) HPOTP turbine radial accelerometer, (2) HPOTP turbine axial accelerometer, (3) HPOT shaft speed, (4) HPOTP turbine discharge pressure, (5) HPOTP turbine discharge temperature, (6) HPOTP turbine seal cavity pressure, and (7) HPOTP primary seal drain pressure.

Test correlation with failure mode: None

Rank No.: 44
Component: High Pressure Fuel Turbopump
Failure Mode: Failure to Restrain Shaft Movement During Turbopump Startup
Line Replaceable Unit - Failure Mode No.: **B200-24**

Possible causes: (1) Failure of thrust - carrying ball bearing due to ball, cage, or race failure, corrosion or contamination; (2) Failure of thrust ball; and (3) Failure of shaft insert.

Possible effects: (1) Excess shaft movement can result in rubbing of components causing turbopump performance degradation; (2) Controller senses decreased flow and increases fuel preburner oxidizer flow; and (3) Increased turbine discharge temperature.

Available sensors: (1) HPFTP turbine accelerometer, (2) HPFTP turbine discharge temperature, (3) HPFTP discharge pressure, (4) HPFTP shaft speed, (5) HPFTP housing strain, and (6) FPOV actuator position.

Test correlation with failure mode: None

Rank No.: 45
Component: High Pressure Fuel Turbopump
Failure Mode: Loss of Balancing Capability
Line Replaceable Unit - Failure Mode No.: **B200-23**

Possible causes: (1) High pressure orifice failure; and (2) Low pressure orifice failure.

Possible effects: (1) Rubbing of turbine platform seals, and/or rubbing of third-stage impeller back shroud against low pressure orifice results in reduced turbopump performance, damage to rubbing parts, and reduced coolant flow to turbine; and (2) Possible pump inlet burst due to pressure surge.

Available sensors: (1) HPFTP inlet temperature, (2) HPFTP inlet pressure, (3) HPFTP inlet HF pressure, (4) HPFTP turbine discharge temperature, (5) HPFTP discharge pressure, (6) HPFTP discharge HF pressure, (7) HPFTP shaft speed, and (8) HPFTP turbine accelerometers.

Test correlation with failure mode: None

ATTACHMENT 4

CHANGES IN INDIVIDUAL MEASUREMENTS FOR SELECTED DEGRADATIONS

RESISTANCE CHANGE OF -50% FOR THE PRIMARY FACE-PLATE FOR PH II AT 104% PL

DATE - 08/25/89 VERSION 3.9 TIME - 14:08

PARM	PARAMETER TITLE	PH II NOMINAL BASELINE AT 104%	SIGMA ENGINE TO ENGINE 104%	PH II -50% PRM FP RES AT 104%	DELTA -50% PRM FP RES - NOM. VALUES	% DIFF -50% PRM FP RES VS NOM VALUES	NEW SIGMA FOR THIS CASE
	INDEPENDENT PARAMETER						
4119	Primary Fcplte Res	11.32	0.0	5.66	-5.66	-50.0	-5.66
	MODEL INPUT DATA						
4001	Power Level	1.03999	0.0	1.03999	0.0	0.0	0.0
4002	Engine MR	6.011	0.0	6.011	0.0	0.0	0.0
4004	LPFP Inlet Pr	30.0	0.0	30.0	0.0	0.0	0.0
4005	LPOP Inlet Pr	100.0	0.0	100.0	0.0	0.0	0.0
4006	LPFP Inlet Tmp	37.0	0.0	37.0	0.0	0.0	0.0
4007	LPOP Inlet Tmp	164.0	0.0	164.0	0.0	0.0	0.0
4008	Fuel Repress Flow	0.728	0.0	0.728	0.0	0.0	0.0
4009	Ox Repress Flow	1.612	0.0	1.612	0.0	0.0	0.0
4050	Chamber Pressure Command	3126.2	0.0	3126.2	0.0	0.0	0.0
	ENGINE PERFORMANCE						
4358	Vacuum Thrust	492035.0	983.06	492035.0	-0.0625	-.000013	-.000064
4741	Engine Flow	1089.51	3.11868	1089.51	0.0	0.0	0.0
4701	Engine Ox Flow	934.115	2.67395	934.115	0.0	0.0	0.0
4661	Engine Fuel Flow	155.399	0.44484	155.399	.0000153	.0000098	.0000343
4658	Vehicle ISP	452.581	0.64378	452.581	0.0	0.0	0.0
4557	Engine MR-w/pres flow	6.01109	0.0	6.01109	0.0	0.0	0.0
4186	MCC C-Star Mult	1.00056	0.00221	1.00056	0.0	0.0	0.0
	KEY OPERATING PARAMETERS						
4629	HPFT T/D Tmp Average	1641.05	46.6774	1640.88	-.171143	-.010429	-.003666
4638	HPOT T/D Tmp Average	1354.61	39.3918	1357.91	3.29321	0.243111	.0836015
4420	FPB Chamber Pr	5234.98	42.7615	5230.29	-4.68359	-.089467	-.109528
4443	OPB Chamber Pr	5299.15	37.3274	5295.82	-3.33203	-.062879	-.089265
4360	HPFT Speed	35231.2	204.051	35211.2	-20.0547	-.056923	-.098283
4365	HPOT Speed	28165.0	355.67	28165.2	0.179688	0.000638	.0005052
4359	LPFT Speed	15953.7	318.941	16031.9	78.207	0.490214	0.245209
4364	LPOT Speed	5161.29	60.8609	5161.37	0.078125	.0015137	.0012837
4486	HPFP Disch Pr	6418.12	34.8877	6411.96	-6.16406	-.096042	-.176683
4488	HPOP Disch Pr	4317.02	60.9193	4317.14	0.117188	.0027145	.0019237
4460	HPFP Inlet Pr	260.81	15.8503	263.935	3.12524	1.19829	0.197173
4464	HPOP Inlet Pr	383.517	7.98399	383.533	.0166016	.0043288	.0020794
4626	HPFP Disch Tmp	95.2211	1.6578	95.1934	-.027725	-.029117	-.016724
4634	HPOP Disch Tmp	192.728	1.11614	192.728	.0006104	.0003167	.0005468
4615	HPFP Inlet Tmp	42.7938	0.2752	42.8274	.0335999	.0785157	0.122092
4596	HPOP Inlet Tmp	169.801	0.21168	169.801	.0001678	.0000988	.0007929
4798	OPOV Position	0.685252	0.0133	0.685099	-.000153	-.022354	-.011518
4799	FPOV Position	0.762557	0.00997	0.761881	-.000676	-.088709	-.067849
4489	PBP Disch Pr	7388.36	121.458	7389.49	1.13672	.0153853	.0093589
4635	PBP Disch Tmp	206.023	1.7864	206.029	.0063629	.0030885	.0035619
4461	LPFT Inlet Pr	4651.61	48.1437	4634.08	-17.5313	-.376886	-.364144
4616	LPFT Inlet Tmp	461.257	19.1996	459.512	-1.74438	-.378181	-.090855
4435	Main Inj HG Orif In Pr	3366.87	31.3215	3364.06	-2.80835	-.083411	-.089662
4536	Main Inj Ox Inlet Pr	3720.01	24.3633	3720.09	0.083252	0.002238	.0034171
4432	Main Inj End Pr	3126.2	0.0	3126.2	0.0	0.0	0.0

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PARM	PARAMETER TITLE	PH II NOMINAL BASELINE AT 104%	SIGMA ENGINE TO ENGINE 104%	PH II CSTAR CASE AT 104%	DELTA CSTAR CASE - NOM. VALUES	% DIFF CSTAR CASE VS NOM VALUES	NEW SIGMA FOR THIS CASE
	INDEPENDENT PARAMETER						
4186	MCC C-Star Mult	1.00056	0.00221	0.986086	-.014474	-1.44655	-6.54915
	MODEL INPUT DATA						
4001	Power Level	1.03999	0.0	1.03999	0.0	0.0	0.0
4002	Engine MR	6.011	0.0	6.011	0.0	0.0	0.0
4004	LPFP Inlet Pr	30.0	0.0	30.0	0.0	0.0	0.0
4005	LPOP Inlet Pr	100.0	0.0	100.0	0.0	0.0	0.0
4006	LPFP Inlet Tmp	37.0	0.0	37.0	0.0	0.0	0.0
4007	LPOP Inlet Tmp	164.0	0.0	164.0	0.0	0.0	0.0
4008	Fuel Repress Flow	0.728	0.0	0.724999	-.003001	-.412271	-.003001
4009	Ox Repress Flow	1.612	0.0	1.612	0.0	0.0	0.0
4050	Chamber Pressure Command	3126.2	0.0	3126.2	0.0	0.0	0.0
	ENGINE PERFORMANCE						
4358	Vacuum Thrust	492035.0	983.06	493457.0	1422.13	0.289029	1.44663
4741	Engine Flow	1089.51	3.11868	1109.87	20.3557	1.86833	6.52703
4701	Engine Ox Flow	934.115	2.67395	954.471	20.3555	2.17912	7.61251
4661	Engine Fuel Flow	155.399	0.44484	155.399	.0000153	.0000098	.0000343
4658	Vehicle ISP	452.581	0.64378	445.546	-7.03516	-1.55445	-10.9279
4557	Engine MR-w/pres flow	6.01109	0.0	6.14208	0.130989	2.17912	0.130989
4186	MCC C-Star Mult	1.00056	0.00221	0.986086	-.014474	-1.44655	-6.54915
	KEY OPERATING PARAMETERS						
4629	HPFT T/D Tmp Average	1641.05	46.6774	1622.72	-18.3308	-1.11701	-.392713
4638	HPOT T/D Tmp Average	1354.61	39.3918	1433.3	78.6824	5.80847	1.99743
4420	FPB Chamber Pr	5234.98	42.7615	5244.01	9.03516	0.172592	0.211292
4443	OPB Chamber Pr	5299.15	37.3274	5347.2	48.0508	0.906764	1.28728
4360	HPFT Speed	35231.2	204.051	35264.7	33.5352	.0951859	0.164347
4365	HPOT Speed	28165.0	355.67	28602.7	437.629	1.5538	1.23044
4359	LPFT Speed	15953.7	318.941	15997.5	43.8711	0.274991	0.137552
4364	LPOT Speed	5161.29	60.8609	5189.99	28.7031	0.556123	0.471618
4486	HPFP Disch Pr	6418.12	34.8877	6436.91	18.7891	0.29275	0.538558
4488	HPOP Disch Pr	4317.02	60.9193	4373.96	56.9336	1.31882	0.934574
4460	HPFP Inlet Pr	260.81	15.8503	262.559	1.74878	0.670519	0.110331
4464	HPOP Inlet Pr	383.517	7.98399	378.419	-5.09741	-1.32912	-.638454
4626	HPFP Disch Tmp	95.2211	1.6578	95.3433	0.122177	0.128309	.0736983
4634	HPOP Disch Tmp	192.728	1.11614	193.393	0.665497	0.345304	0.596248
4615	HPFP Inlet Tmp	42.7938	0.2752	42.8198	0.026001	.0607588	.0944803
4596	HPOP Inlet Tmp	169.801	0.21168	169.865	.0636597	.0374907	0.300735
4798	OPOV Position	0.685252	0.0133	0.692942	.0076898	1.12219	0.578183
4799	FPOV Position	0.762557	0.00997	0.752518	-.010039	-1.31654	-1.00696
4489	PBP Disch Pr	7388.36	121.458	7549.05	160.699	2.17503	1.32308
4635	PBP Disch Tmp	206.023	1.7864	207.177	1.15427	0.560261	0.646141
4461	LPFT Inlet Pr	4651.61	48.1437	4661.91	10.3008	0.221446	0.213959
4616	LPFT Inlet Tmp	461.257	19.1996	459.58	-1.67627	-.363414	-.087308
4435	Main Inj HG Orif In Pr	3366.87	31.3215	3369.11	2.24146	.0665739	.0715628
4536	Main Inj Ox Inlet Pr	3720.01	24.3633	3748.53	28.5186	0.766626	1.17055
4432	Main Inj End Pr	3126.2	0.0	3126.2	0.0	0.0	0.0

CHANGE OF HPOP EFF MULT. DUE TO RATED HPOT T/D TEMP (NOM + 2SIGMA)

DATE - 08/25/89 VERSION 3.9 TIME - 12:24

PARM PARAMETER TITLE	PH II NOMINAL BASELINE AT 104%	SIGMA ENGINE TO ENGINE 104%	PH II HPOP EFF MULT 104%	DELTA HPOP EFF MLT CASE - NOM. VALUES	% DIFF HPOP EFF MLT CASE VS NOM VALUES	NEW SIGMA FOR THIS CASE
INDEPENDENT PARAMETER						
4063 HPOP Eff Mult	1.0	0.01952	0.965095	-.034905	-3.49047	-1.78815
MODEL INPUT DATA						
4001 Power Level	1.03999	0.0	1.03999	0.0	0.0	0.0
4002 Engine MR	6.011	0.0	6.011	0.0	0.0	0.0
4004 LPFP Inlet Pr	30.0	0.0	30.0	0.0	0.0	0.0
4005 LPOP Inlet Pr	100.0	0.0	100.0	0.0	0.0	0.0
4006 LPFP Inlet Tmp	37.0	0.0	37.0	0.0	0.0	0.0
4007 LPOP Inlet Tmp	164.0	0.0	164.0	0.0	0.0	0.0
4008 Fuel Repress Flow	0.728	0.0	0.72503	-0.00297	-0.40794	-0.00297
4009 Ox Repress Flow	1.612	0.0	1.612	0.0	0.0	0.0
4050 Chamber Pressure Command	3126.2	0.0	3126.2	0.0	0.0	0.0
ENGINE PERFORMANCE						
4358 Vacuum Thrust	492035.0	983.06	492032.0	-2.875	-.000584	-.002925
4741 Engine Flow	1089.51	3.11868	1089.5	-.012207	-0.00112	-.003914
4701 Engine Ox Flow	934.115	2.67395	934.103	-.012451	-.001333	-.004656
4661 Engine Fuel Flow	155.399	0.44484	155.399	.0000153	.0000098	.0000343
4658 Vehicle ISP	452.581	0.64378	452.583	.0012207	.0002697	.0018961
4557 Engine MR-w/pres flow	6.01109	0.0	6.01101	-.000079	-.001317	-.000079
4186 MCC C-Star Mult	1.00056	0.00221	1.00056	0.0	0.0	0.0
KEY OPERATING PARAMETERS						
4629 HPFT T/D Tmp Average	1641.05	46.6774	1623.92	-17.1387	-1.04437	-.367173
4638 HPOT T/D Tmp Average	1354.61	39.3918	1433.3	78.687	5.80882	1.99755
4420 FPB Chamber Pr	5234.98	42.7615	5243.84	8.86719	0.169384	0.207364
4443 OPB Chamber Pr	5299.15	37.3274	5344.82	45.668	0.861798	1.22344
4360 HPFT Speed	35231.2	204.051	35263.4	32.1953	.0913829	0.157781
4365 HPOT Speed	28165.0	355.67	28173.2	8.20313	.0291252	.0230639
4359 LPFT Speed	15953.7	318.941	15995.5	41.8008	0.262014	0.131061
4364 LPOT Speed	5161.29	60.8609	5165.36	4.07031	.0788623	.0668789
4486 HPFP Disch Pr	6418.12	34.8877	6436.14	18.0234	0.280821	0.516613
4488 HPOP Disch Pr	4317.02	60.9193	4318.55	1.53125	0.03547	.0251357
4460 HPFP Inlet Pr	260.81	15.8503	262.476	1.66602	0.638786	0.105109
4464 HPOP Inlet Pr	383.517	7.98399	384.39	0.873047	0.227643	0.10935
4626 HPFP Disch Tmp	95.2211	1.6578	95.3383	0.117172	0.123053	.0706794
4634 HPOP Disch Tmp	192.728	1.11614	194.442	1.71402	0.889347	1.53567
4615 HPFP Inlet Tmp	42.7938	0.2752	42.8186	0.024826	.0580132	.0902109
4596 HPOP Inlet Tmp	169.801	0.21168	170.045	0.243668	0.143502	1.15111
4798 OPOV Position	0.685252	0.0133	0.714236	.0289838	4.22965	2.17923
4799 FPOV Position	0.762557	0.00997	0.764777	.0022193	0.291036	0.2226
4489 PBP Disch Pr	7388.36	121.458	7360.11	-28.25	-.382358	-.232591
4635 PBP Disch Tmp	206.023	1.7864	207.736	1.71271	0.831319	0.958748
4461 LPFT Inlet Pr	4651.61	48.1437	4661.6	9.99219	0.214811	0.207549
4616 LPFT Inlet Tmp	461.257	19.1996	459.65	-1.6062	-.348223	-.083658
4435 Main Inj HG Orif In Pr	3366.87	31.3215	3369.27	2.39648	.0711784	.0765125
4536 Main Inj Ox Inlet Pr	3720.01	24.3633	3720.71	0.698975	.0187896	.0286897
4432 Main Inj End Pr	3126.2	0.0	3126.2	0.0	0.0	0.0

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PARM PARAMETER TITLE	PH II NOMINAL BASELINE AT 104%	SIGMA ENGINE TO ENGINE 104%	PH II HPFP EFF MULT 104%	DELTA HPFP EFF MLT CASE - NOM. VALUES	% DIFF HPFP EFF MLT CASE VS NOM VALUES	NEW SIGMA FOR THIS CASE
INDEPENDENT PARAMETER						
4059 HPFP Eff Mult	1.0142	0.01398	0.9787	-0.0355	-3.50032	-2.53936
MODEL INPUT DATA						
4001 Power Level	1.03999	0.0	1.03999	0.0	0.0	0.0
4002 Engine MR	6.011	0.0	6.011	0.0	0.0	0.0
4004 LPFP Inlet Pr	30.0	0.0	30.0	0.0	0.0	0.0
4005 LPOP Inlet Pr	100.0	0.0	100.0	0.0	0.0	0.0
4006 LPFP Inlet Tmp	37.0	0.0	37.0	0.0	0.0	0.0
4007 LPOP Inlet Tmp	164.0	0.0	164.0	0.0	0.0	0.0
4008 Fuel Repress Flow	0.728	0.0	0.728	0.0	0.0	0.0
4009 Ox Repress Flow	1.612	0.0	1.612	0.0	0.0	0.0
4050 Chamber Pressure Command	3126.2	0.0	3126.2	0.0	0.0	0.0
ENGINE PERFORMANCE						
4358 Vacuum Thrust	492035.0	983.06	492036.0	0.9375	.0001905	.0009537
4741 Engine Flow	1089.51	3.11868	1089.51	.0004883	.0000448	.0001566
4701 Engine Ox Flow	934.115	2.67395	934.116	.0002441	.0000261	.0000913
4661 Engine Fuel Flow	155.399	0.44484	155.399	.0000153	.0000098	.0000343
4658 Vehicle ISP	452.581	0.64378	452.582	.0007324	.0001618	.0011377
4557 Engine MR-w/pres flow	6.01109	0.0	6.0111	.0000019	.0000317	.0000019
4186 MCC C-Star Mult	1.00056	0.00221	1.00056	0.0	0.0	0.0
KEY OPERATING PARAMETERS						
4629 HPFT T/D Tmp Average	1641.05	46.6774	1709.42	68.3689	4.16616	1.46471
4638 HPOT T/D Tmp Average	1354.61	39.3918	1313.18	-41.4312	-3.05852	-1.05177
4420 FPB Chamber Pr	5234.98	42.7615	5290.71	55.7344	1.06465	1.30338
4443 OPB Chamber Pr	5299.15	37.3274	5313.43	14.2813	0.269501	0.382594
4360 HPFT Speed	35231.2	204.051	35311.1	79.8633	0.226683	0.391389
4365 HPOT Speed	28165.0	355.67	28155.8	-9.25	-.032842	-.026007
4359 LPFT Speed	15953.7	318.941	16059.6	105.91	0.663861	0.332068
4364 LPOT Speed	5161.29	60.8609	5157.28	-4.00781	-.077651	-.065852
4486 HPFP Disch Pr	6418.12	34.8877	6459.81	41.6914	0.649589	1.19502
4488 HPOP Disch Pr	4317.02	60.9193	4311.0	-6.02734	-.139618	-0.09894
4460 HPFP Inlet Pr	260.81	15.8503	265.036	4.22583	1.62027	0.266609
4464 HPOP Inlet Pr	383.517	7.98399	382.68	-.836914	-.218221	-.104824
4626 HPFP Disch Tmp	95.2211	1.6578	99.6033	4.38219	4.60212	2.64338
4634 HPOP Disch Tmp	192.728	1.11614	192.697	-.030869	-.016017	-.027656
4615 HPFP Inlet Tmp	42.7938	0.2752	42.8691	.0753021	0.175965	0.273627
4596 HPOP Inlet Tmp	169.801	0.21168	169.792	-.009033	-0.00532	-.042674
4798 OPOV Position	0.685252	0.0133	0.684299	-.000952	-.138989	-.071611
4799 FPOV Position	0.762557	0.00997	0.781372	.0188143	2.46727	1.88709
4489 PBP Disch Pr	7388.36	121.458	7342.27	-46.082	-.623712	-.379407
4635 PBP Disch Tmp	206.023	1.7864	205.779	-.243317	-.118102	-.136205
4461 LPFT Inlet Pr	4651.61	48.1437	4671.87	20.2617	0.435585	0.420859
4616 LPFT Inlet Tmp	461.257	19.1996	461.937	0.679932	0.147409	.0354138
4435 Main Inj HG Orif In Pr	3366.87	31.3215	3373.03	6.16357	0.183065	0.196784
4536 Main Inj Ox Inlet Pr	3720.01	24.3633	3716.83	-3.18164	-.085528	-.130592
4432 Main Inj End Pr	3126.2	0.0	3126.2	0.0	0.0	0.0

SIMULATES A 5% NOZZLE LEAK FOR PHASE II AT 104% POWER LEVEL

DATE - 08/25/89 VERSION 3.9 TIME - 13:54

PARM PARAMETER TITLE	PH II NOMINAL BASELINE AT 104%	SIGMA ENGINE TO ENGINE 104%	PH II NOZ FUEL LK CASE AT 104%	DELTA NOZ FUEL LK CASE - NOM. VALUES	% DIFF NOZ FUEL LK CASE VS NOM VALUES	NEW SIGMA FOR THIS CASE
MODEL INPUT DATA						
4001 Power Level	1.03999	0.0	1.03999	0.0	0.0	0.0
4002 Engine MR	6.011	0.0	6.011	0.0	0.0	0.0
4004 LPFP Inlet Pr	30.0	0.0	30.0	0.0	0.0	0.0
4005 LPOP Inlet Pr	100.0	0.0	100.0	0.0	0.0	0.0
4006 LPFP Inlet Tmp	37.0	0.0	37.0	0.0	0.0	0.0
4007 LPOP Inlet Tmp	164.0	0.0	164.0	0.0	0.0	0.0
4008 Fuel Repress Flow	0.728	0.0	0.725508	-.002492	-.342252	-.002492
4009 Ox Repress Flow	1.612	0.0	1.612	0.0	0.0	0.0
4050 Chamber Pressure Command	3126.2	0.0	3126.2	0.0	0.0	0.0
ENGINE PERFORMANCE						
4358 Vacuum Thrust	492035.0	983.06	493850.0	1815.63	0.369004	1.84691
4741 Engine Flow	1089.51	3.11868	1098.07	8.55396	0.785116	2.74281
4701 Engine Ox Flow	934.115	2.67395	942.669	8.55371	0.915702	3.1989
4661 Engine Fuel Flow	155.399	0.44484	155.399	0.0	0.0	0.0
4658 Vehicle ISP	452.581	0.64378	450.704	-1.8772	-.414776	-2.9159
4557 Engine MR-w/pres flow	6.01109	0.0	6.06614	.0550451	0.915726	.0550451
4186 MCC C-Star Mult	1.00056	0.00221	1.00056	0.0	0.0	0.0
KEY OPERATING PARAMETERS						
4629 HPFT T/D Tmp Average	1641.05	46.6774	1662.24	21.1877	1.29111	0.453919
4638 HPOT T/D Tmp Average	1354.61	39.3918	1432.09	77.4763	5.71944	1.96681
4420 FPB Chamber Pr	5234.98	42.7615	5223.68	-11.3008	-.215871	-.264275
4443 OPB Chamber Pr	5299.15	37.3274	5307.75	8.59375	0.162172	0.230226
4360 HPFT Speed	35231.2	204.051	35177.6	-53.6016	-.152142	-.262687
4365 HPOT Speed	28165.0	355.67	28343.7	178.629	0.634222	0.502232
4359 LPFT Speed	15953.7	318.941	15876.2	-77.4297	-.485341	-.242771
4364 LPOT Speed	5161.29	60.8609	5171.43	10.1406	0.196475	0.16662
4486 HPFP Disch Pr	6418.12	34.8877	6387.52	-30.5977	-.476738	-.877033
4488 HPOP Disch Pr	4317.02	60.9193	4338.07	21.0508	0.487623	0.345552
4460 HPFP Inlet Pr	260.81	15.8503	257.736	-3.07422	-1.17872	-.193953
4464 HPOP Inlet Pr	383.517	7.98399	380.934	-2.58252	-.673379	-.323462
4626 HPFP Disch Tmp	95.2211	1.6578	95.0217	-.199478	-.209489	-.120327
4634 HPOP Disch Tmp	192.728	1.11614	192.988	0.259766	0.134784	0.232736
4615 HPFP Inlet Tmp	42.7938	0.2752	42.7493	-.044495	-.103974	-.161681
4596 HPOP Inlet Tmp	169.801	0.21168	169.823	0.022049	.0129852	0.104162
4798 OPOV Position	0.685252	0.0133	0.697473	.0122211	1.78345	0.918879
4799 FPOV Position	0.762557	0.00997	0.760482	-.002075	-.272097	-.208114
4489 PBP Disch Pr	7388.36	121.458	7434.62	46.2656	0.626196	0.380919
4635 PBP Disch Tmp	206.023	1.7864	206.385	0.36264	0.17602	0.203001
4461 LPFT Inlet Pr	4651.61	48.1437	4636.5	-15.1055	-.324736	-.313758
4616 LPFT Inlet Tmp	461.257	19.1996	464.133	2.87598	0.623509	0.149794
4435 Main Inj HG Orif In Pr	3366.87	31.3215	3366.07	-.797607	-0.02369	-.025465
4536 Main Inj Ox Inlet Pr	3720.01	24.3633	3730.47	10.4602	0.281188	0.429343
4432 Main Inj End Pr	3126.2	0.0	3126.2	0.0	0.0	0.0

ATTACHMENT 5

SUMMARY OF EXPECTED PLUME CONTAMINANTS

KEY TO ATTACHMENT 5

Column 1 - SSME FMEA Failure Mode Designation

Field 1 (1 digit) Component Type, example: B200-15

A = COMBUSTION DEVICES
B = TURBOMACHINERY
C = PNEUMATICS
D = PROPELLANT VALVES
E = ACTUATORS
F = CONTROLLER/FASCOS
G = IGNITERS
H = ELECTRICAL HARNESSES
J = SENSORS/INSTRUMENTATION
K = LINES AND DUCTS
L = JOINTS
M = GIMBAL
N = ORIFICES

Field 2 (3 digits) Specific Component Designation, example: B200-15

Field 3 (2 digits) Failure Mode Designation, example: B200-15

Column 2 - Specific Component (corresponds to field 2 of column 1)

Column 3 - Reaction Time: imm(ediate) = 0-1 second
sec(onds) = 1 - 60 seconds
min(utes) = 1 - 60 minutes

Column 4 - Cause or Effect of Failure Mode (null = effect)

Column 5 - Component Within Assembly Expected to Contaminate Plume

Column 6 - Material(s) Corresponding to Column 5 Component

Column 7 - Composition of Materials in Column 6 (%wt)

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

FAILURE MODE	ASSEMBLY	Rxt	C/E	COMPONENT	MATERIAL	Cr	Ni	Co	W	Fe	Mo	Mn	Ti	Cu	Ag	Al	Ta	Nb+Ta
A050/01	Power Head	sec		Main Injector Baffle	NARloy-A									96	3 +			
					Inconel 718	19	53			18	3							5
				Faceplate	SS347	18	11			68		2 -						
				Main Inj. Elem. Tip	Haynes 188	22	22	40	14	1 +								
				Main Inj. Faceplate	SS347	18	11			68		2 -						
				Main Inj. Nut	A286	15	26			56	1 +		2 +					
				Main Inj. Baffle	NARloy-A									96	3 +			
				Heat Exchg Liner	Incoloy 903		38	15		40			1 +			1		3
A150/01	Heat Exchanger	imm		Coil	316L Cres	17	12			67	2 +	2 -						
					Haynes 188	22	22	40	14	1 +								
				HGM Liner	Incoloy 903		38	15		40			1 +			1		3
				HPOTP Turbine	misc.													
				Main Inj. Elem. Tip	Haynes 188	22	22	40	14	1 +								
				Main Inj. Faceplate	SS347	18	11			68		2 -						
				Main Inj. Nut	A286	15	26			56	1 +		2 +					
				Main Inj. Baffle	NARloy-A									96	3 +			
A200/02	Main Injector	sec		ASI Cmb Ch wall	NARloy-A									96	3 +			
				ASI Injector	Haynes 188	22	22	40	14	1 +								
					SS347	18	11			68		2 -						
					NARloy-A									96	3 +			
/03		sec		ASI CmbCh wall	NARloy-A									96	3 +			
				ASI Injector	Haynes 188	22	22	40	14	1 +								
					SS347	18	11			68		2 -						
					NARloy-A									96	3 +			
/04		n/a		Main Inj. Elem. Tip	Haynes 188	22	22	40	14	1 +								
				Main Inj. Faceplate	SS347	18	11			68		2 -						
				Main Inj. Baffle	NARloy-A									96	3 +			
/05		sec		Post	Haynes 188	22	22	40	14	1 +								
				Post Nut	A286	15	26			56	1 +		2 +					

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

FAILURE MODE	ASSEMBLY	Rxt	C/E	COMPONENT	MATERIAL	Cr	Ni	Co	W	Fe	Mo	Mn	Ti	Cu	Ag	Al	Ta						Nb+Ta
						COMPOSITION																	
A200/06	Main Injector	sec		Post	Haynes 188	22	22	40	14	1 +													
	(con't)			Main Inj. Elem. Tip	Haynes 188	22	22	40	14	1 +													
				Main Inj. Faceplate	SS347	18	11			68		2 -											
				Main Inj. Baffle	NARloy-A									96	3 +								
				FPB Injector	NARloy-A									96	3 +								
					Inconel 625																		
					SS304L																		
				Fuel Turbine	misc.																		
/09		Imm		Power Head	Inconel 718	19	53			18	3												5
				Main Inj. Elem. Tip	Haynes 188	22	22	40	14	1 +													
				Main Inj. Faceplate	SS347	18	11			68		2 -											
				Main Inj. Baffle	NARloy-A									96	3 +								
A600/02	Fuel Pre-burn	sec		ASI CmbCh wall	NARloy-A									96	3 +								
					Inconel 625																		
				PB Inj Faceplate	Inconel 625																		
				PB Inj Element Tip	SS304L																		
				PB Inj Baffle	NARloy-A									96	3 +								
/03		sec		ASI CmbCh wall	NARloy-A									96	3 +								
					Inconel 625																		
				PB Inj Faceplate	Inconel 625																		
				PB Inj Element Tip	SS304L																		
				PB Inj Baffle	NARloy-A									96	3 +								
/04		sec		Cmb. Zone Liner	Haynes 188	22	22	40	14	1 +													
				Structural Wall	Inconel 718	19	53			18	3												5
				PB Inj Faceplate	Inconel 625																		
				PB Inj Element Tip	SS304L																		
				PB Inj Baffle	NARloy-A									96	3 +								
/06		sec		Post	Haynes 188	22	22	40	14	1 +													
				Turbine Blade	MAR-M-246	9	60	10	10		2 +		1 +			5 +							1 +
/08		n/a		PB Inj. Baffle	NARloy-A									96	3 +								

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

FAILURE MODE	ASSEMBLY	Rxt	C/E	COMPONENT	MATERIAL	Cr	Ni	Co	W	Fe	Mo	Mn	Ti	Cu	Ag	Al	Ta	Nb+Ta
											COMPOSITION							
A600/09	Fuel Pre-Burn	imm		LOX Manifold	Inconel 625													
	(con't)				Inconel 718	19	53			18	3							5
				PB Inj Faceplate	Inconel 625													
				PB Inj Element Tip	SS304L													
				PB Inj Baffle	NARloy-A									96	3+			
				Turbines	MAR-M-246	9	60	10	10		2+		1+			5+		1+
					Haynes 188	22	22	40	14	1+								
					Incoloy 903		38	15		40			1+			1		3
				Downstream parts	misc.													
A700/02	Oxid. Pre-Burn	sec		ASI CmbCh wall	NARloy-A									96	3+			
					Inconel 625													
				PB Inj Faceplate	Inconel 625													
				PB Inj Element Tip	SS304L													
				PB Inj Baffle	NARloy-A									96	3+			
/03		sec		ASI CmbCh wall	NARloy-A									96	3+			
					Inconel 625													
				PB Inj Faceplate	Inconel 625													
				PB Inj Element Tip	SS304L													
				PB Inj Baffle	NARloy-A									96	3+			
/04		sec		Cmb. Zone Liner	Haynes 188	22	22	40	14	1+								
				Structural Wall	Inconel 718	19	53			18	3							5
				PB Inj Faceplate	Inconel 625													
				PB Inj Element Tip	SS304L													
				PB Inj Baffle	NARloy-A									96	3+			
/06		sec		Post	Haynes 188	22	22	40	14	1+								
				Turbine Blade	MAR-M-246	9	60	10	10		2+		1+			5+		1+

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

FAILURE MODE	ASSEMBLY	Rxt	C/E	COMPONENT	MATERIAL	COMPOSITION Cr	Ni	Co	W	Fe	Mo	Mn	Ti	Cu	Ag	Al	Ta						Nb+Ta
A700/09	Oxid. Pre-Burn	sec		LOX Manifold	Inconel 625																		
	(con't)				Inconel 718	19	53			18	3												5
				PB Inj Faceplate	Inconel 625																		
				PB Inj Element Tip	SS304L																		
				PB Inj Baffle	NARloy-A									96	3 +								
				Turbines	MAR-M-246	9	60	10	10		2 +		1 +			5 +							1 +
					Haynes 188	22	22	40	14	1 +													
					Incoloy 903		38	15		40			1 +			1							3
				Downstream parts	misc.																		
B200/04	HPFTP	Imm		Turbine Blades																			
			c	Tip																			
			c	Tip Seal																			
			c	Housing Pilot Lip																			
			c	Nozzle																			
			c	Platform Seals																			
/08		Imm	c	Seal																			
			c	Platform																			
/11		Imm	c	Kel-F Ring																			
/15		Imm		Turbine Blade																			
			c	Ball																			
			c	Cage																			
			c	Race																			
			c	Bearing Pload Sprg																			
/16		Imm		Turbine Blade																			
/24		sec	c	Ball																			
			c	Cage																			
			c	Race																			
			c	Thrust Ball																			
			c	Shaft Insert																			

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

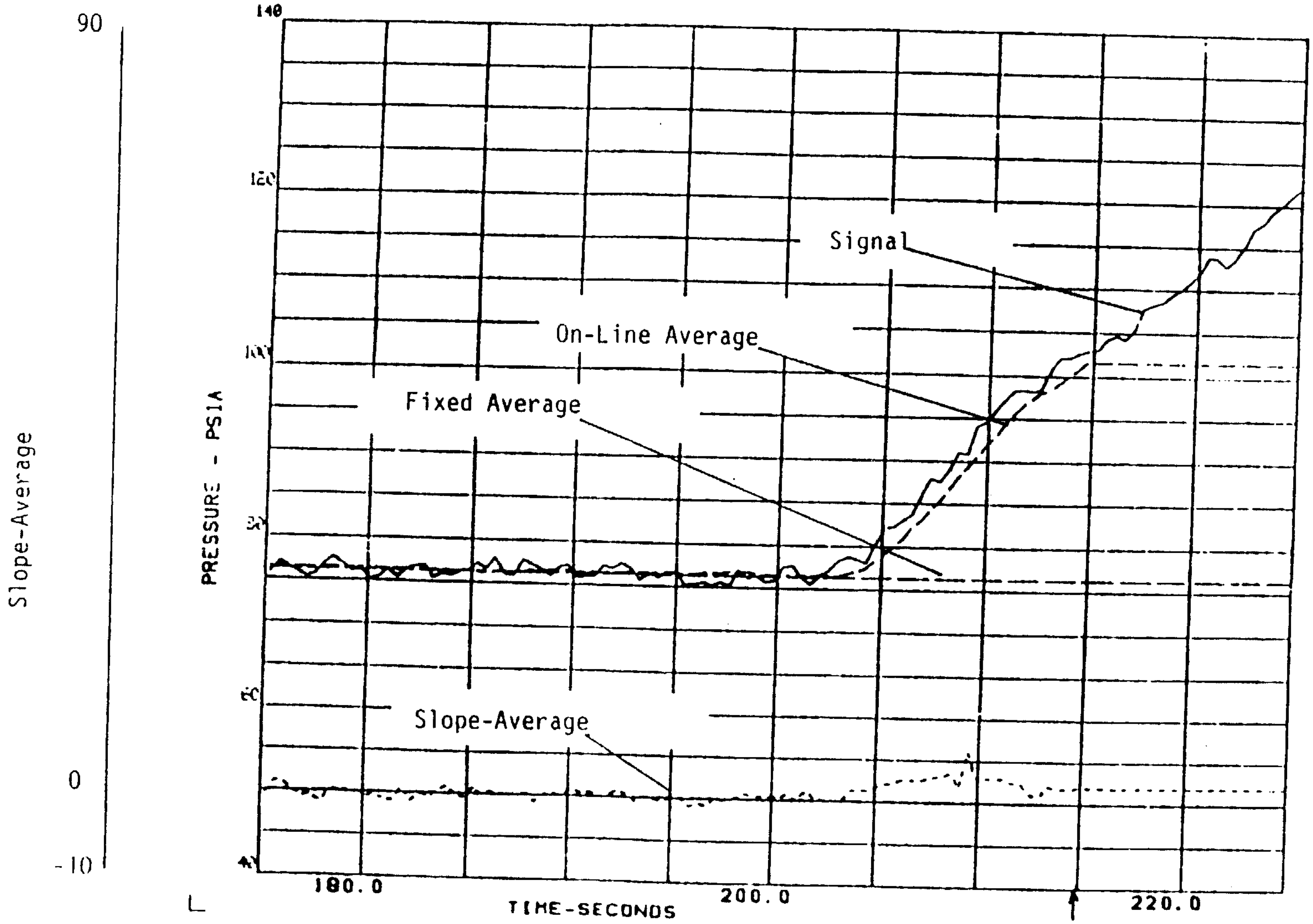
B400/05	HPOTP	Imm	c	Interstage Seal
/13		Imm		Turbine Blade
			c	Ball
			c	Cartidge
			c	Isolator
/14		Imm		Rotating Parts
/15		Imm		Pump Components
/18		sec		Bearings
				Rotating Parts
/19		sec		Seal
/20		sec		Rotating Parts
B600/05	LPFTP	Imm	c	Ball
			c	Cage
			c	Race
			c	Turbine Brg Spring
				Turbopump Parts
/08		sec	c	Carbon Insert
B800/06	LPOTP	Imm	c	Cage
			c	Bearing
			c	Turbine Brg Spring
				Rotor & Misc. Parts
C113/01	Oxidizer Dome	sec		Post
	Purge Chk Valve			Misc. Erosion

SUMMARY OF PLUME CONTAMINANTS EXPECTED BASED ON SSME FMEA

C200/07	Pneumatic Cntrl	min		Post																			
	Assembly			Misc. Erosion																			
D130/01	Fuel Preburner	imm		HPFTP Turbine																			
	Oxidizer Valve																						
D140/01	Ox. Pre-Burn	Imm		Powerhead																			
	Oxidizer Valve			Preburner																			
				HPOTP Turbine																			
				Heat Exchanger																			
NOTES:	A1 - The Hot Gas Liners are coated with several layers of ZrO_2 and Ni and erosion of these is common and not cause for alarm																						

ATTACHMENT 6

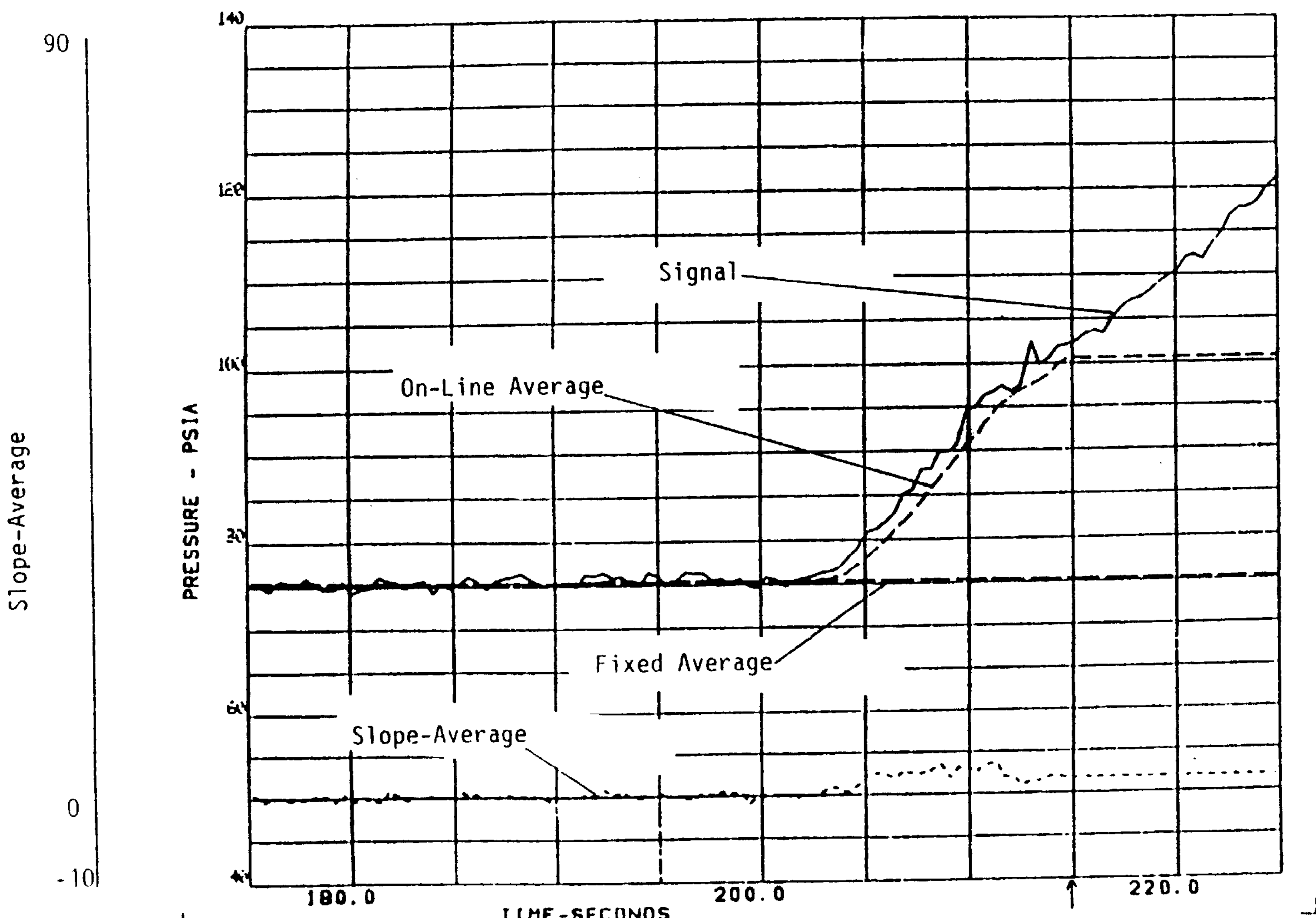
TREND ALGORITHM RESULTS - TEST 901-364



SAFD Algorithm C/O: 214.79 sec

(Redline C/O: 392.15 sec)

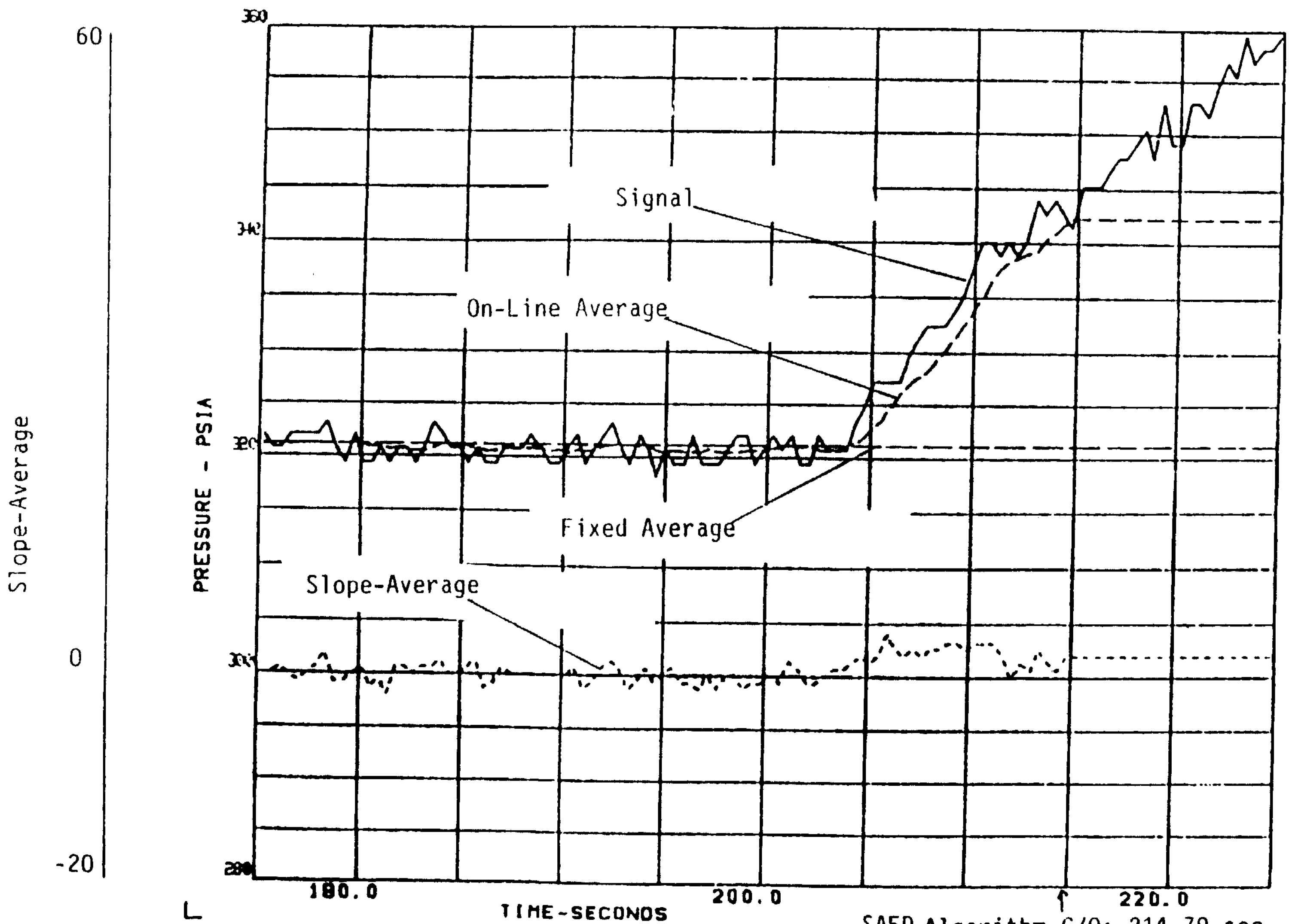
Figure A1 - Facility Oxidizer Flowmeter Discharge Pressure, Test 901-364



SAFD Algorithm C/O/: 214.79 sec

(Redline C/O: 392.15 sec)

Figure A2 - Engine Oxidizer Inlet Pressure
Test 901-364



SAFD Algorithm C/O: 214.79 sec

(Redline C/O: 392.15 sec)

Figure A3 - Low Pressure Oxidizer Pump Discharge Pressure, Test 901-364

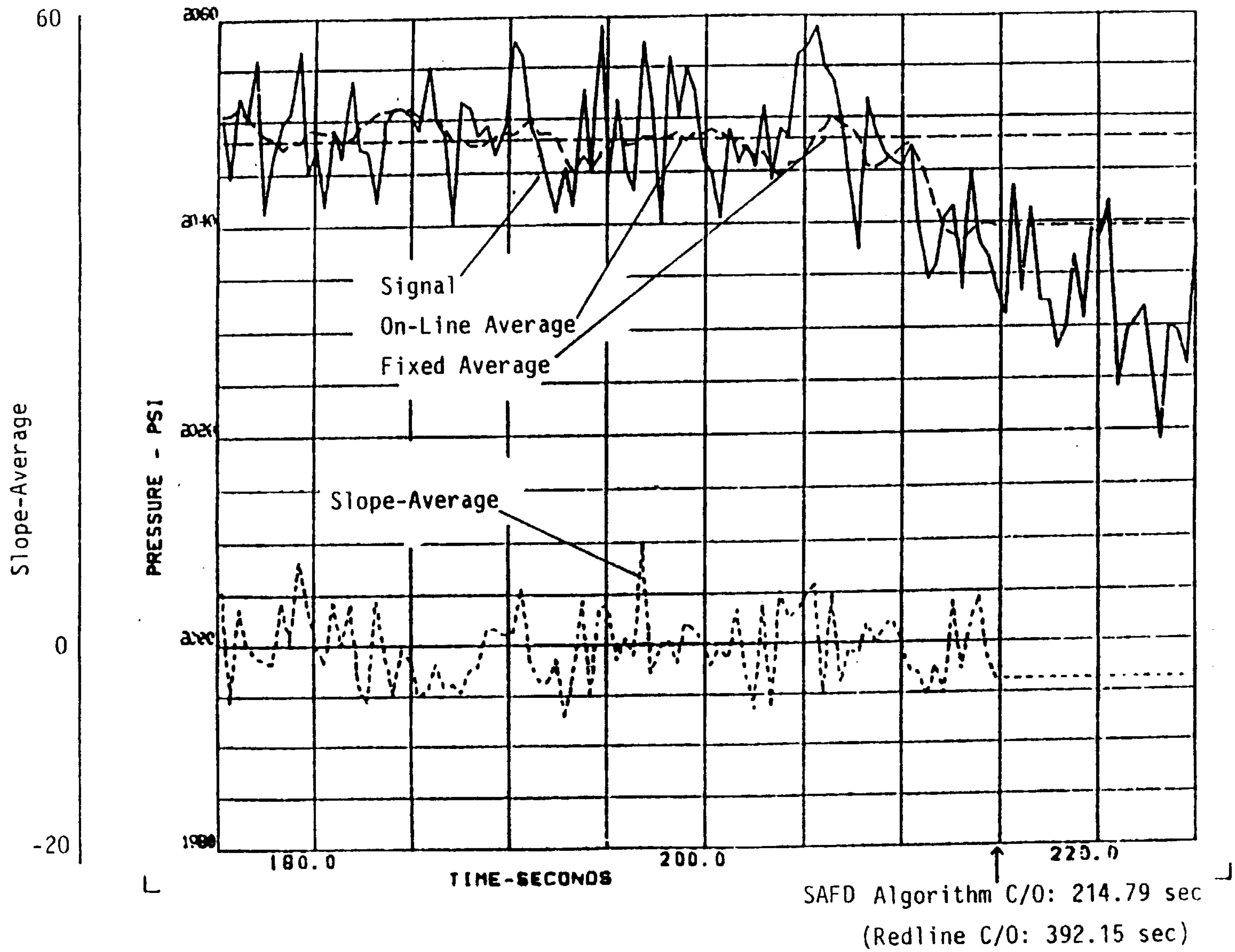
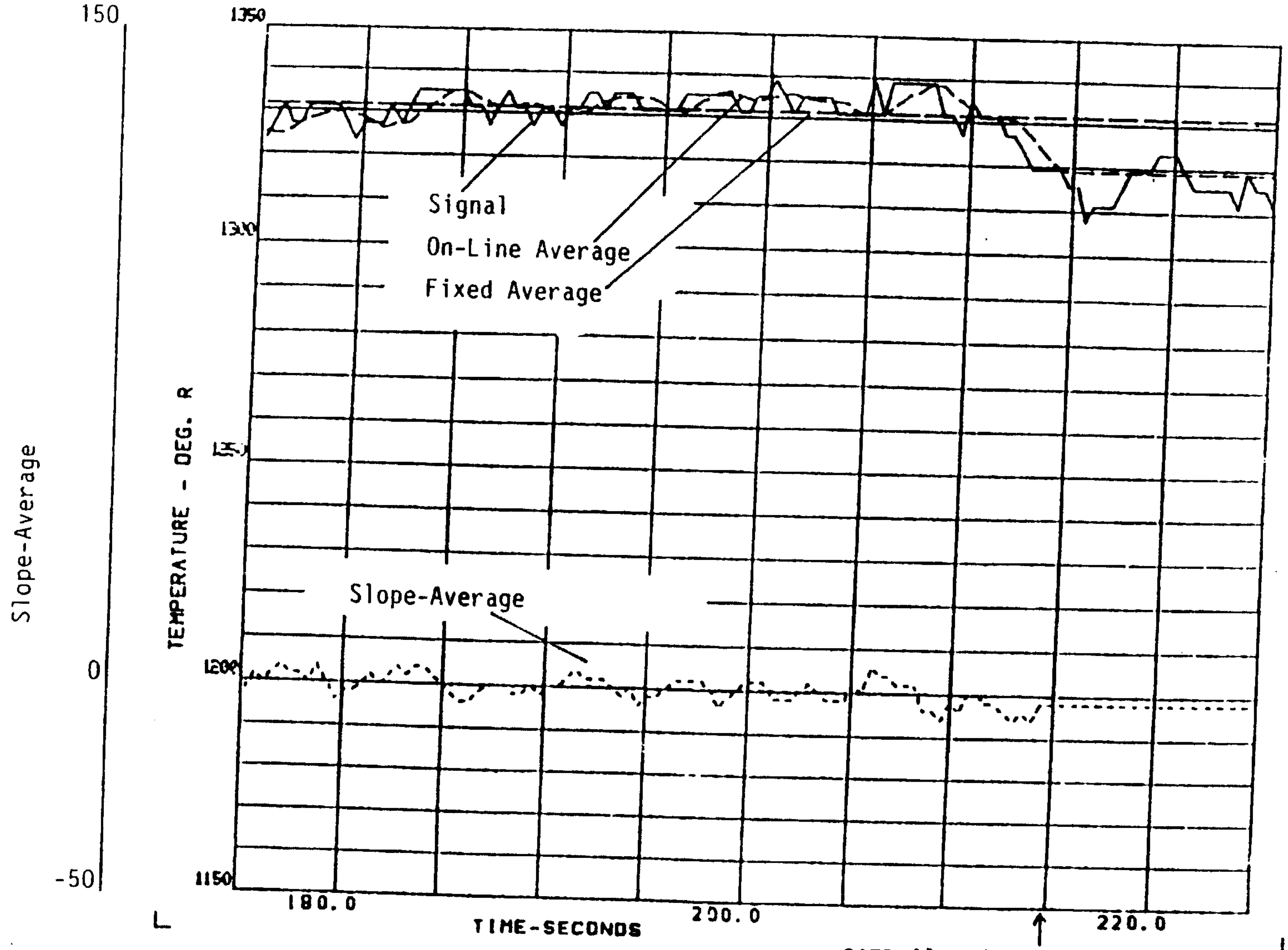
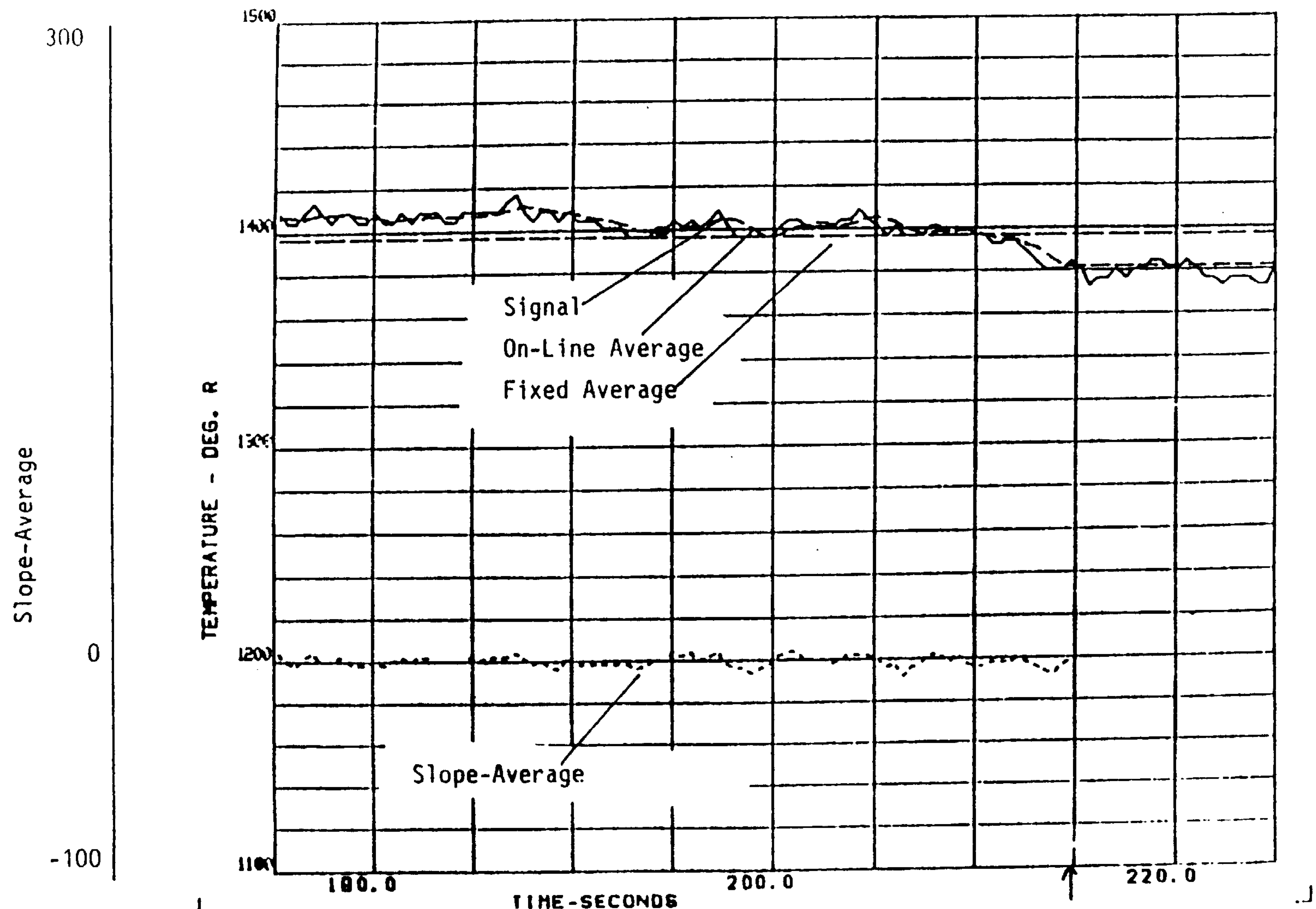


Figure A4- High Pressure Oxidizer Turbine Delta-P, Test 901-364



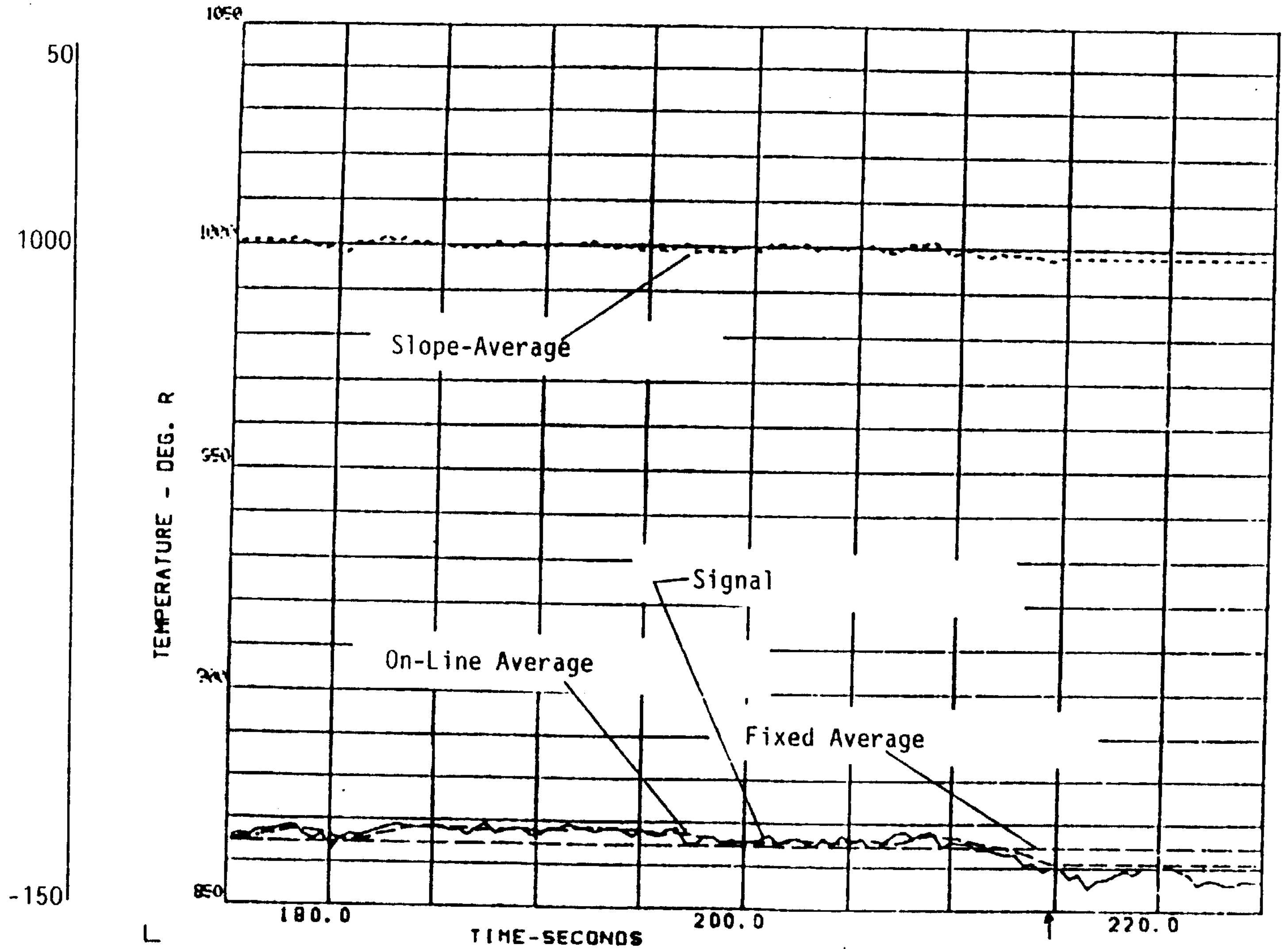
SAFD Algorithm C/O: 214.79 sec
(Redline C/O: 392.15 sec)

Figure A5 - High Pressure Oxidizer Turbine Ds Temp 1, Test 901-364



SAFD Algorithm C/O: 214.79 sec
(Redline C/O: 392.15 sec)

Figure A5 - High Pressure Oxizizer Turbine Ds Temp 2, Test 901-364



SAFD Algorithm C/O: 214.79 sec

(Redline C/O: 392.15 sec)

Figure A7 - Heat Exchanger Interface Temp, Test 901-364

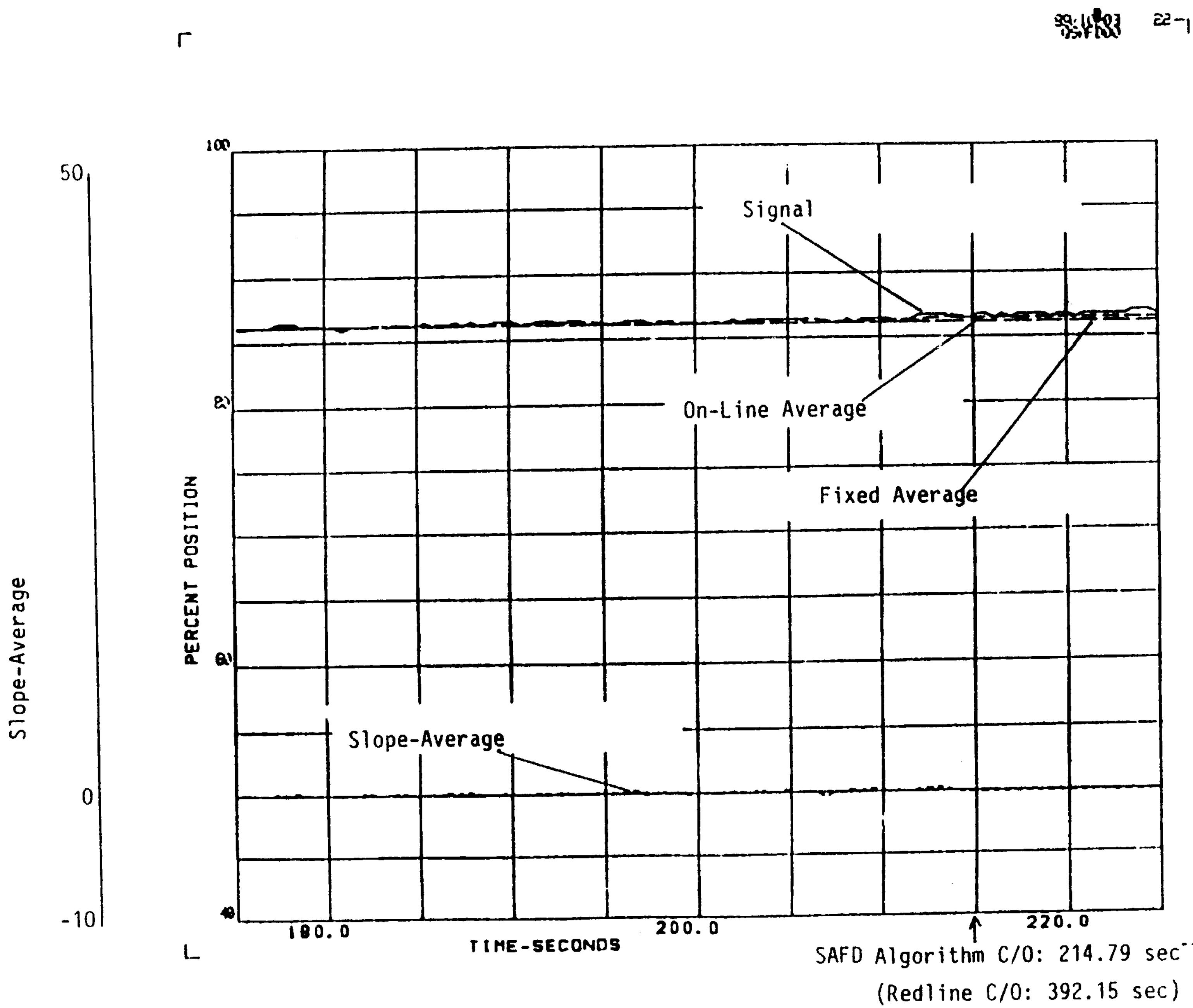


Figure A8 - FPOV Actuator Position, Test 901-364

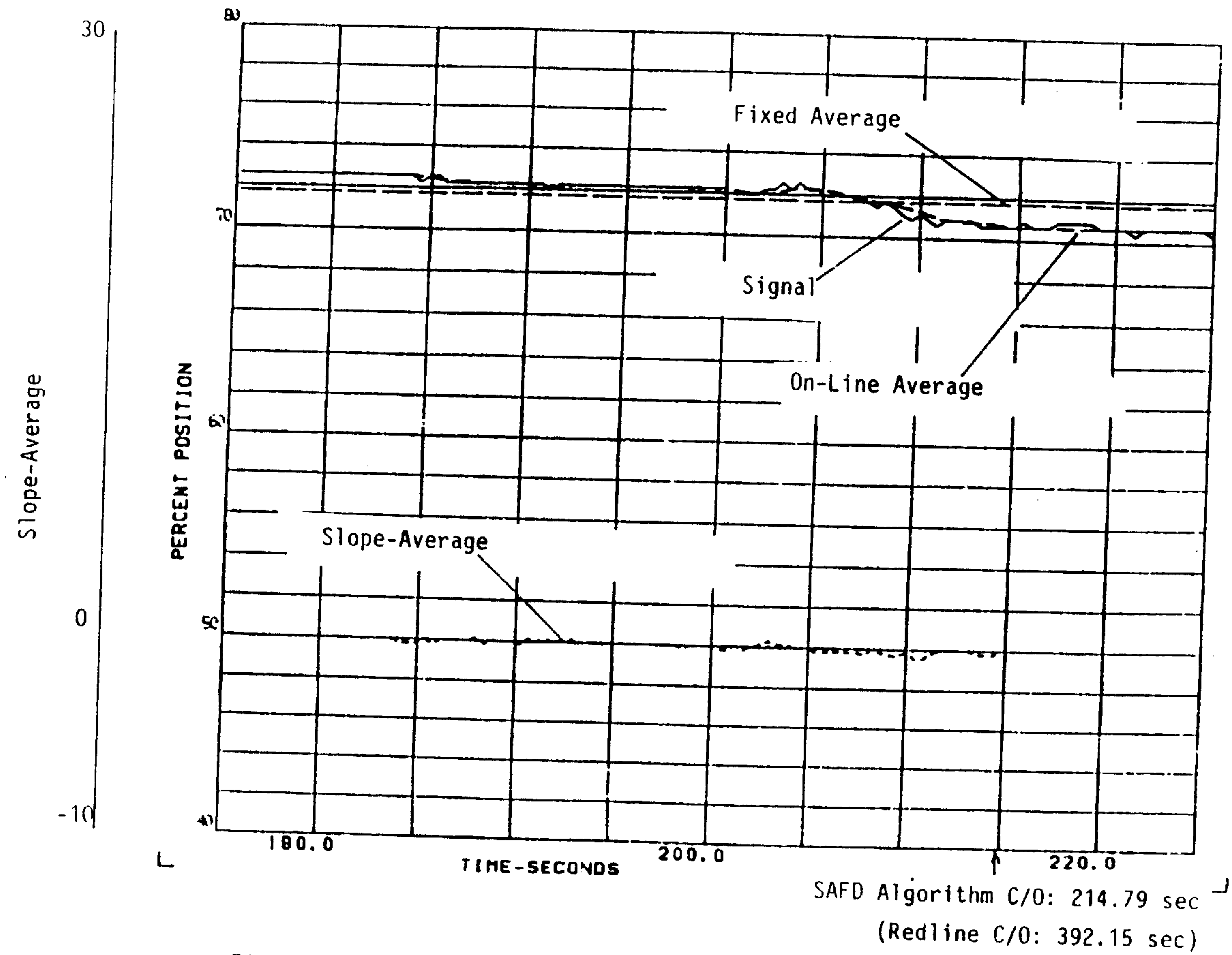
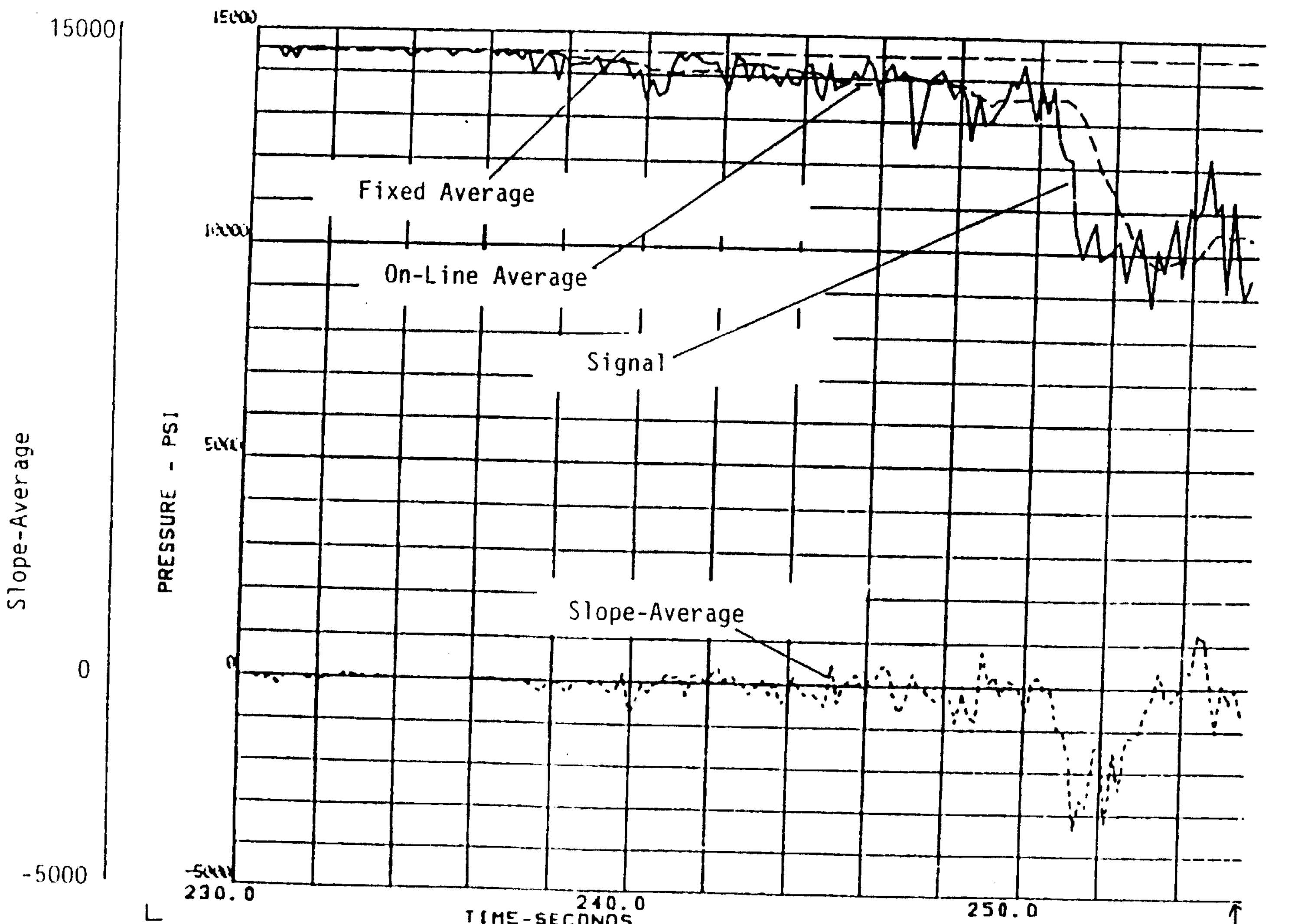


Figure A9 - OPOV Actuator Position, Test 901-364

ATTACHMENT 7

TREND ALGORITHM RESULTS - TEST 901-225



SAFD Algorithm C/O: 255.59 sec
(Redline C/O: 255.63 sec)

Figure B1 - Secondary Injector Faceplate Delta-P, Test 901-225

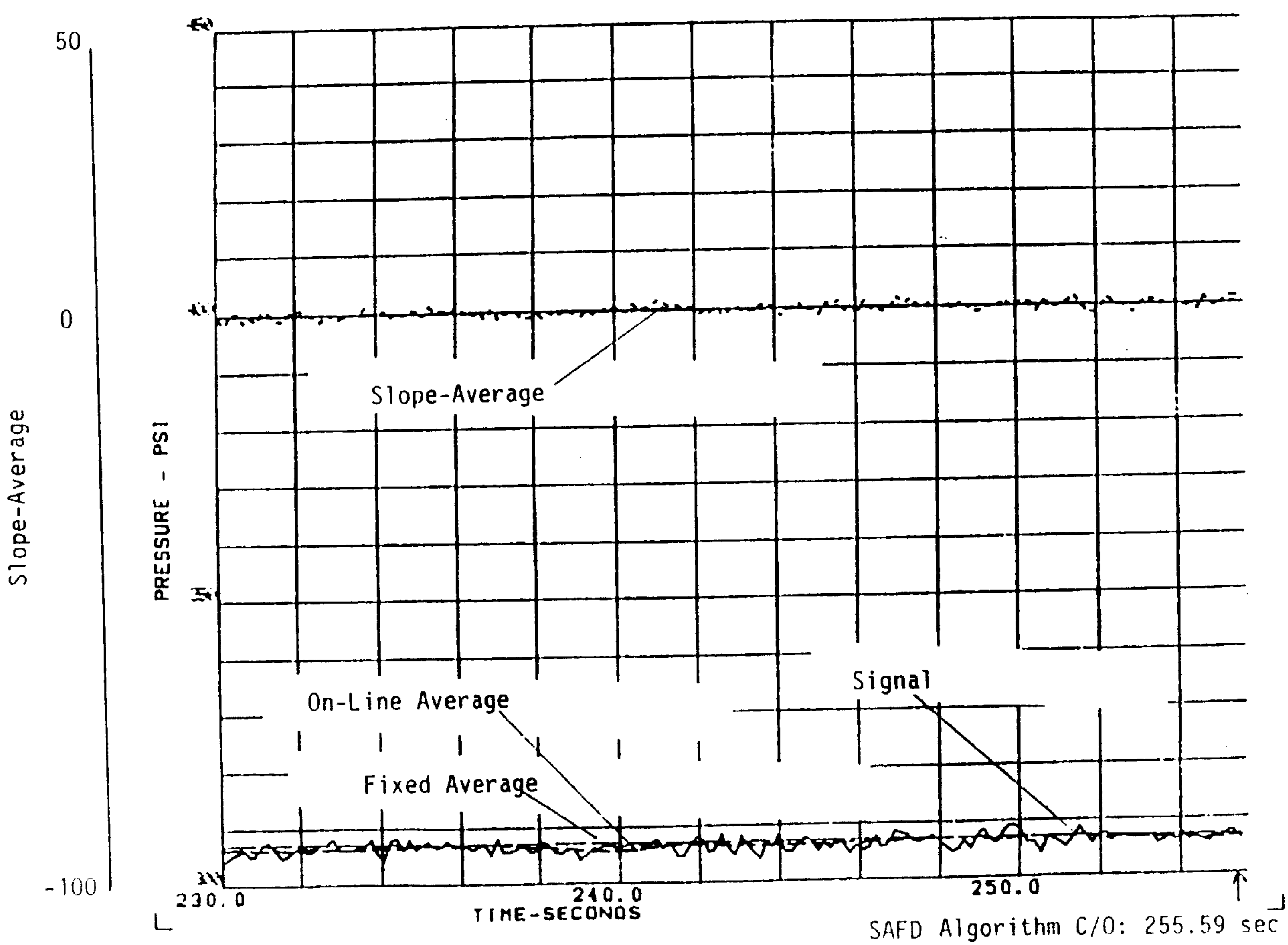
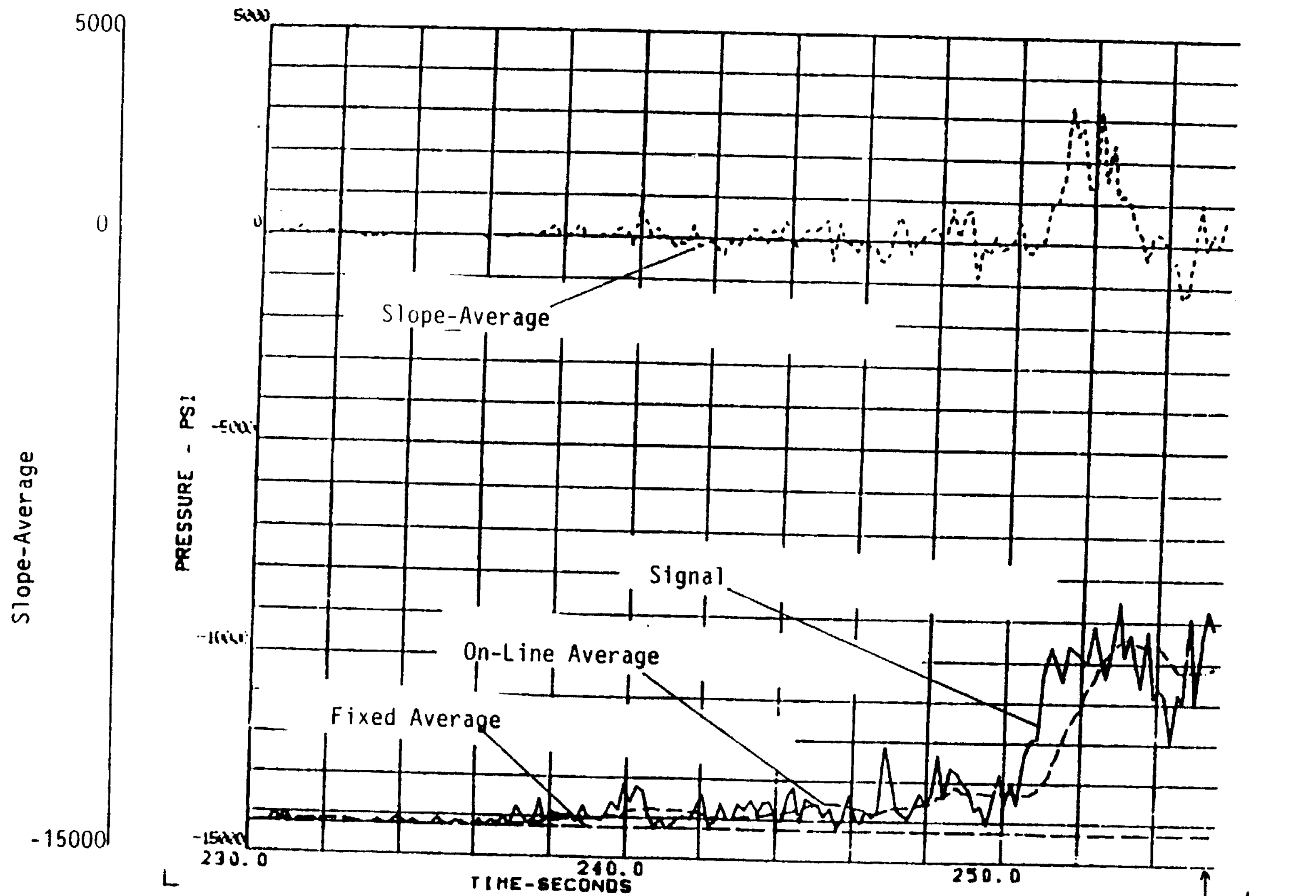


Figure B2 - Primary Injector Faceplate Delta-P, Test 901-225



SAFD Algorithm C/O: 255.59 sec
(Redline C/O: 255.63)

Figure B3 - Hot Gas Injector Delta-P,
Test 901-225

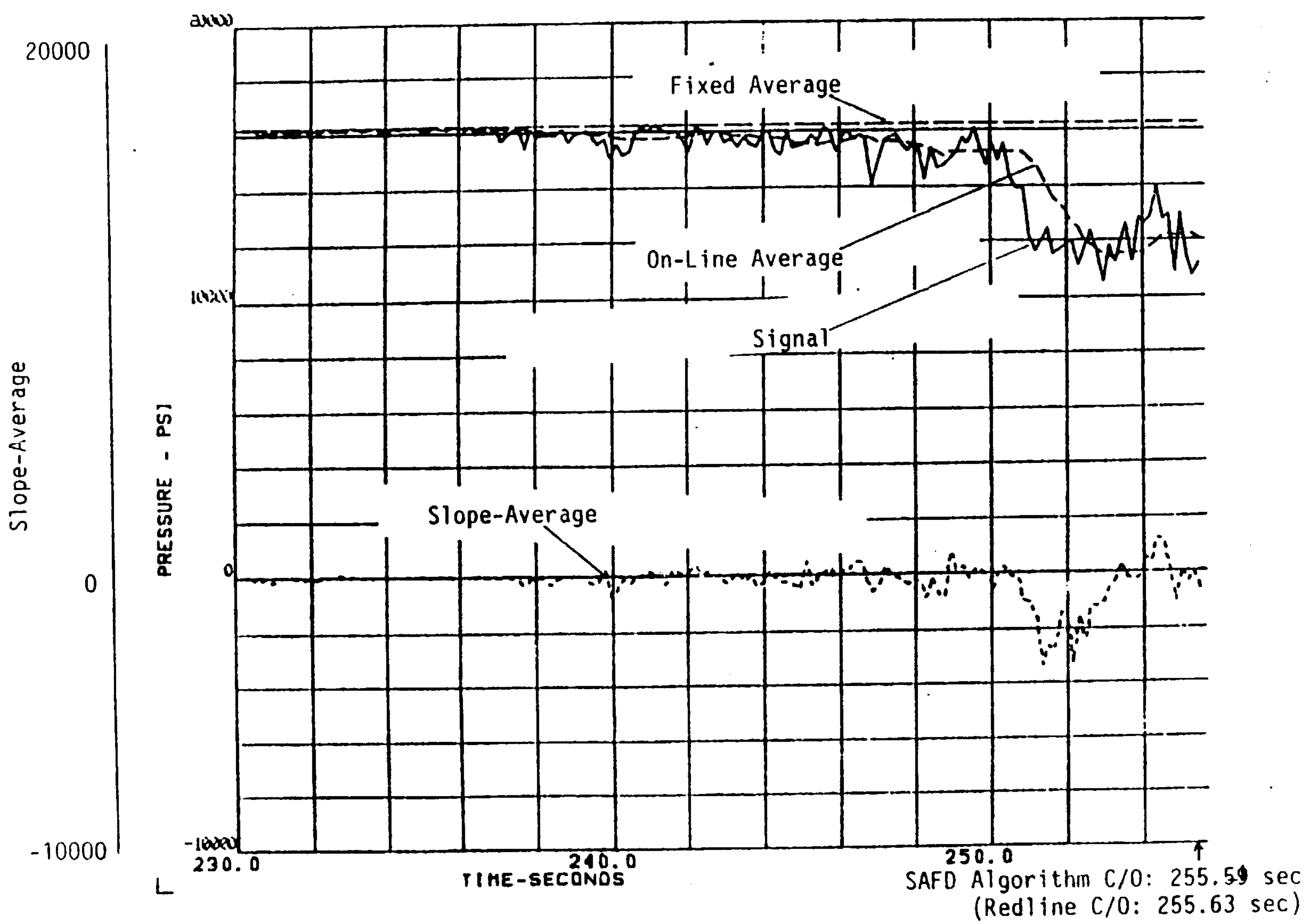


Figure B4 - High Pressure Fuel Turbine Delta-P,
Test 901-225

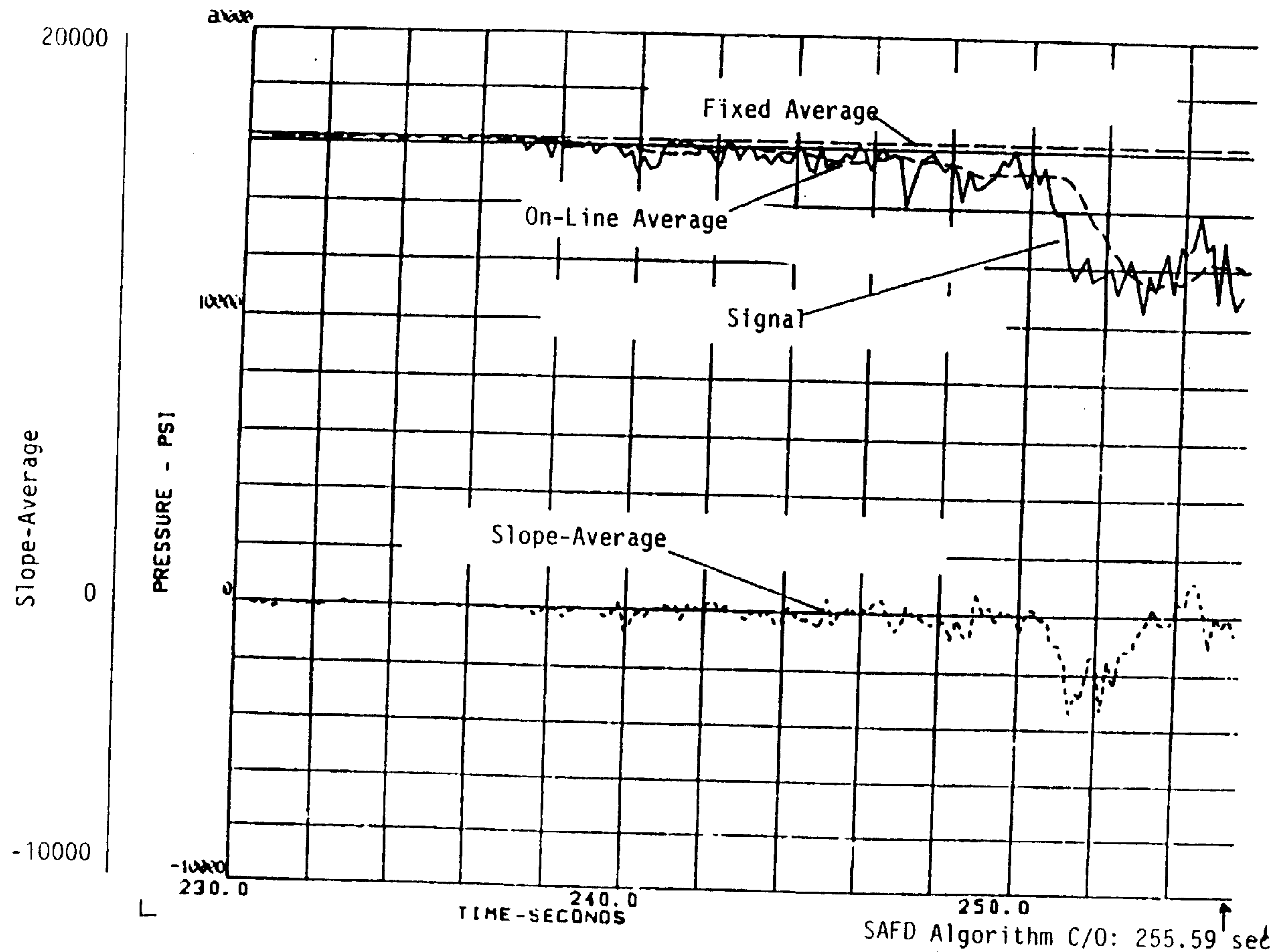
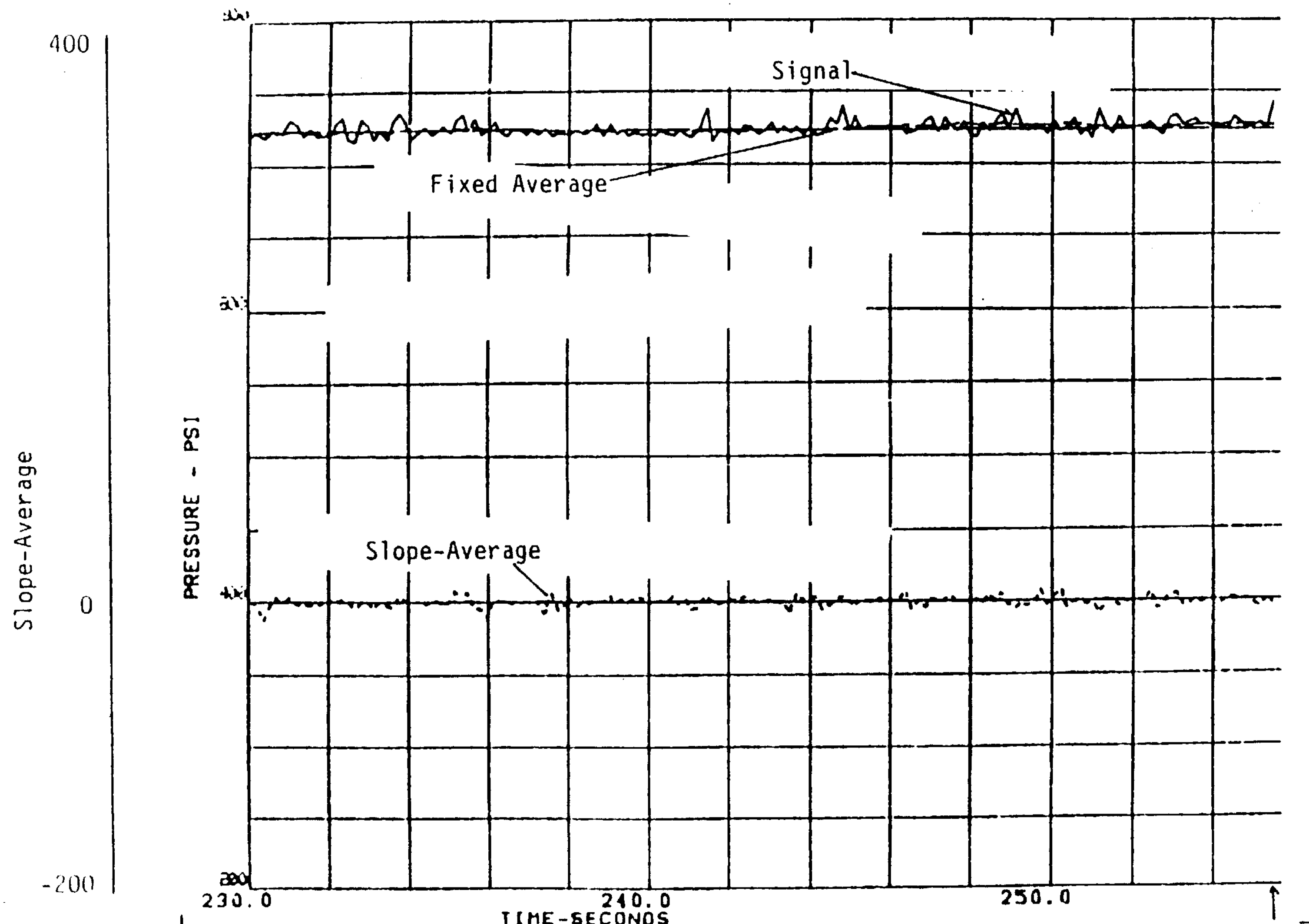


Figure B5- High Pressure Oxidizer Turbine Delta-P, Test 901-225



SAFD Algorithm C/O: 225.59 sec
(Redline C/O: 255.63)

Figure B6 - MCC Oxidizer Injector Pressure - MCC Chamber Pressure, Test 901-225

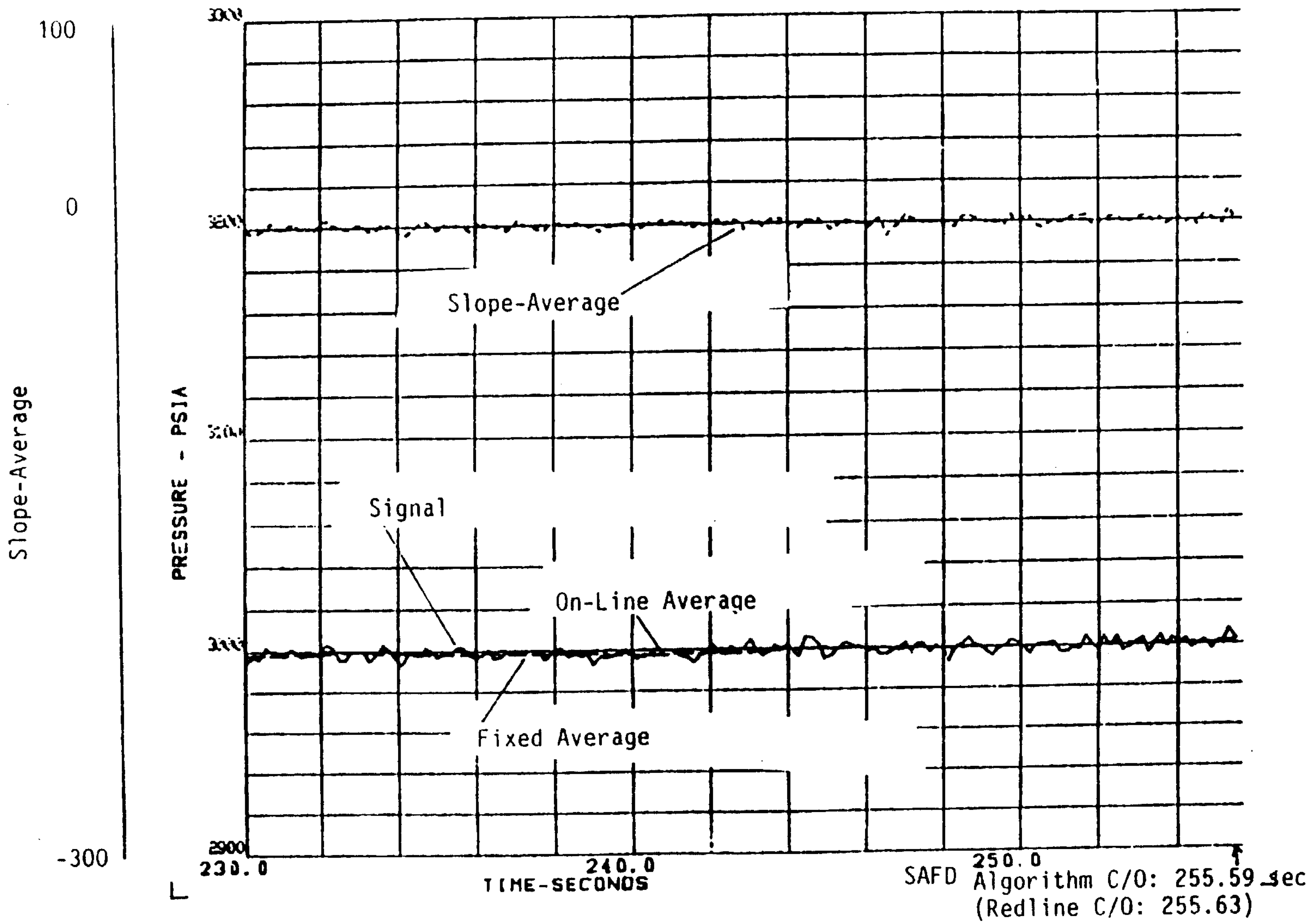


Figure B7 - Main Combustion Chamber Pressure, Test 901-225

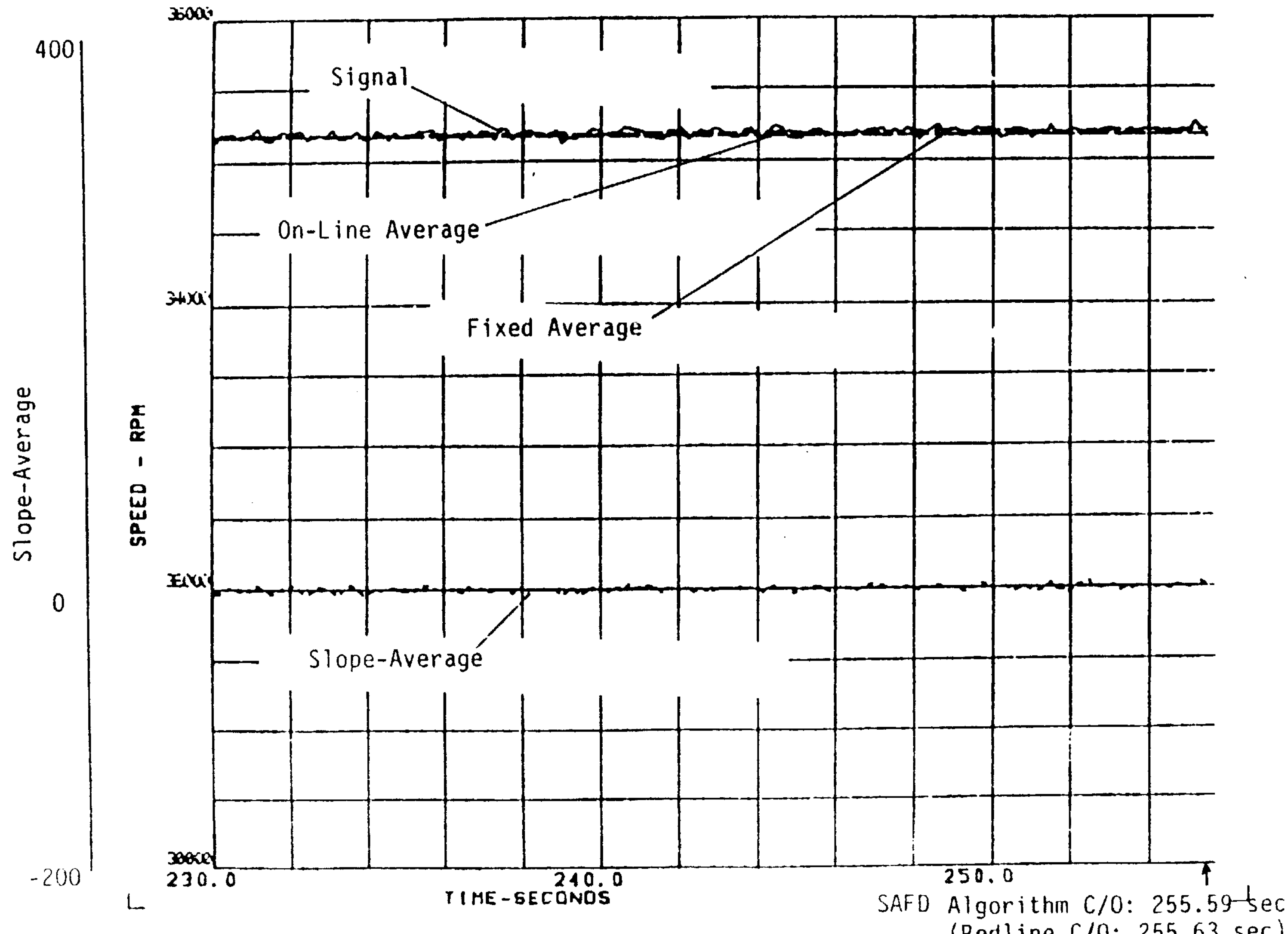


Figure B8 - High Pressure Fuel Pump Speed, Test 901-225

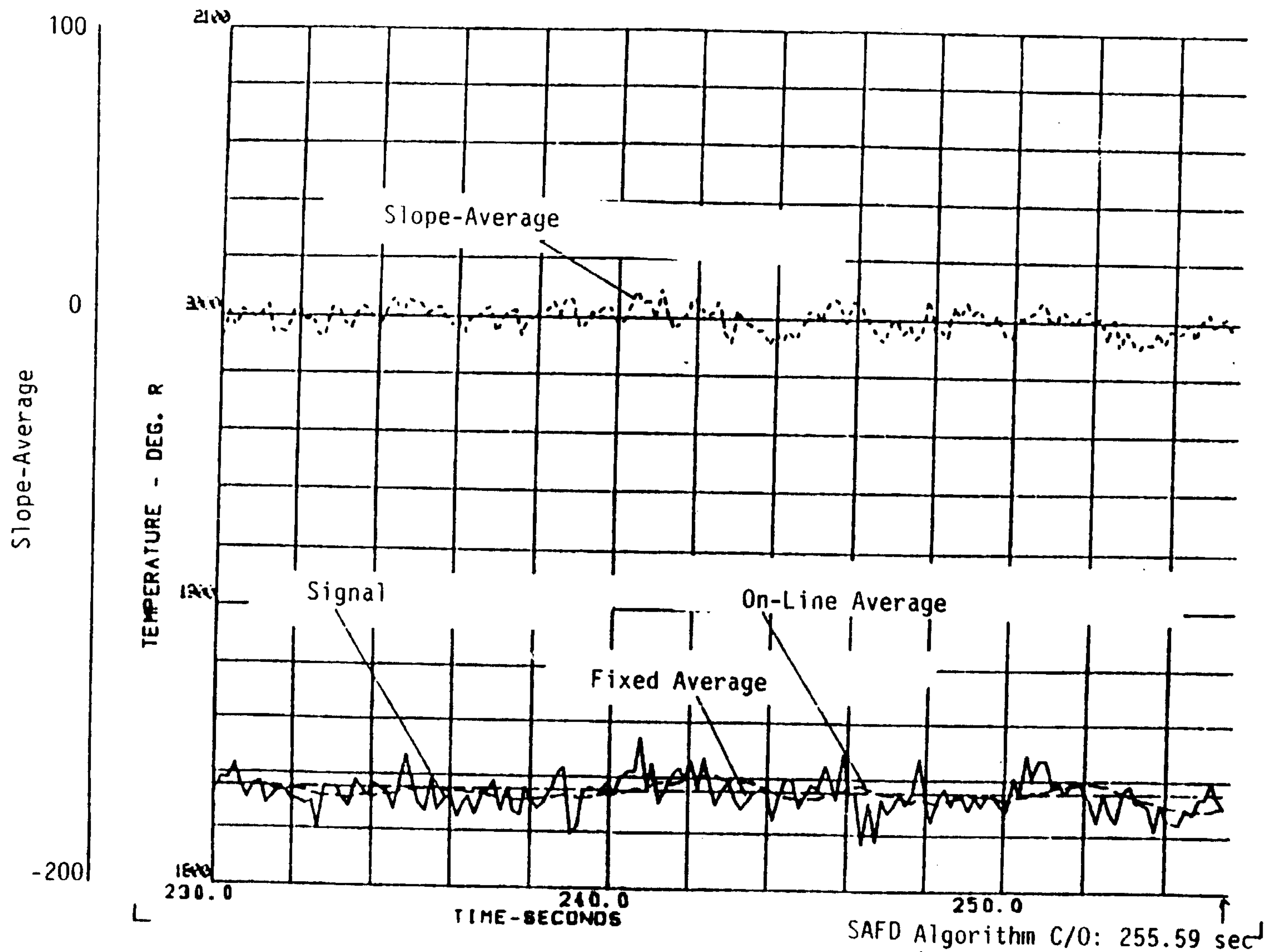


Figure B9 - High Pressure Fuel Turbine Discharge Temperature 1,
Test 901-225

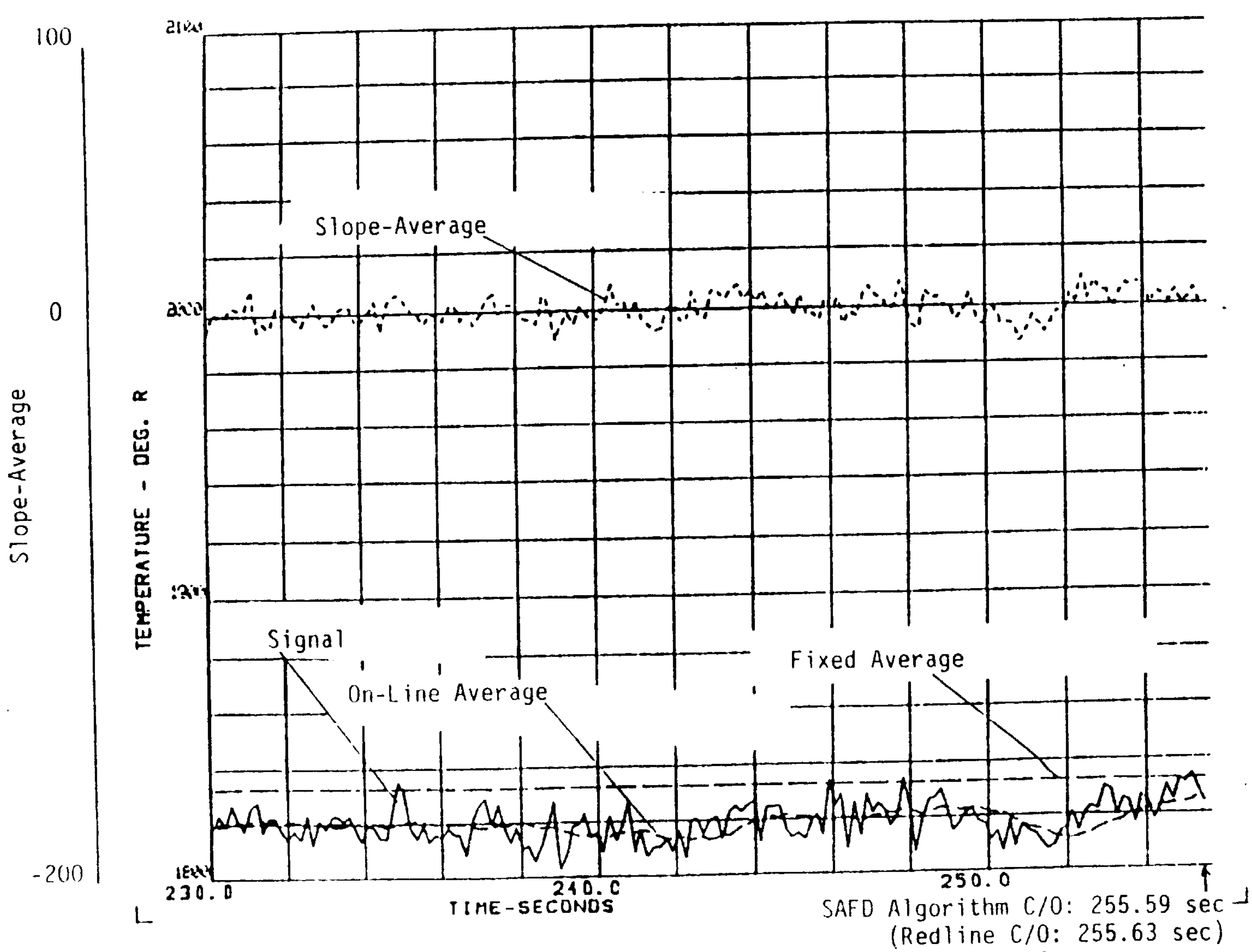
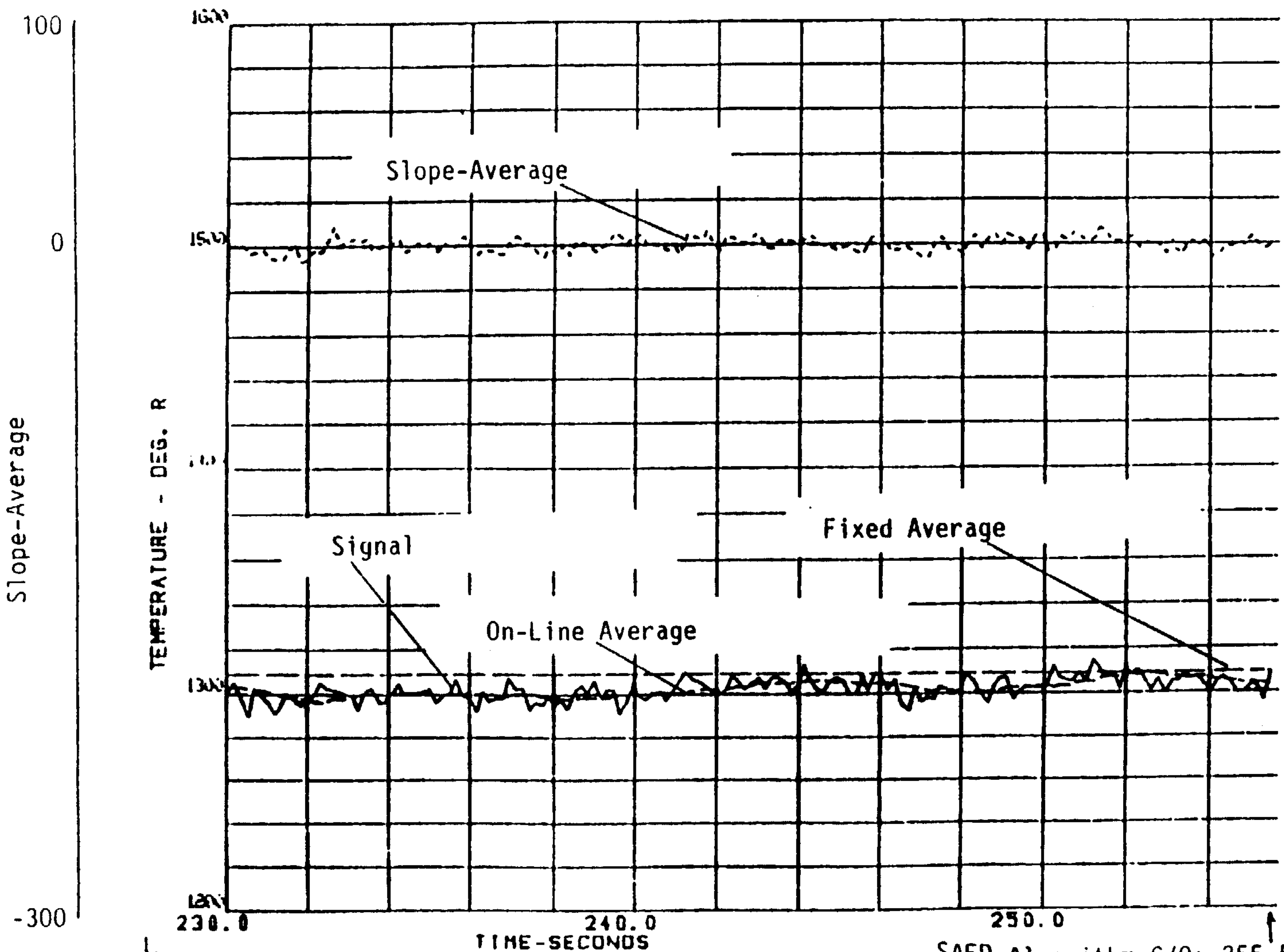
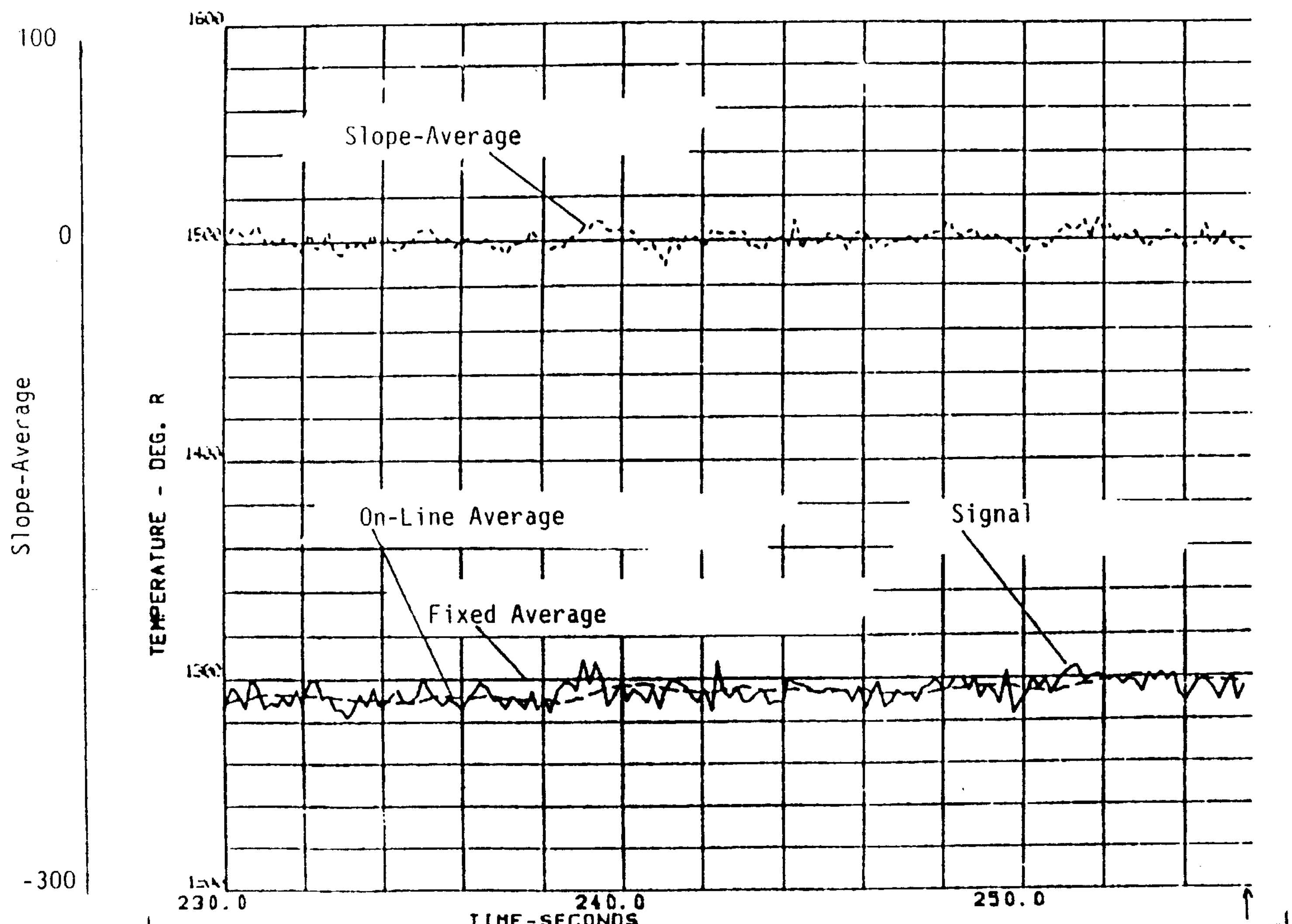


Figure B10 - High Pressure Fule Turbine Discharge Temperature 2,
Test 901-225



SAFD Algorithm C/O: 255.59 sec
(Redline C/O: 255.63 sec)

Figure B11 - High Pressure Oxidizer Turbine Discharge Temperature 1,
Test 901-225



SAFD Algorithm C/O: 255.59 sec
(Redline C/O: 255.63 sec)

Figure B12 - High Pressure Oxidizer Turbine Discharge Temperature 2, Test 901-225

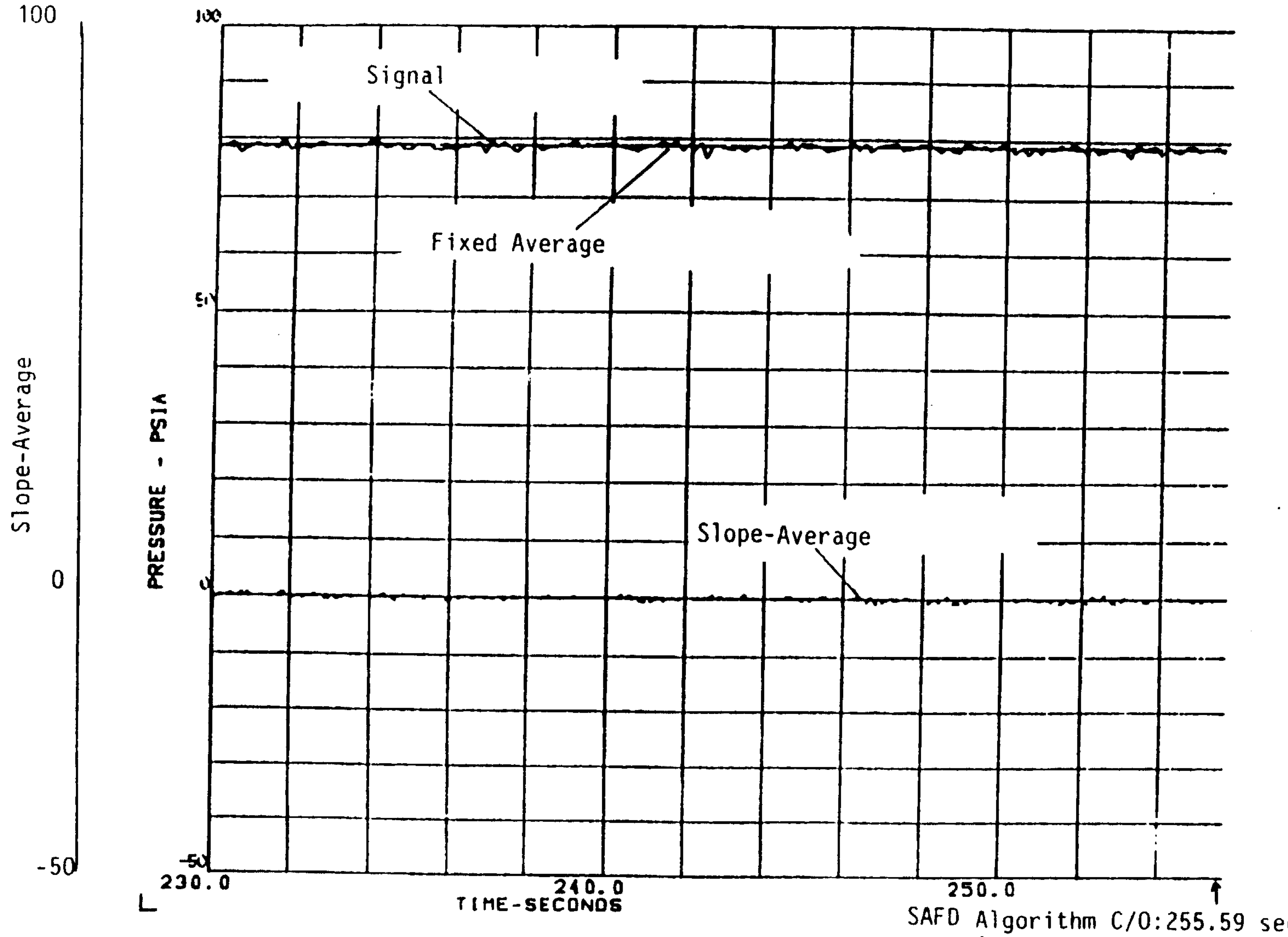


Figure B13 - Engine Oxidizer Inlet Pressure, Test 901-225

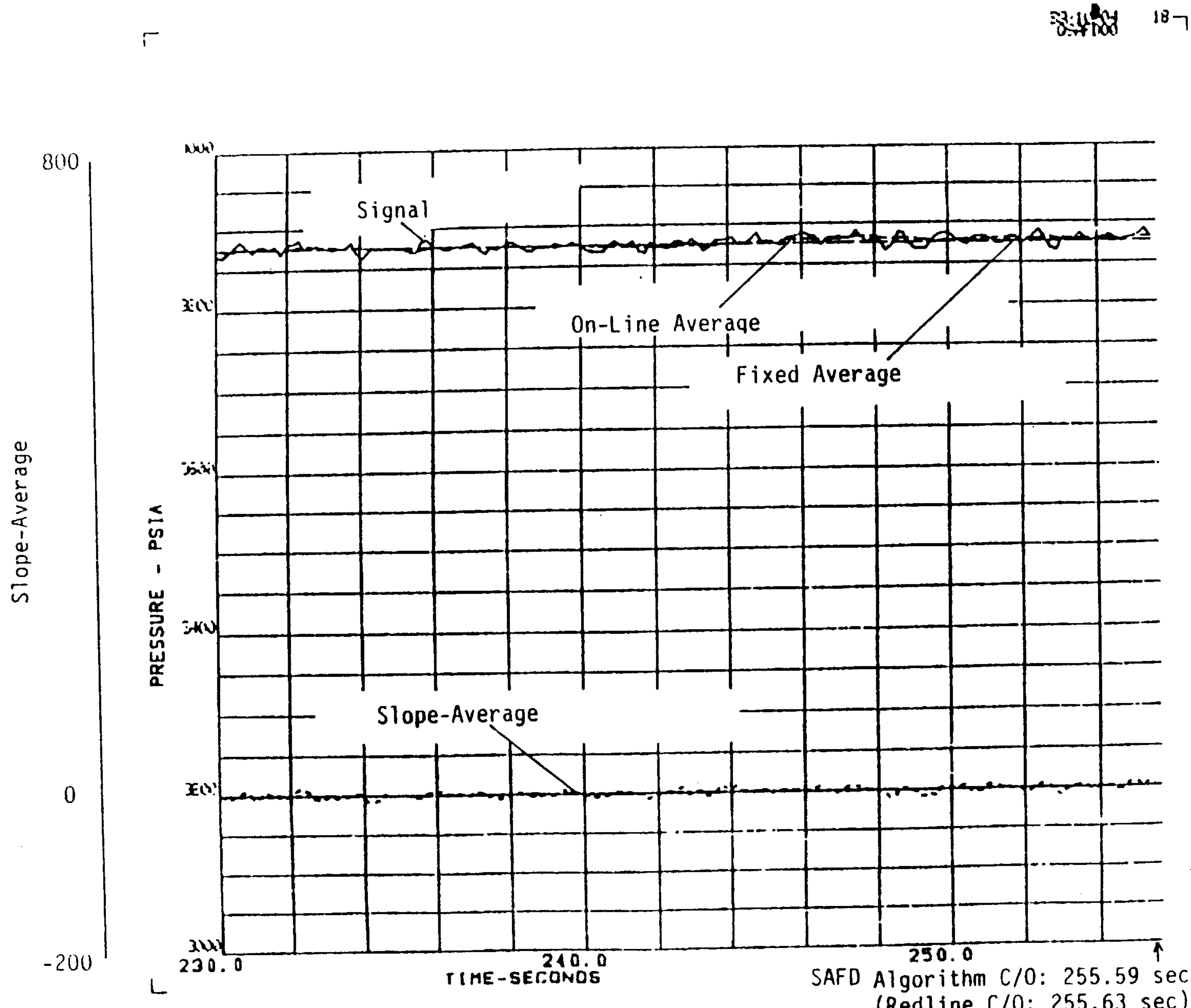
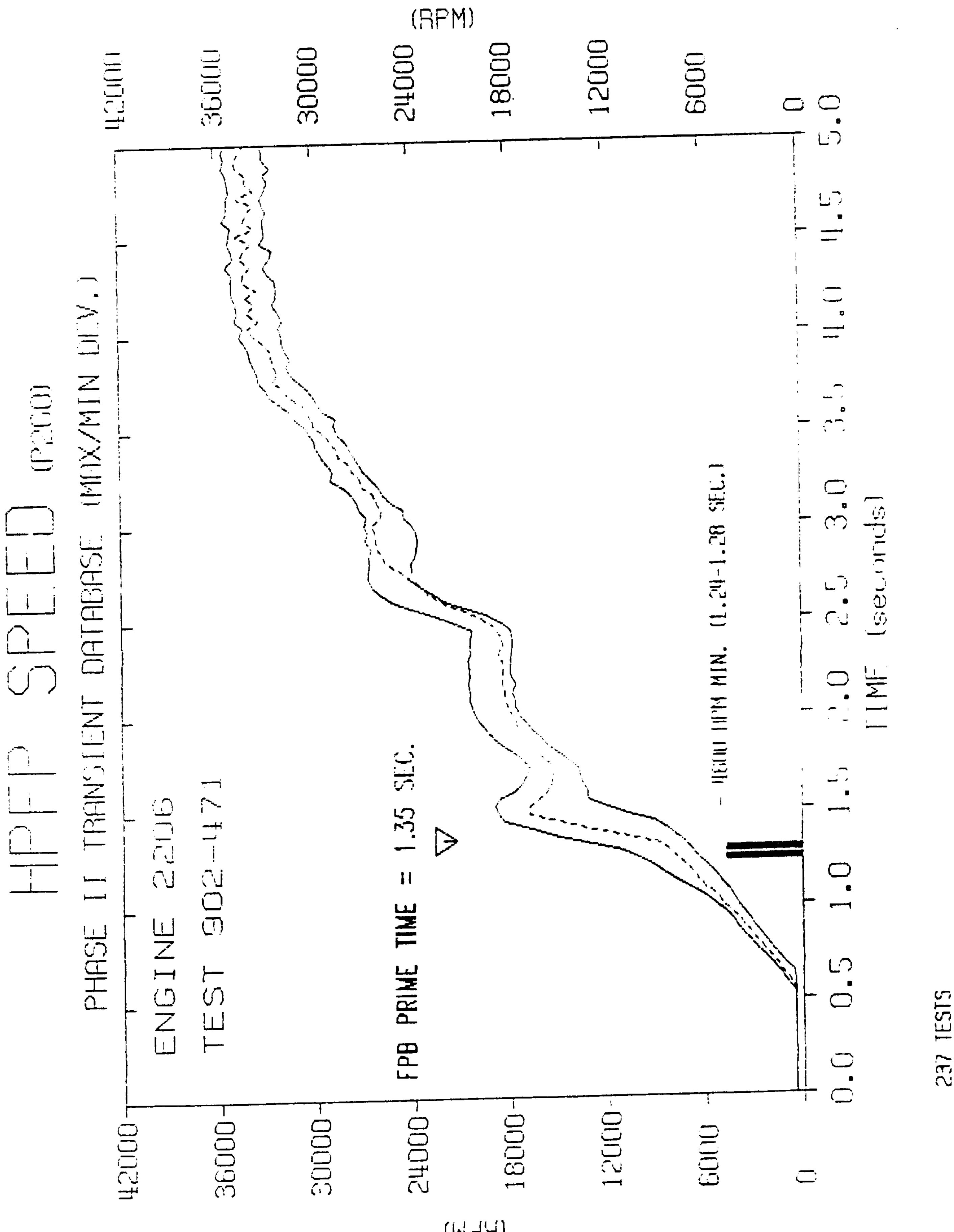


Figure B14 - Heat Exchanger Interface Pressure,
Test 901-225

ATTACHMENT 8

START TRANSIENT FLEETWIDE OPERATING ENVELOPES



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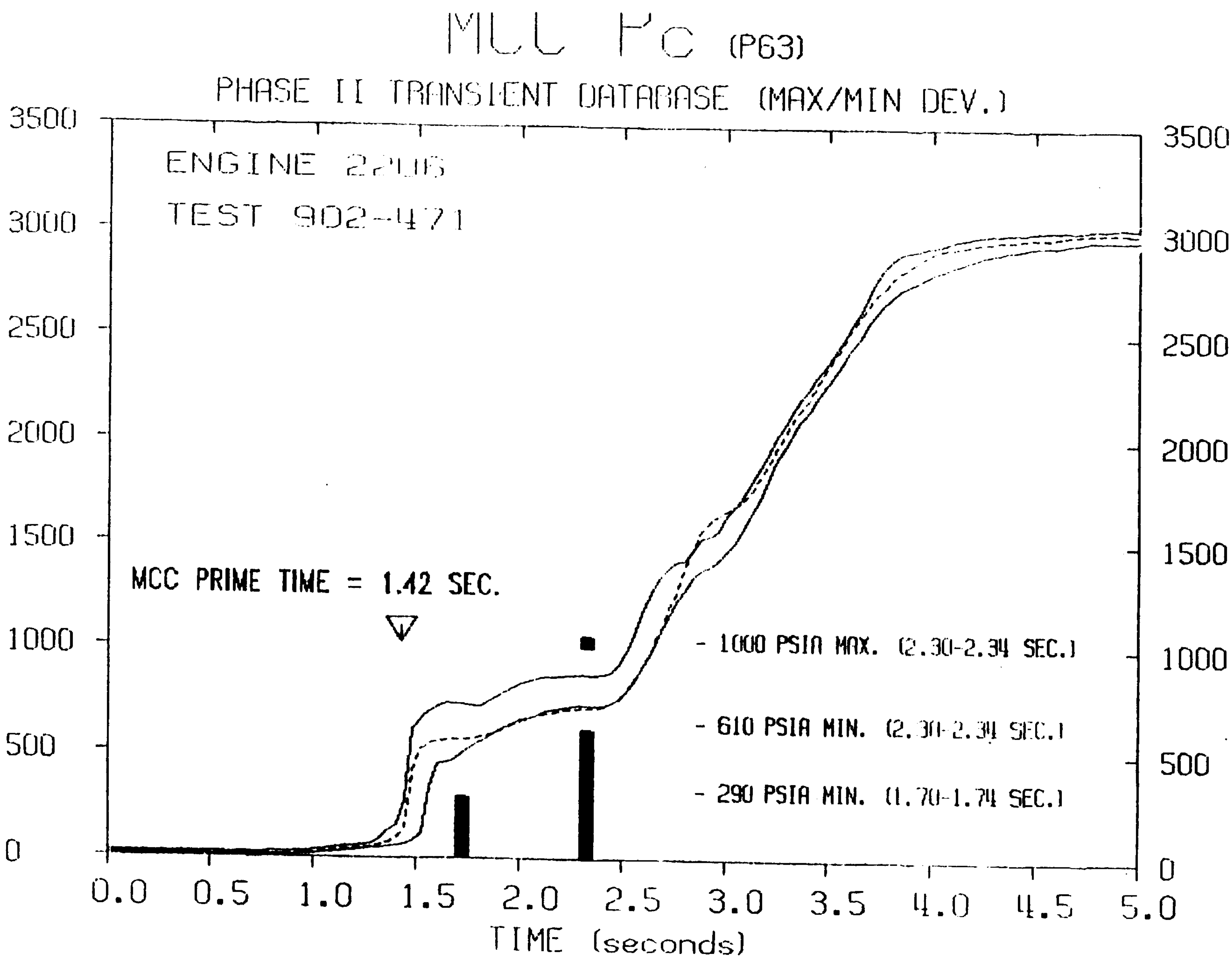
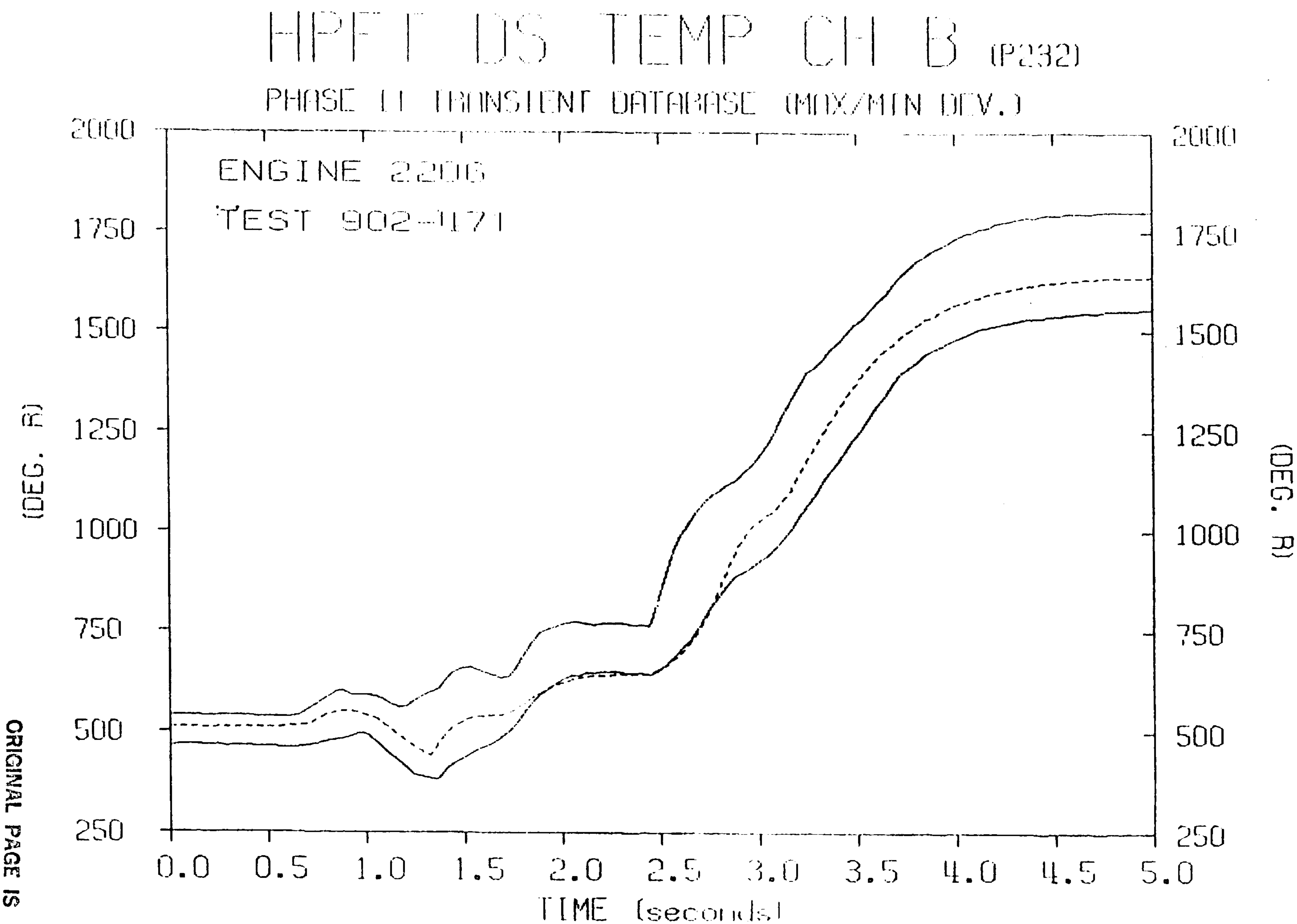

MCC Pc (P63)
PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)
ENGINE 2206
TEST 902-471
MCC PRIME TIME = 1.42 SEC.
- 1000 PSIA MAX. (2.30-2.34 SEC.)
- 610 PSIA MIN. (2.30-2.34 SEC.)
- 290 PSIA MIN. (1.70-1.74 SEC.)
(PSIA)
(PSIA)
TIME (seconds)
0
500
1000
1500
2000
2500
3000
3500
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

239 TESTS



237 TESTS

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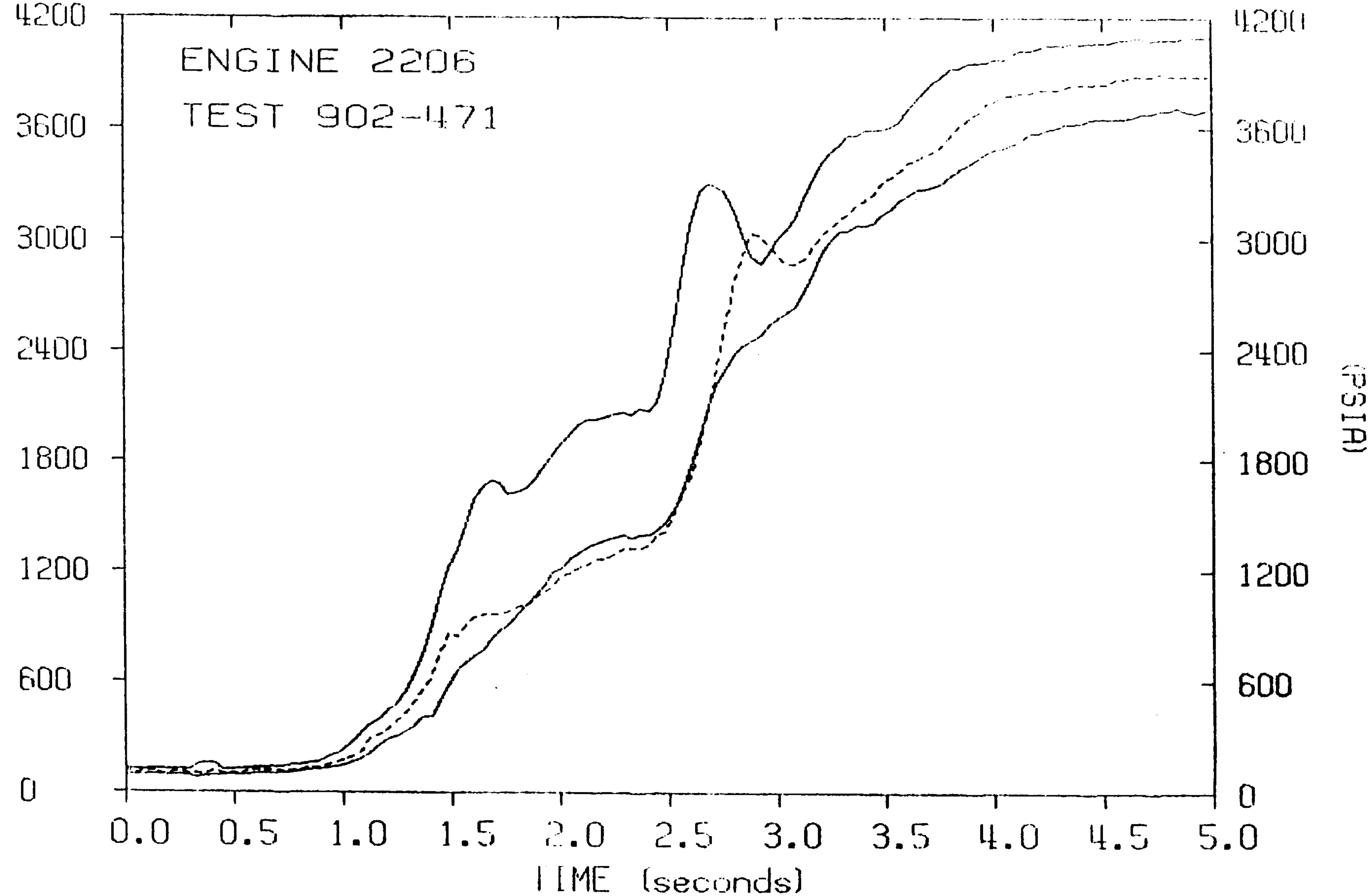
HPOP US PR (P90)

PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



238 TESTS

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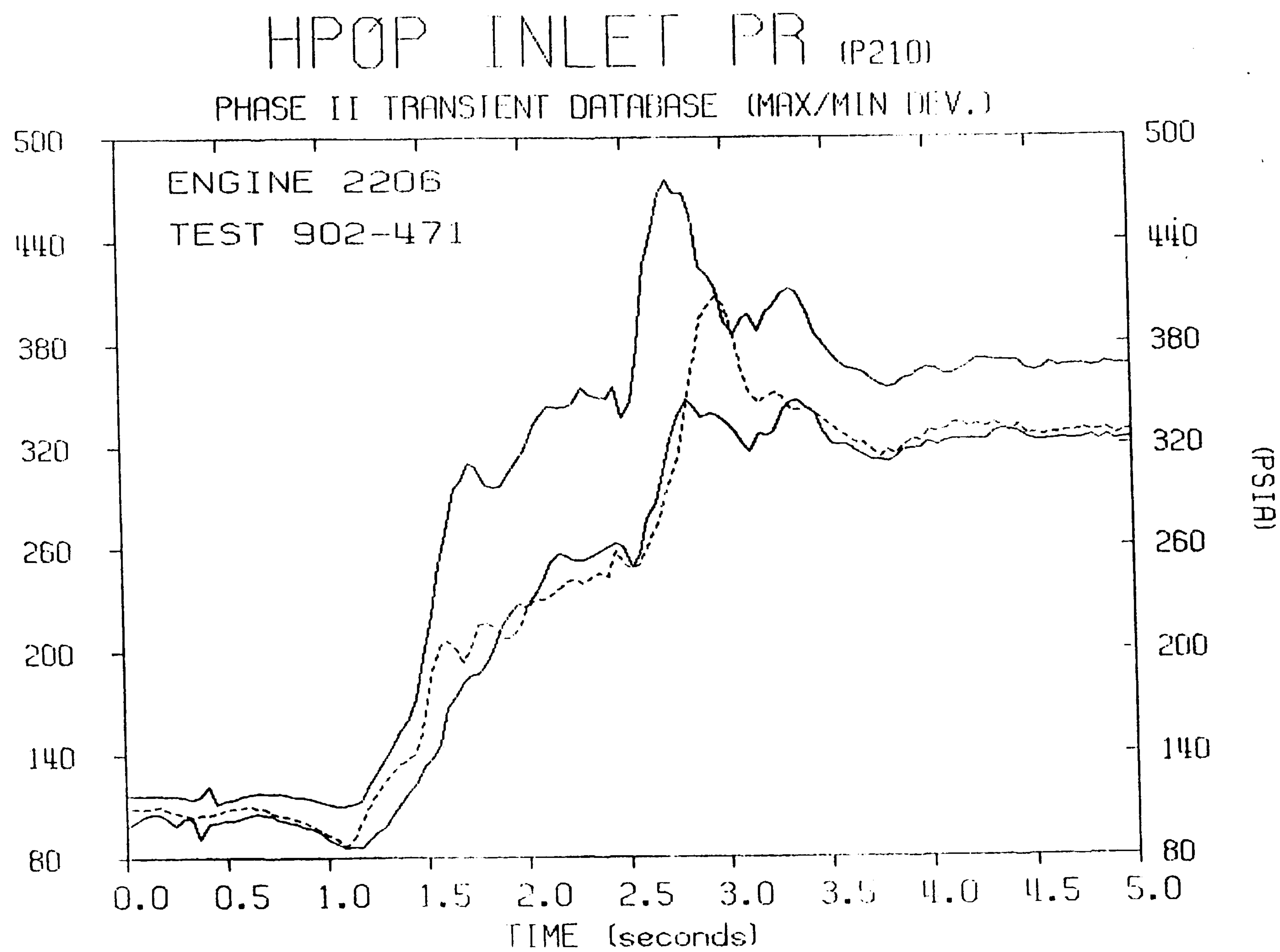
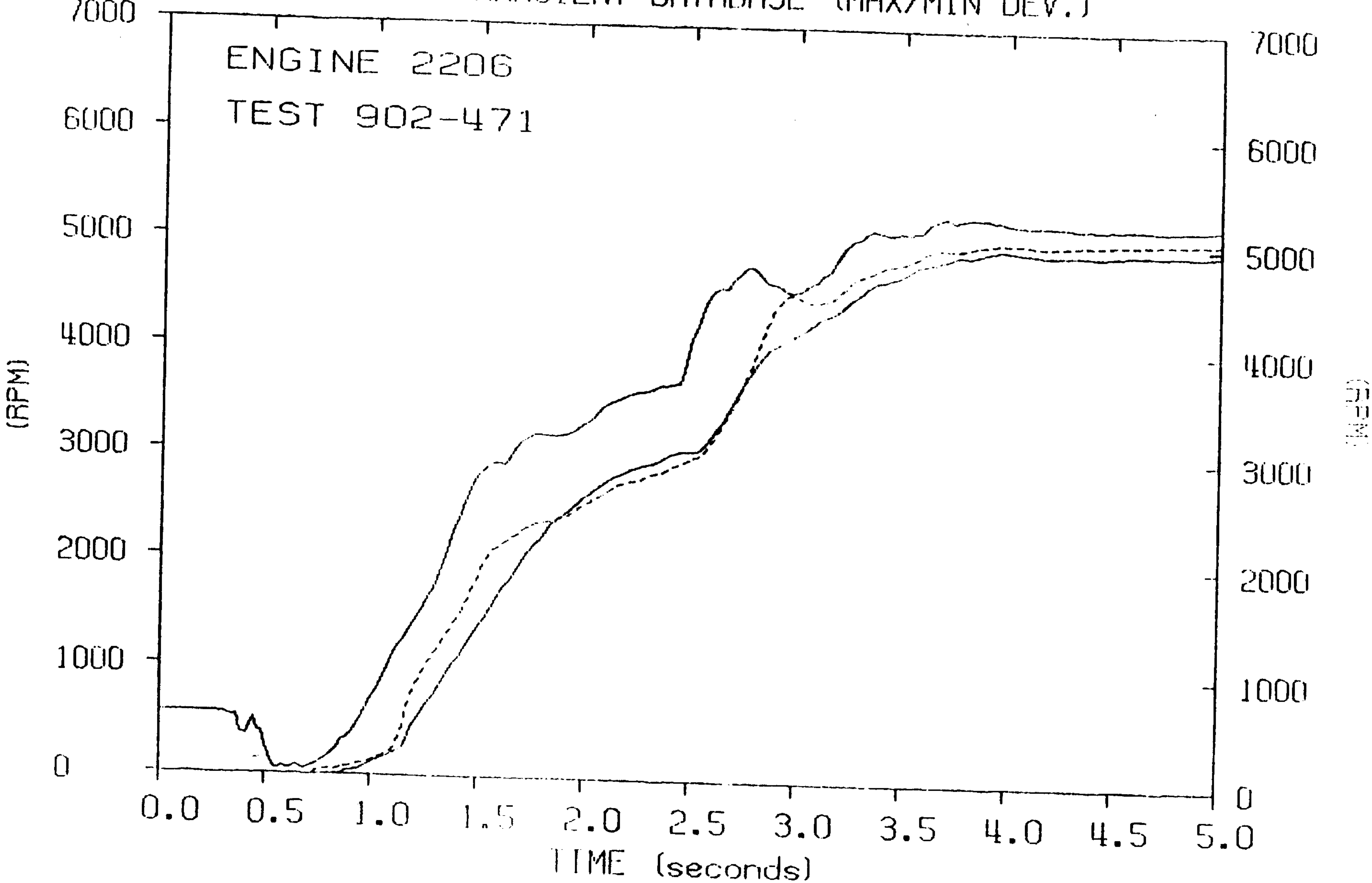


238 TESTS

ORIGINAL PAGE IS
OF POOR QUALITY

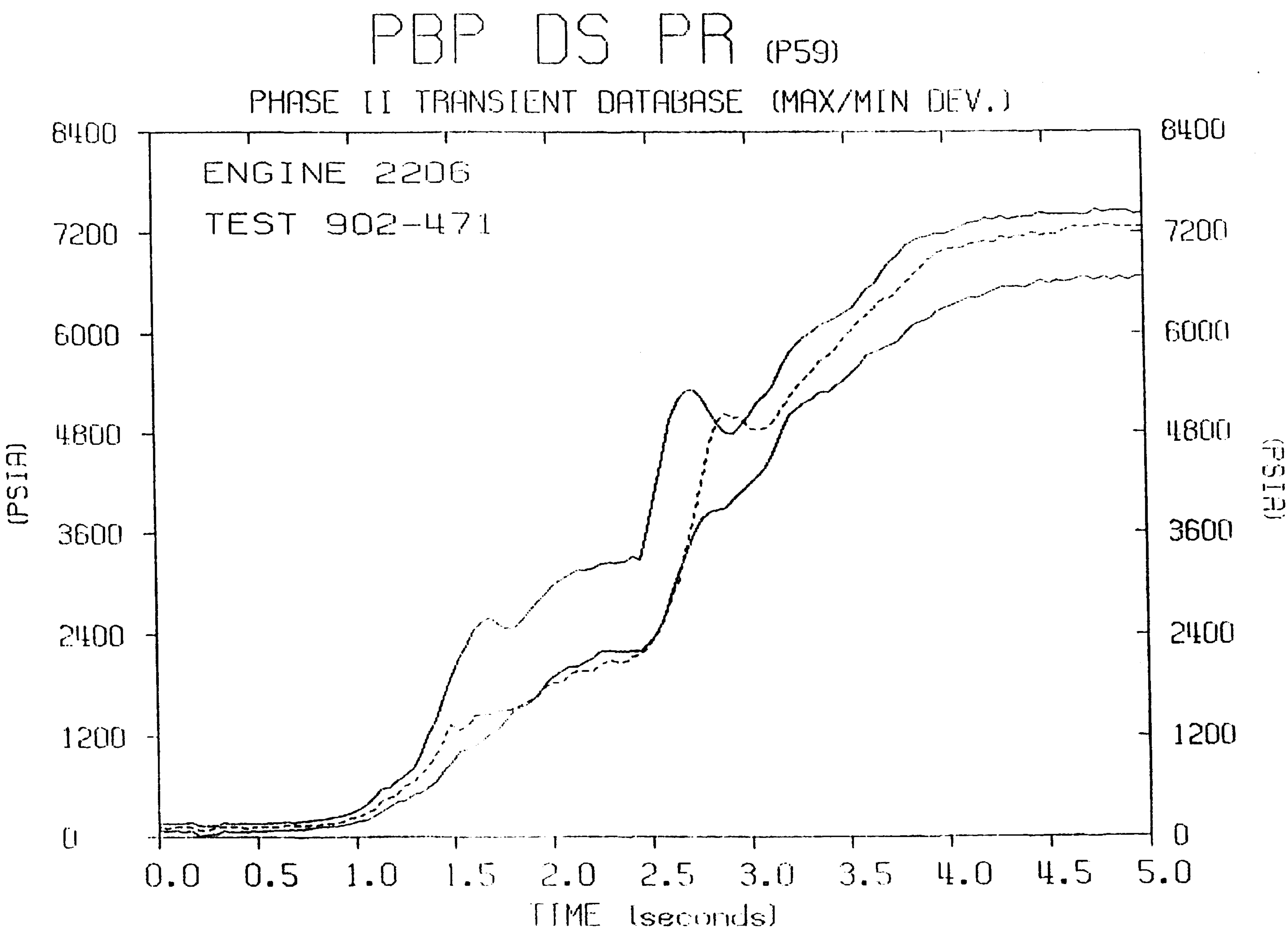
LPØP SPEED (P734)

PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



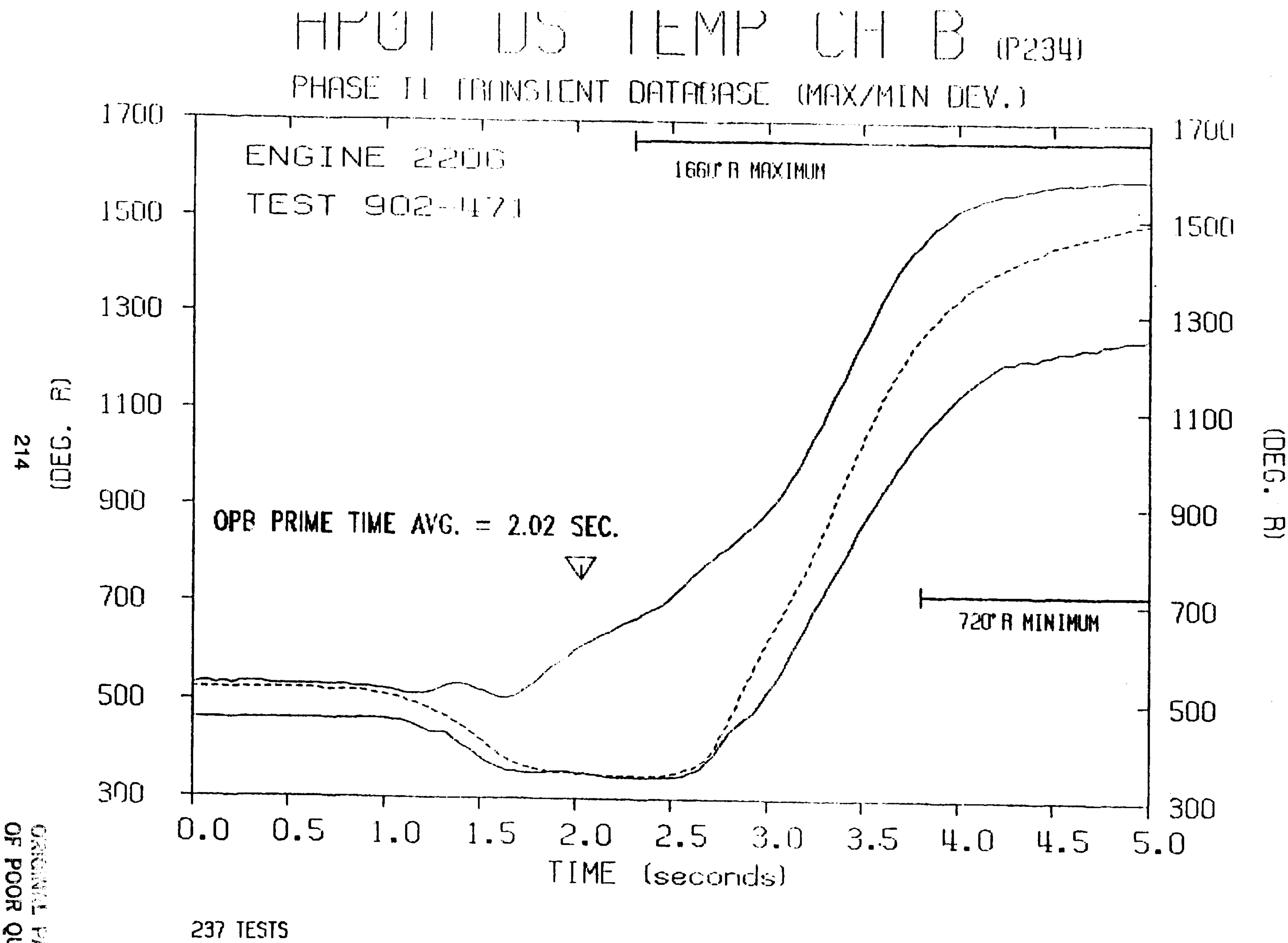
200 TESTS

ORIGINAL PAGE IS
OF POOR QUALITY



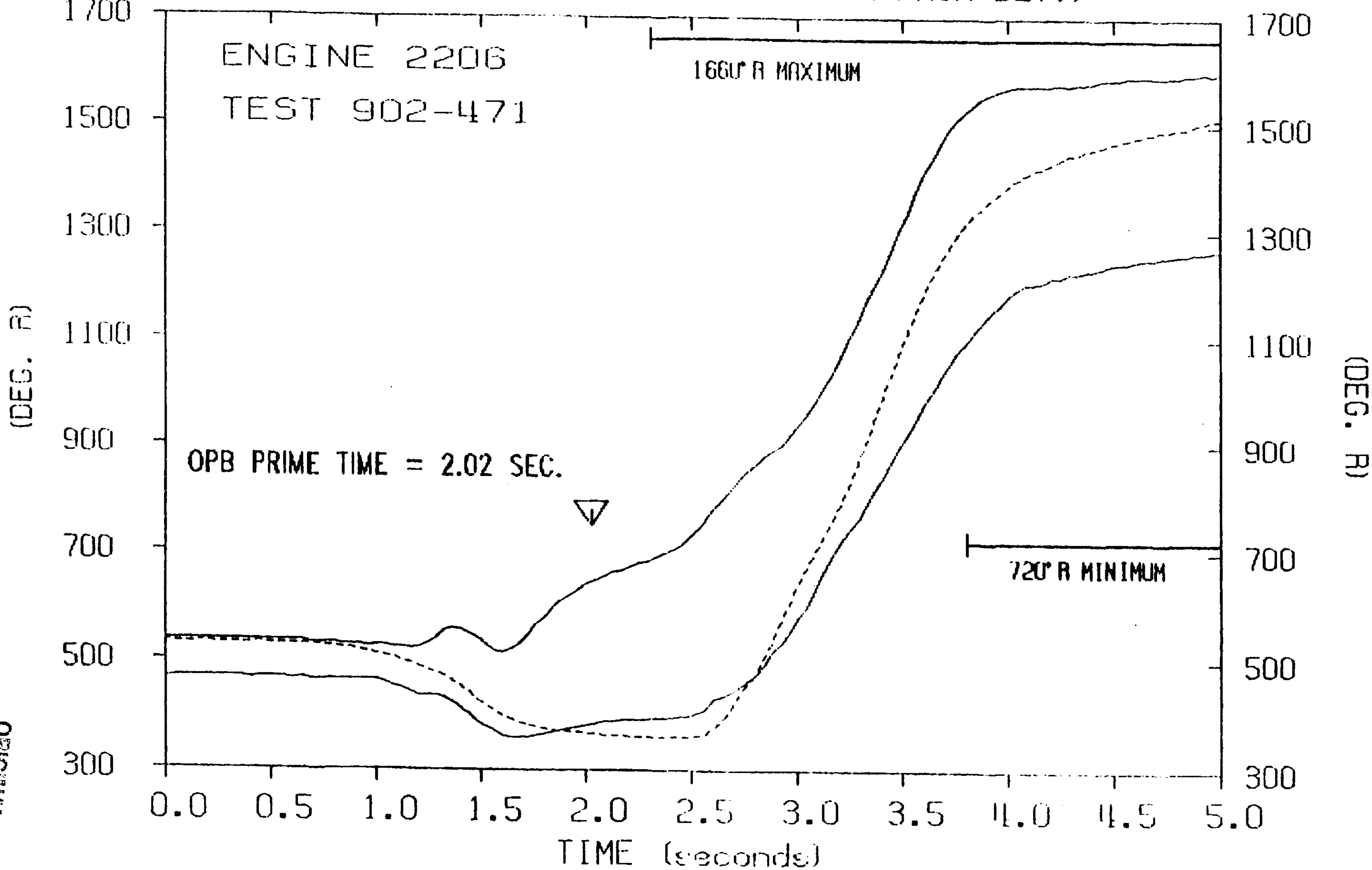
238 TESTS

ORIGINAL PAGE IS
OF POOR QUALITY

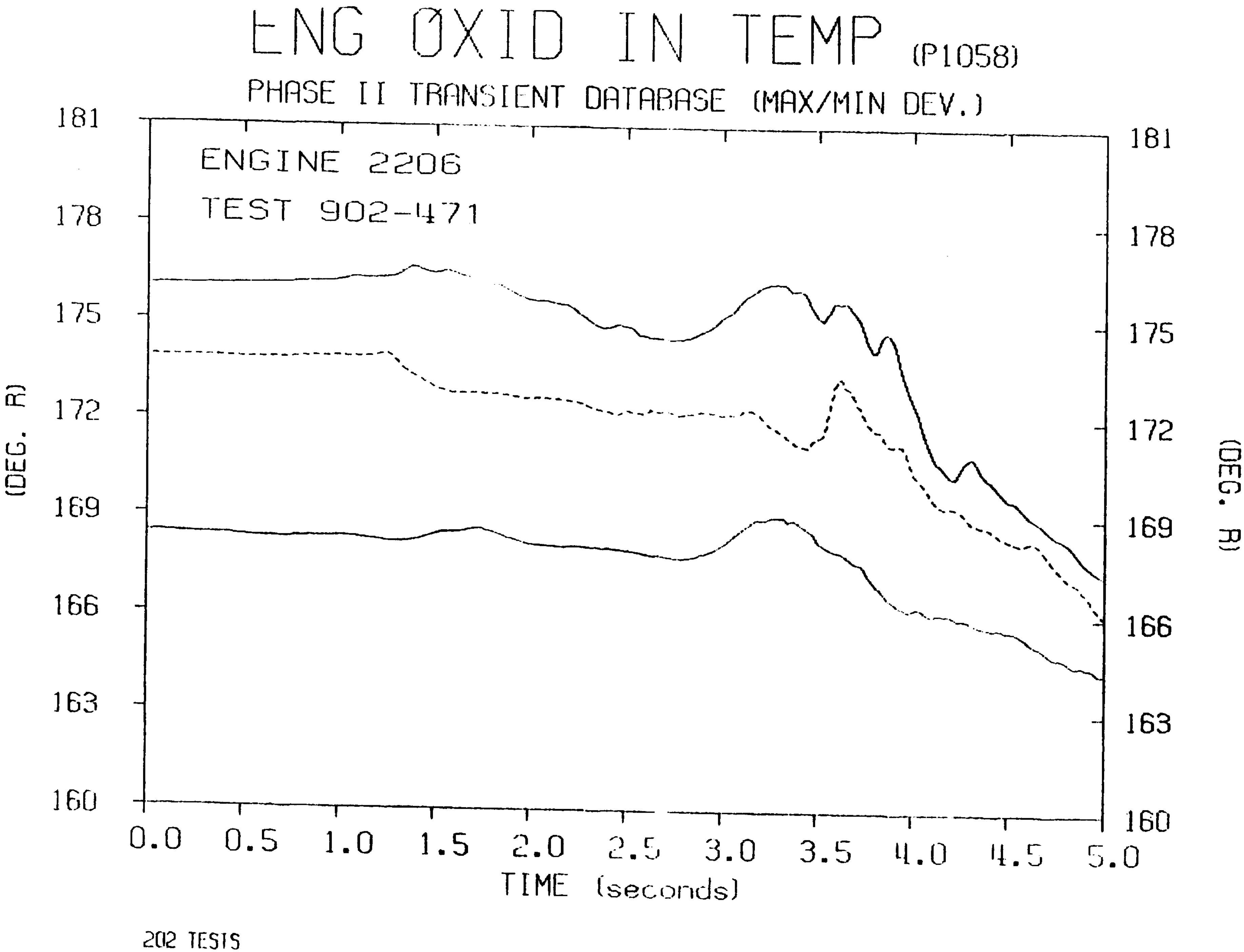

HPOT DS TEMP CH B (P234)
PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)
ENGINE 2206
TEST 902-471
1660°R MAXIMUM
720°R MINIMUM
OPB PRIME TIME AVG. = 2.02 SEC.
1700
1500
1300
1100
900
700
500
300
(DEG. R)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (seconds)
237 TESTS

HPØT DS TEMP CH A (P233)

PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



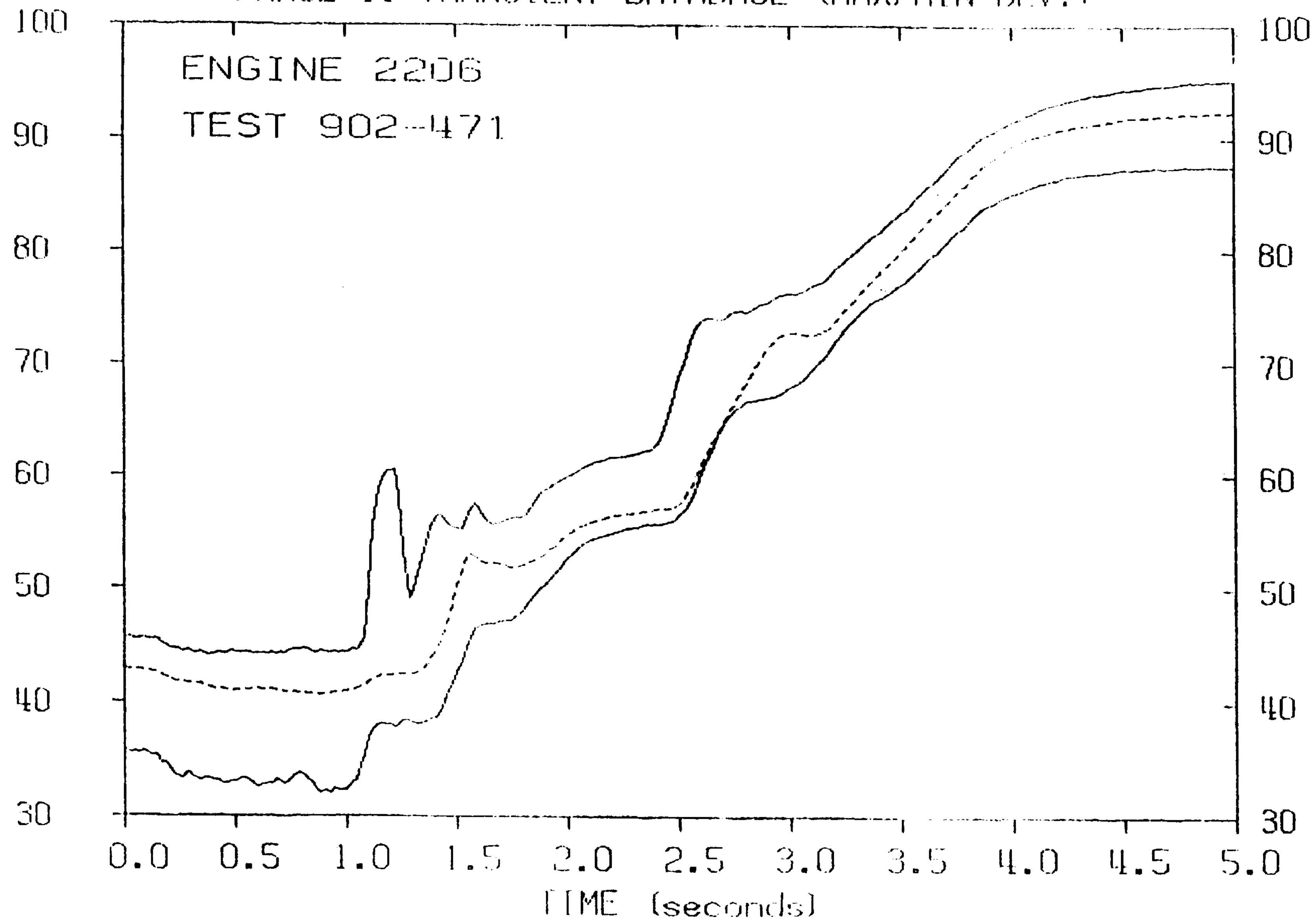
232 TESTS



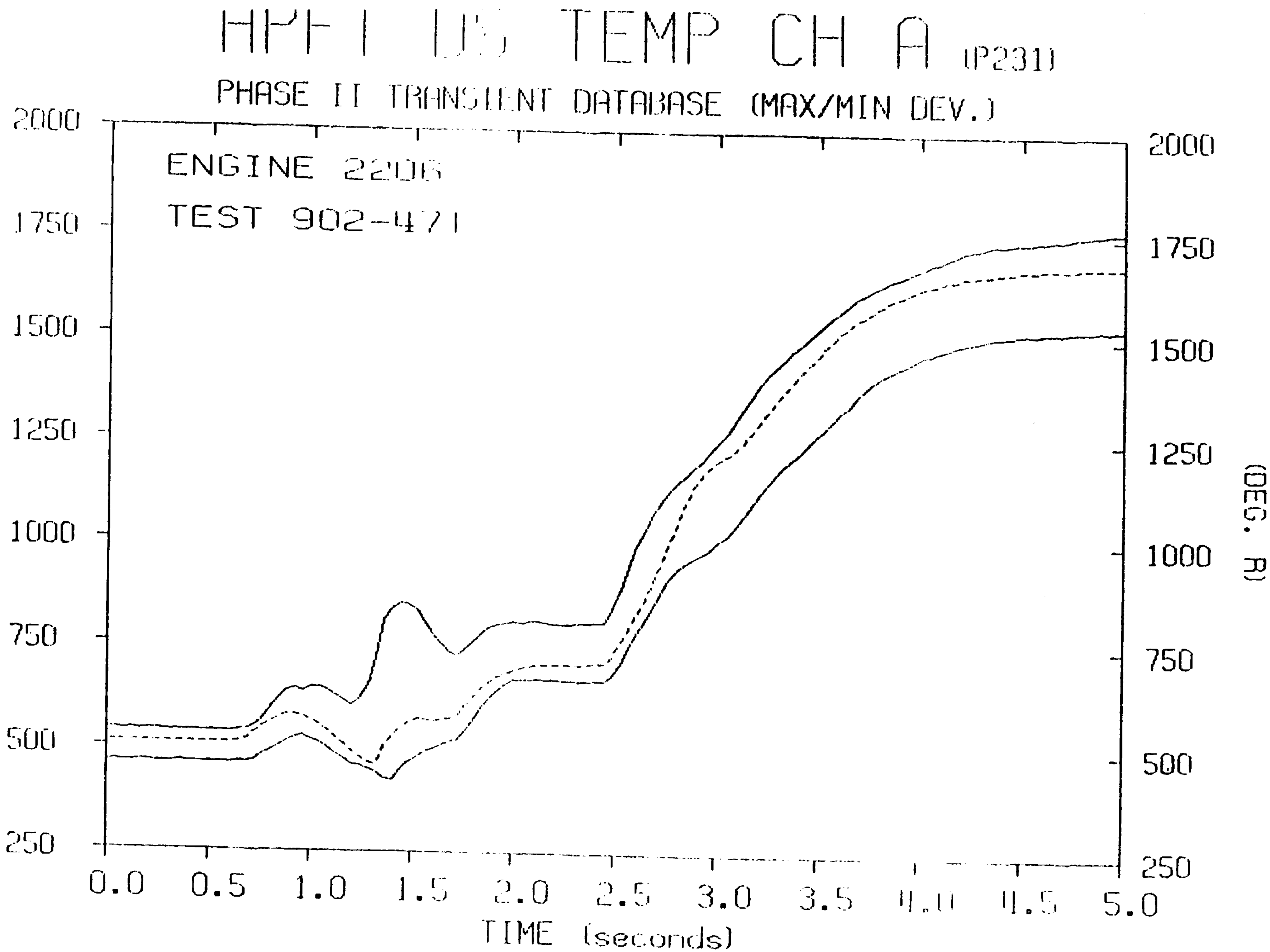
ORIGINAL PAGE IS
OF POOR QUALITY

HPFP DS TEMP (P659)

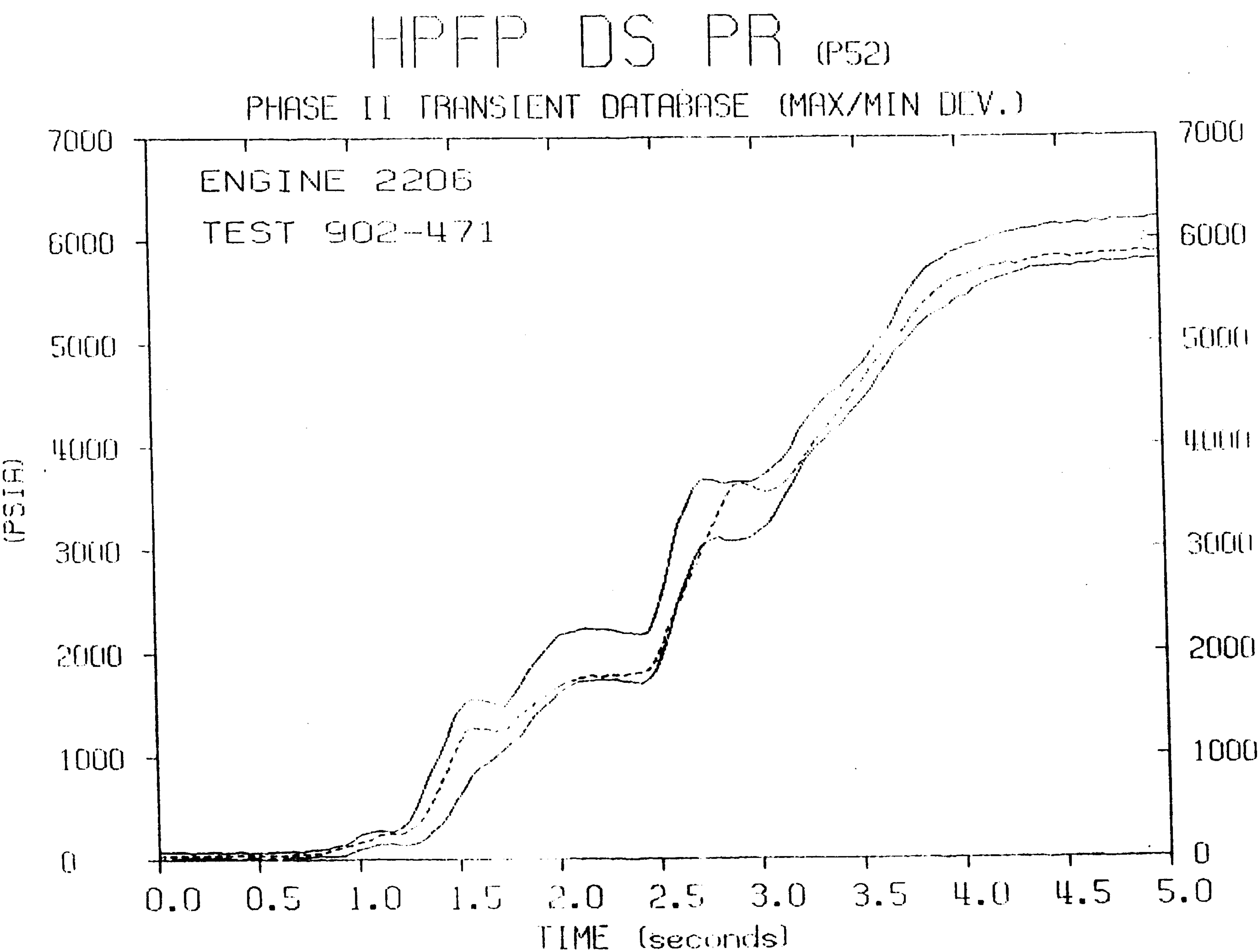
PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



197 TESTS


HPFT US TEMP CH A (P231)
PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)
ENGINE 2206
TEST 902-471
2000
1750
1500
1250
1000
750
500
250
(DEG. R)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (seconds)

232 TESTS

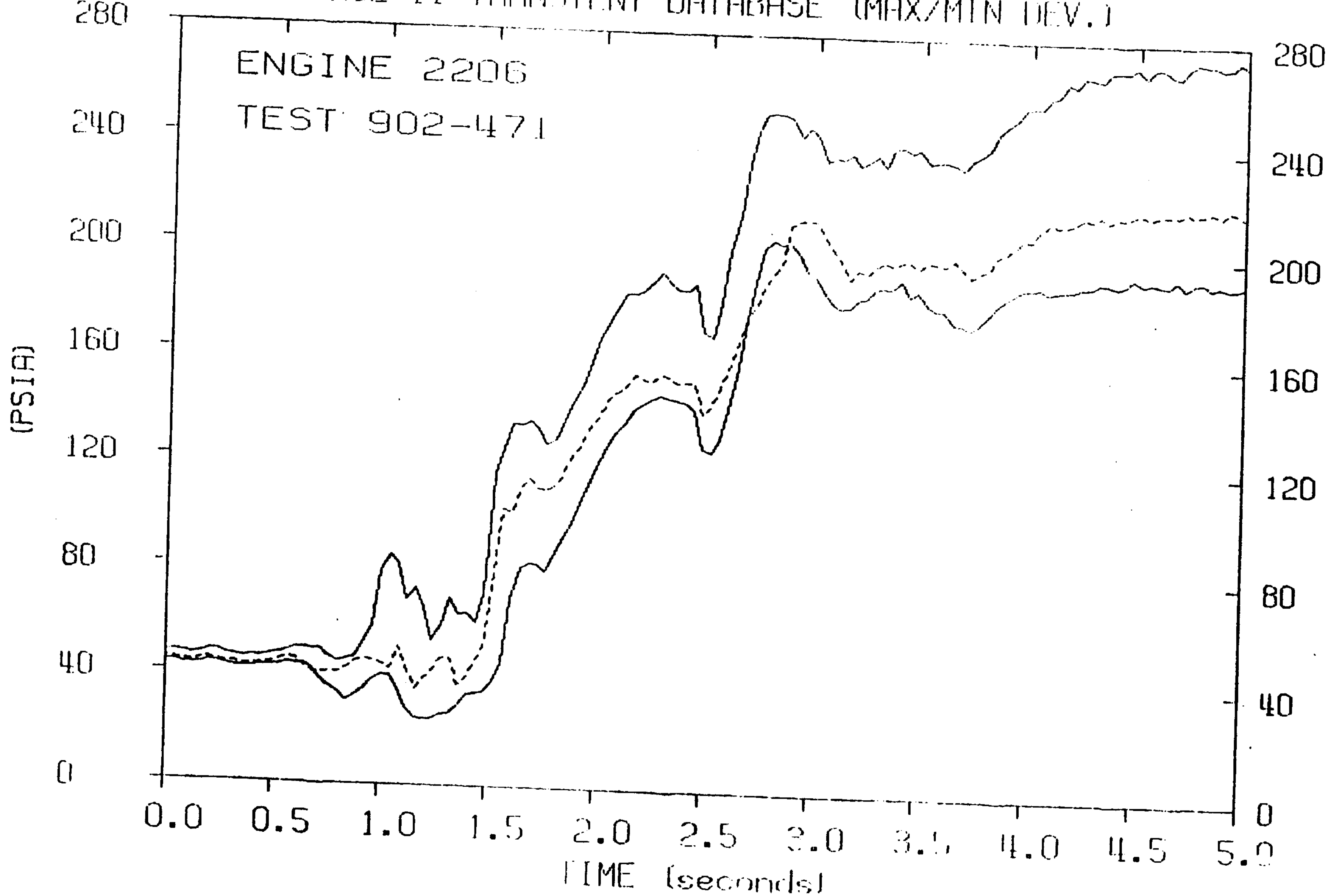


238 TESTS

ORIGINAL PAGE IS
OF POOR QUALITY

HPFP INLET PR (P86)

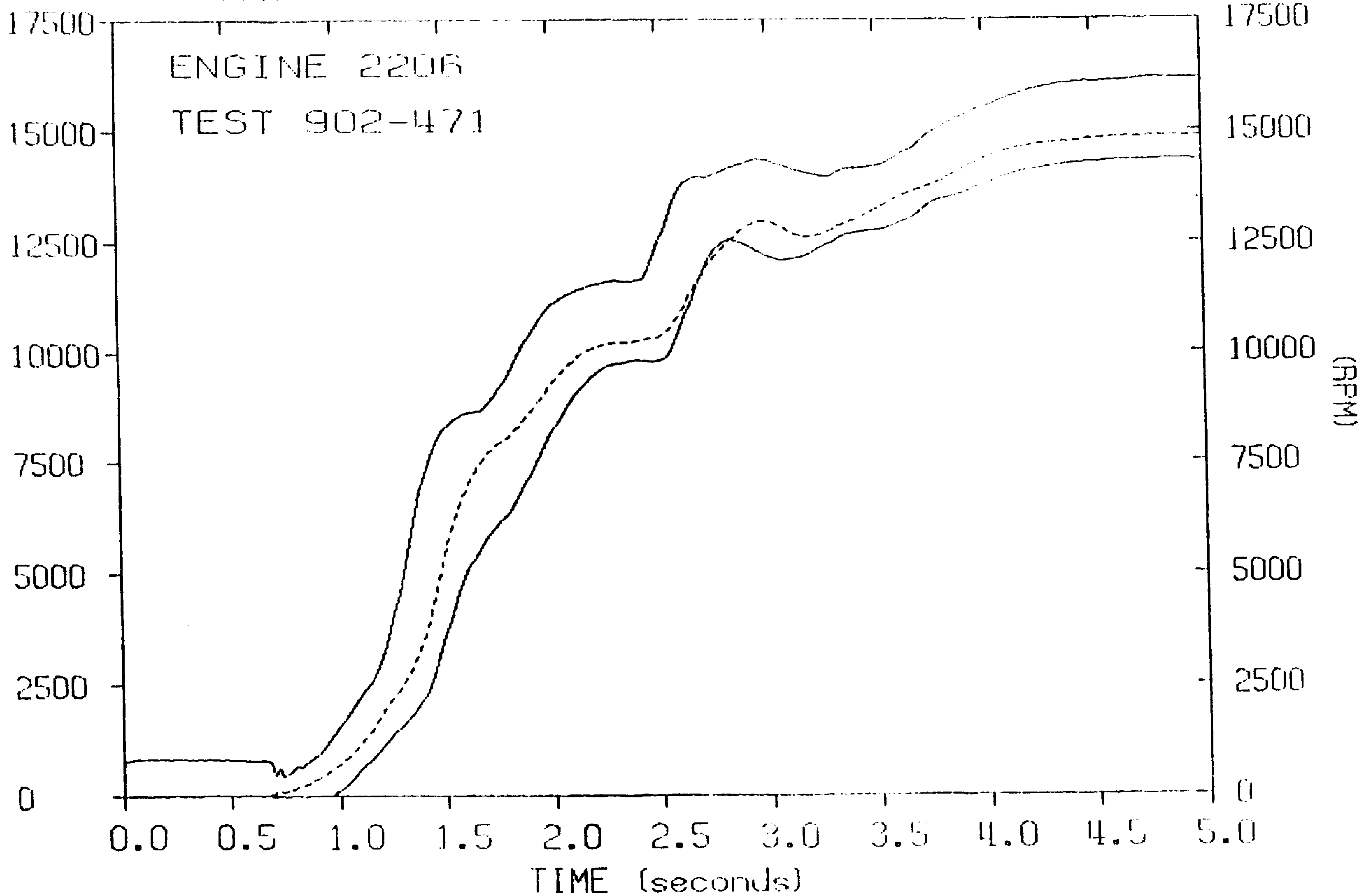
PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



239 TESTS

LPFP SPEED (P754)

PHASE II TRANSIENT DATABASE (MAX/MIN DEV.)



202 TESTS

ATTACHMENT 9

START TRANSIENT ANOMALY INDICATIONS - TEST 902-132

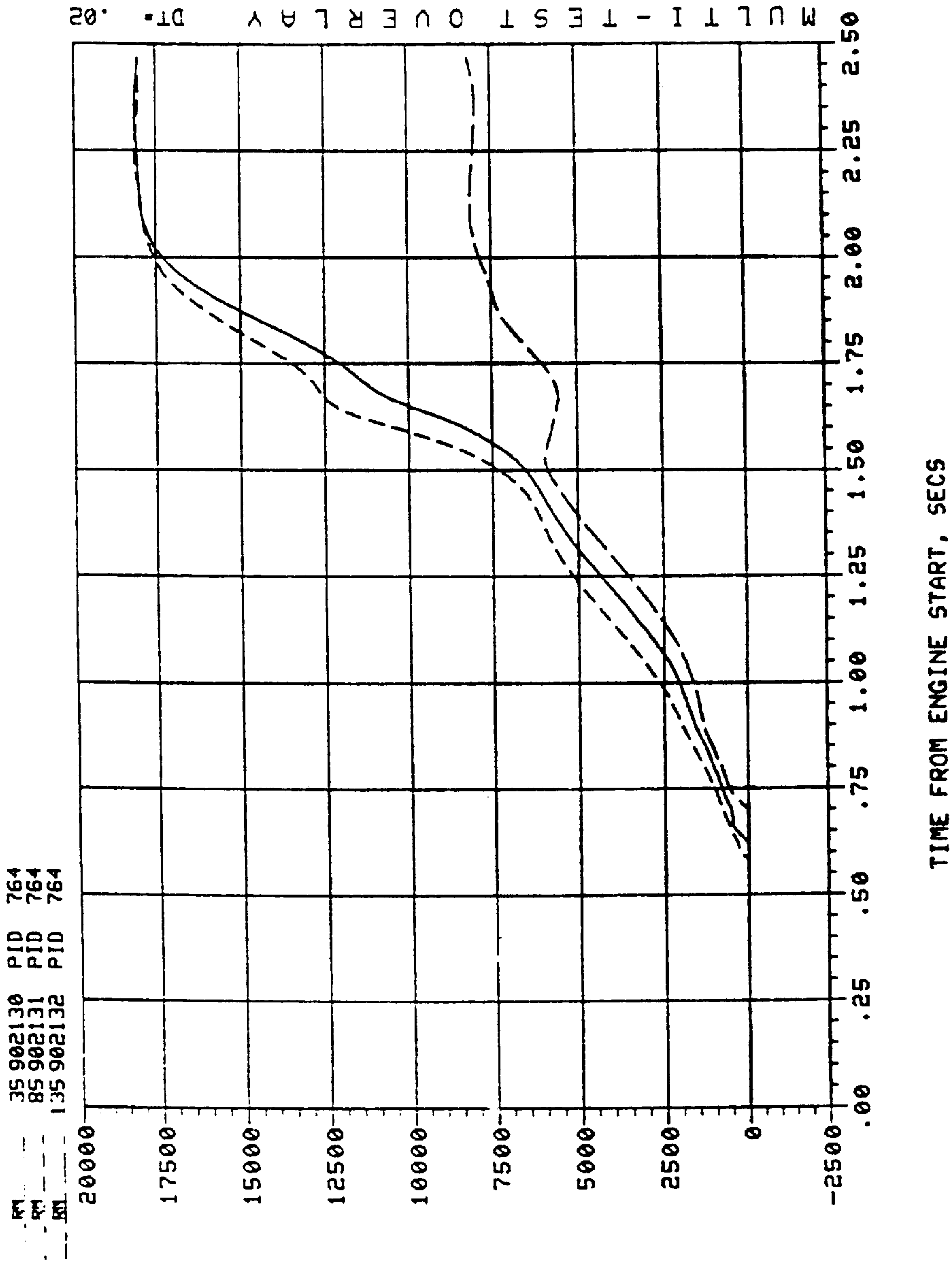


Figure-2: **HPFP Speed**

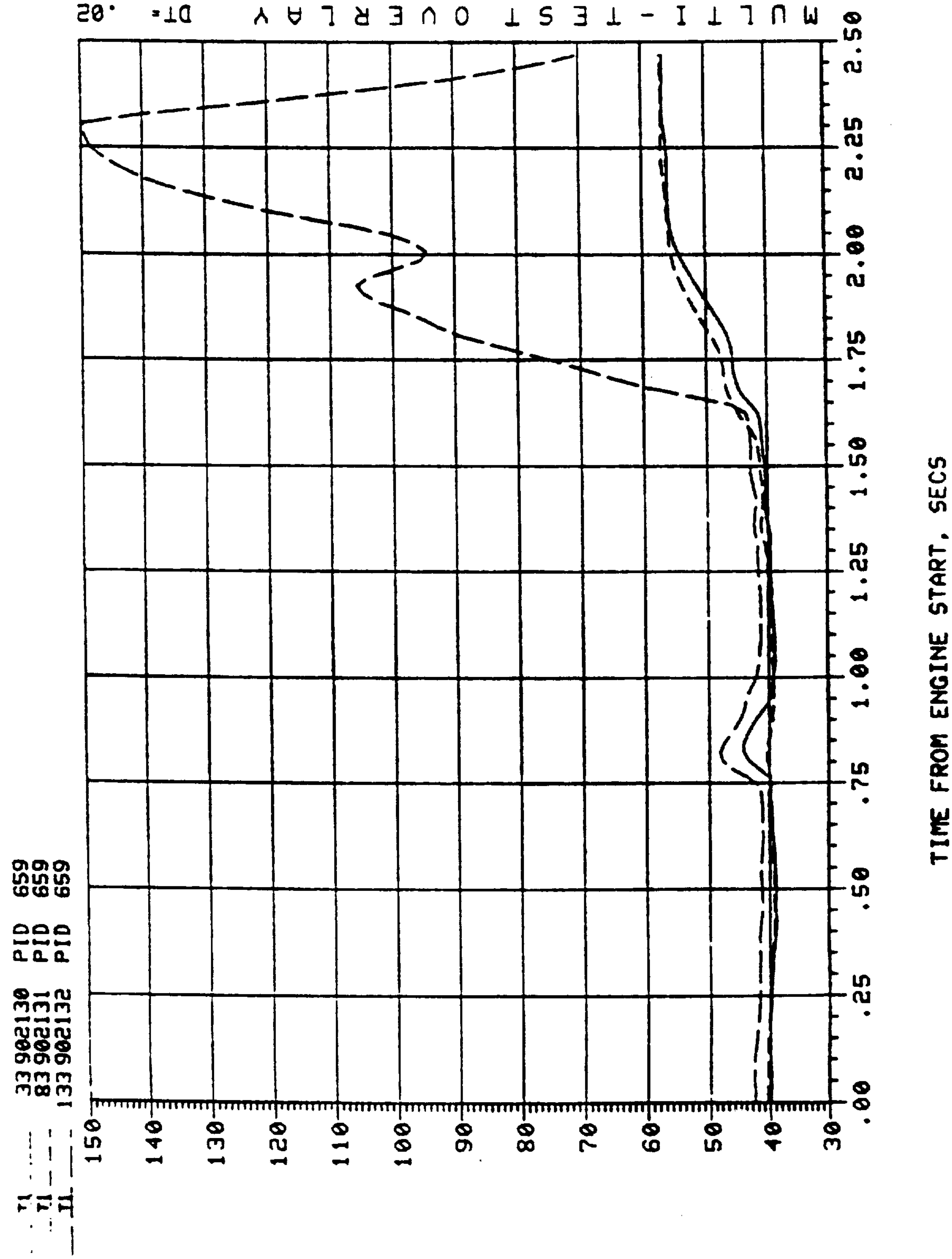


Figure-3: **HPFP Discharge Temperature**

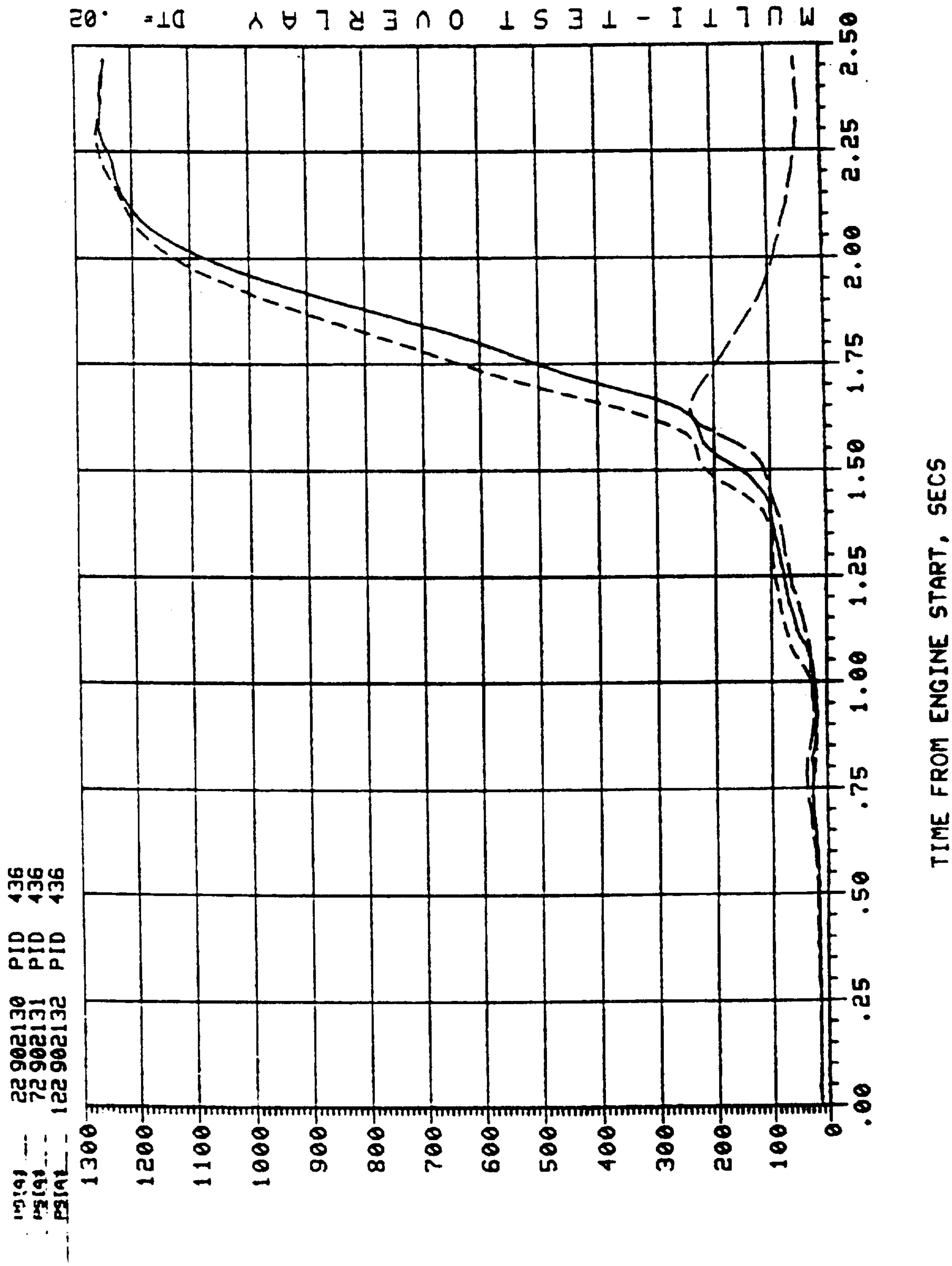


Figure-4: Low Pressure Fuel Turbine Inlet Pressure

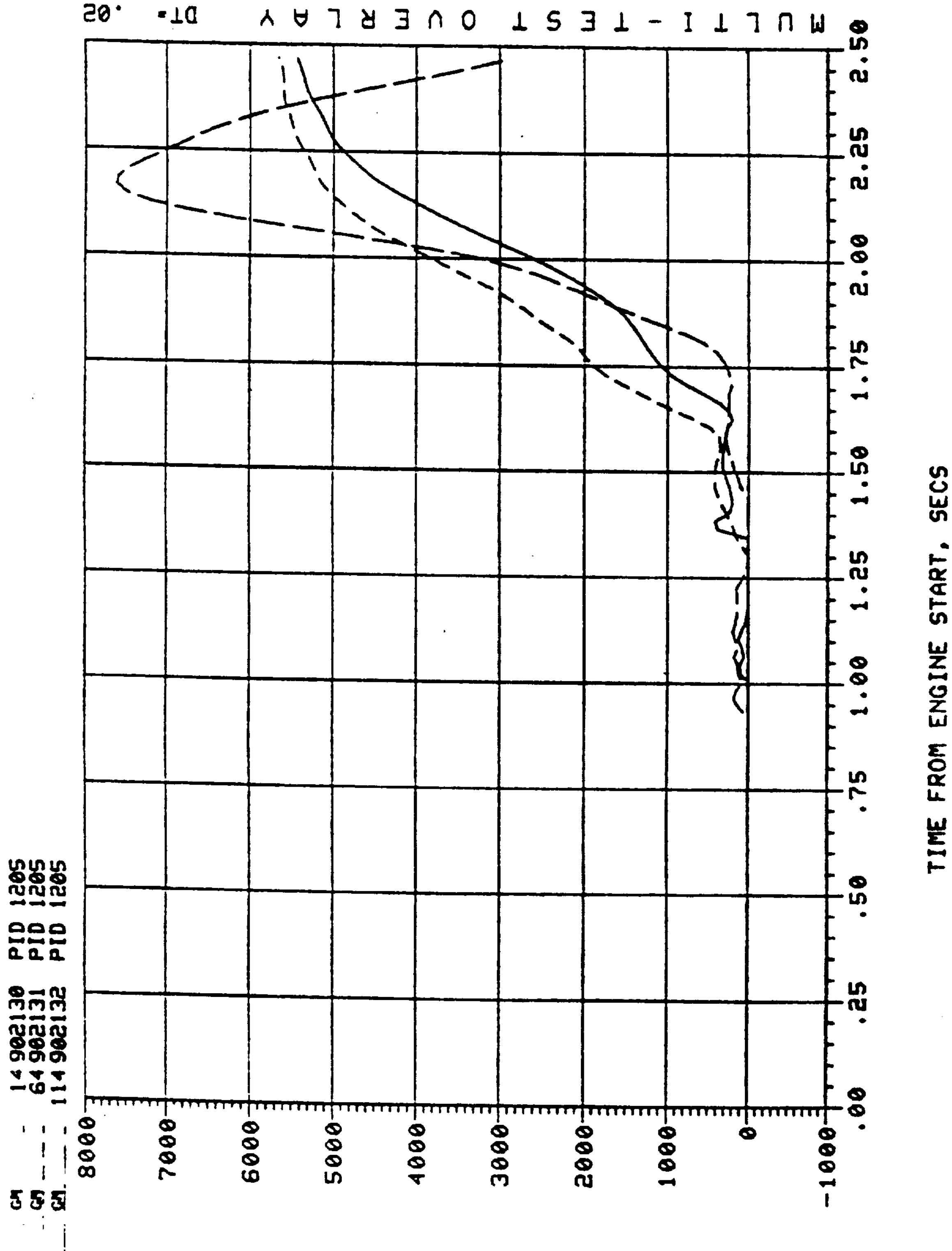


Figure-5: **Facility Fuel Flowrate** (CH-A)

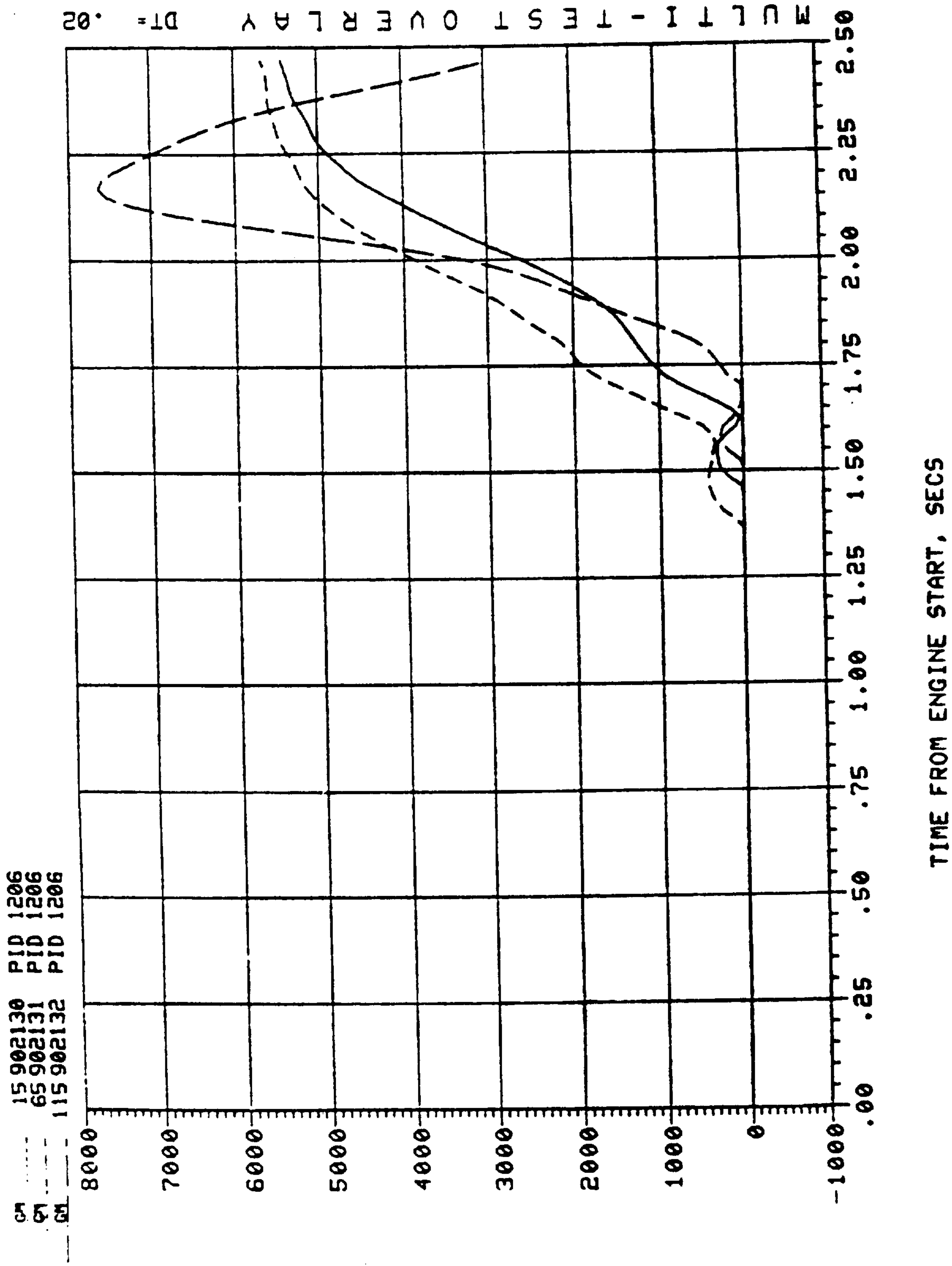


Figure-6: Facility Fuel Flowrate (CH-B)

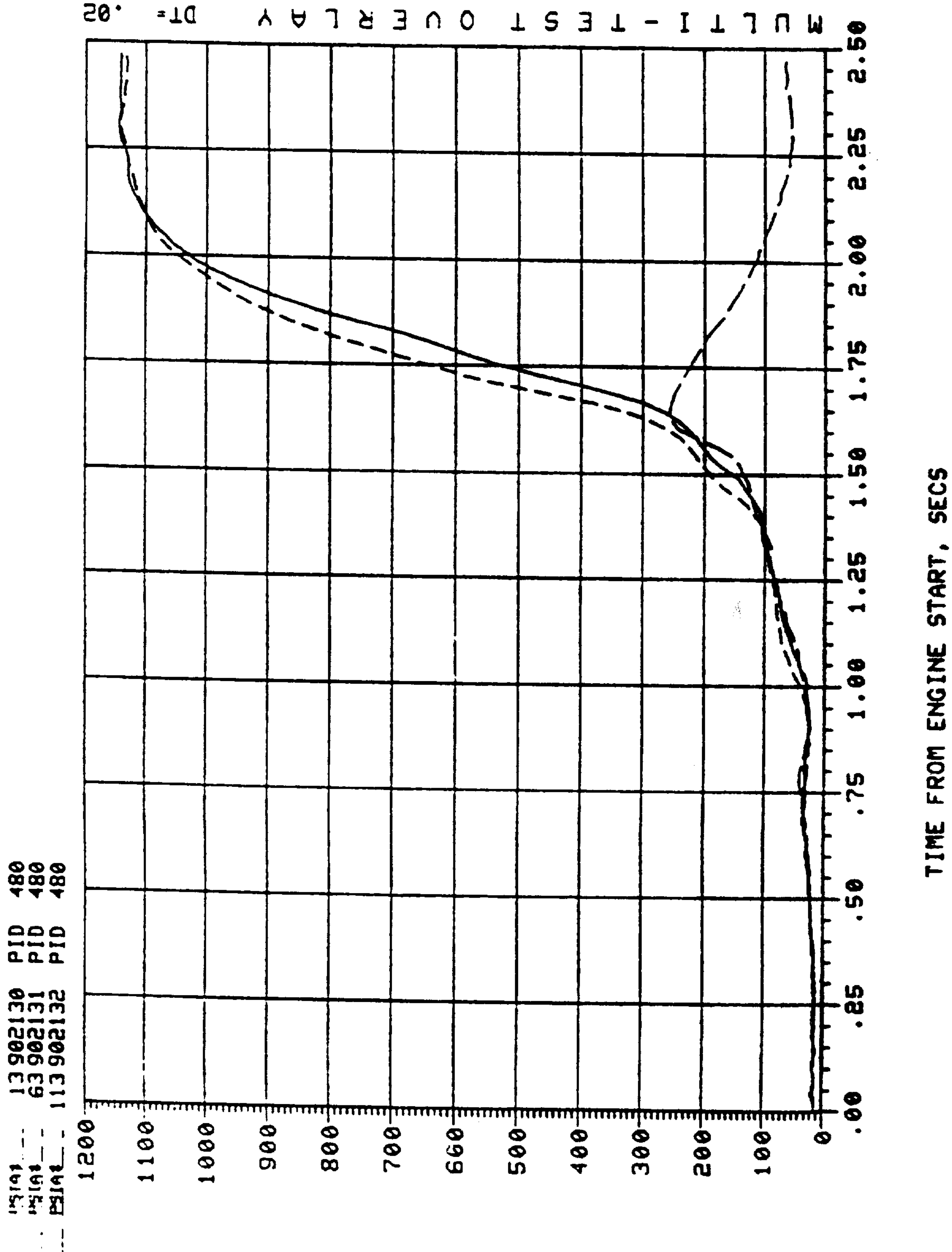


Figure-7: Oxidizer Preburner Chamber Pressure

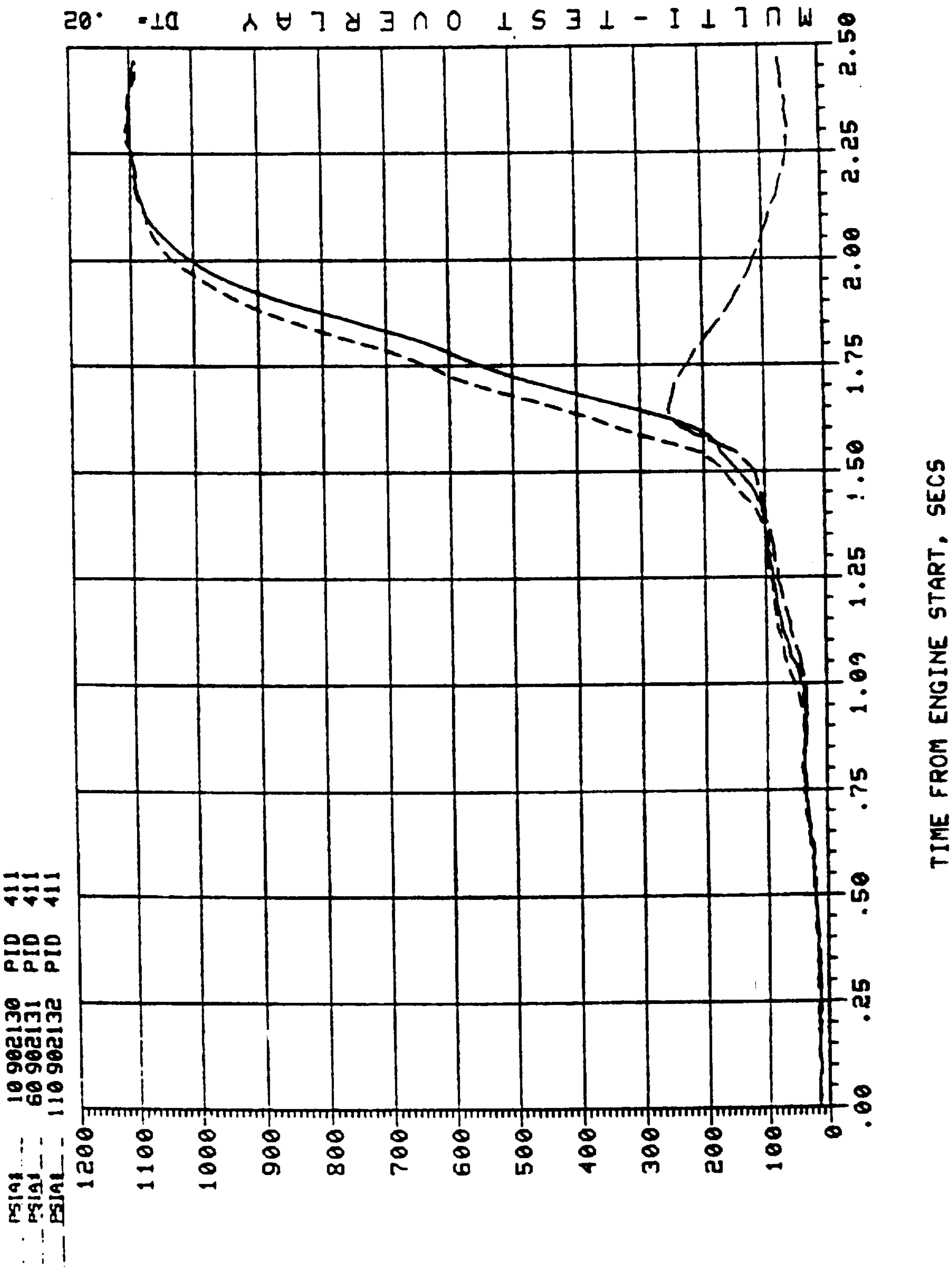


Figure-8: Fuel Preburner Chamber Pressure

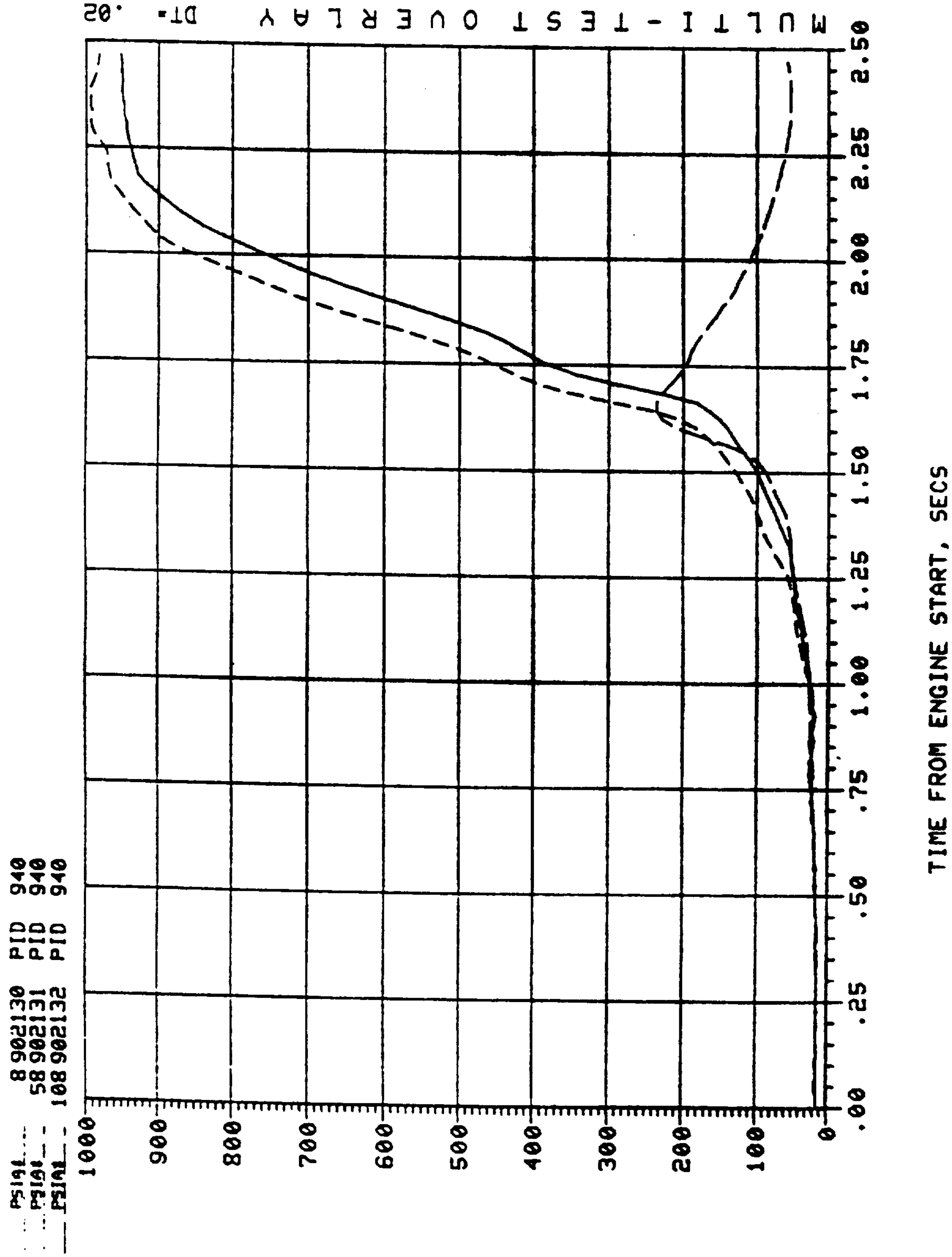


Figure-9: HPFP Coolant Liner Pressure

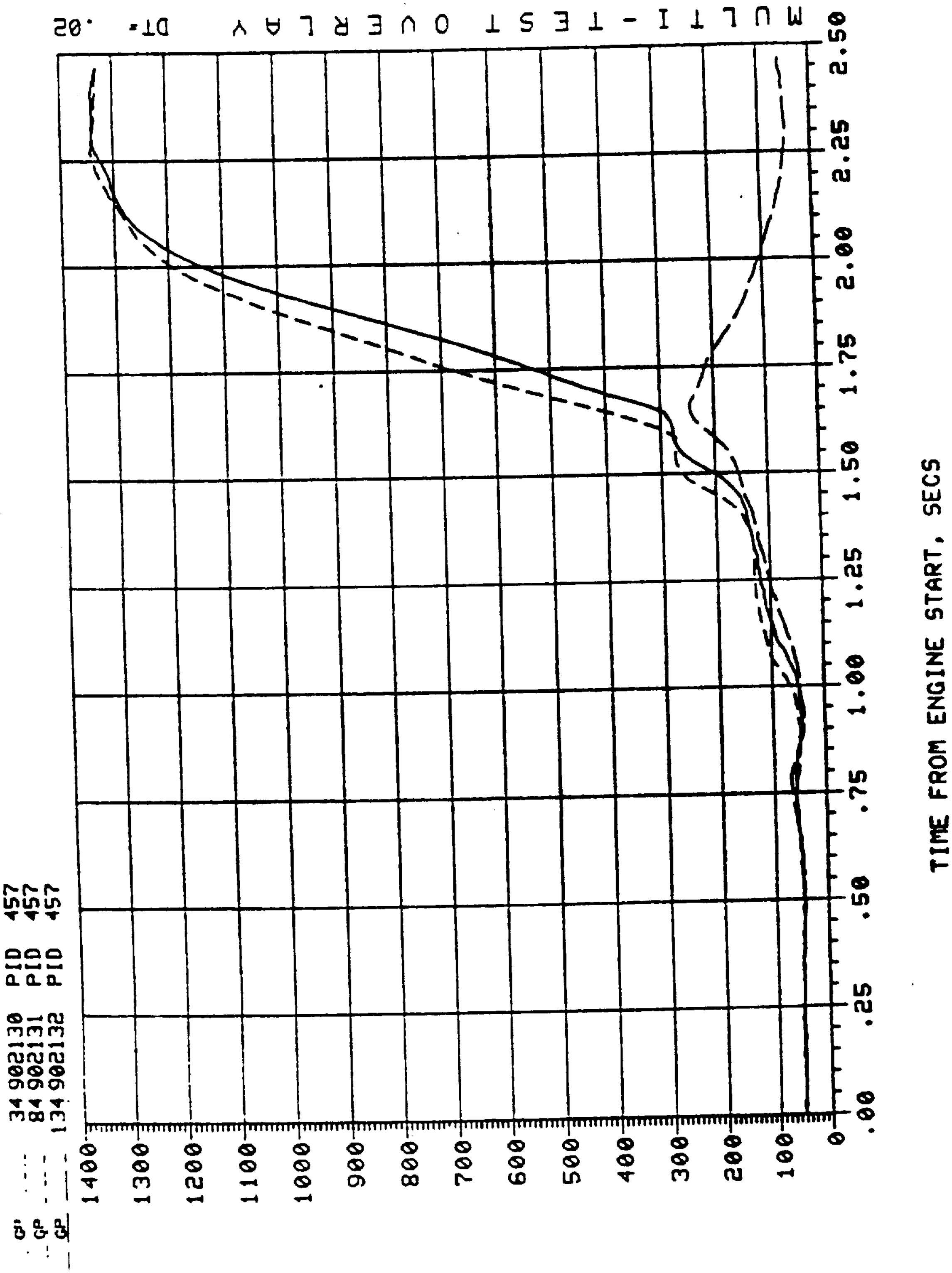


Figure-10: HPFP Balance Cavity Pressure

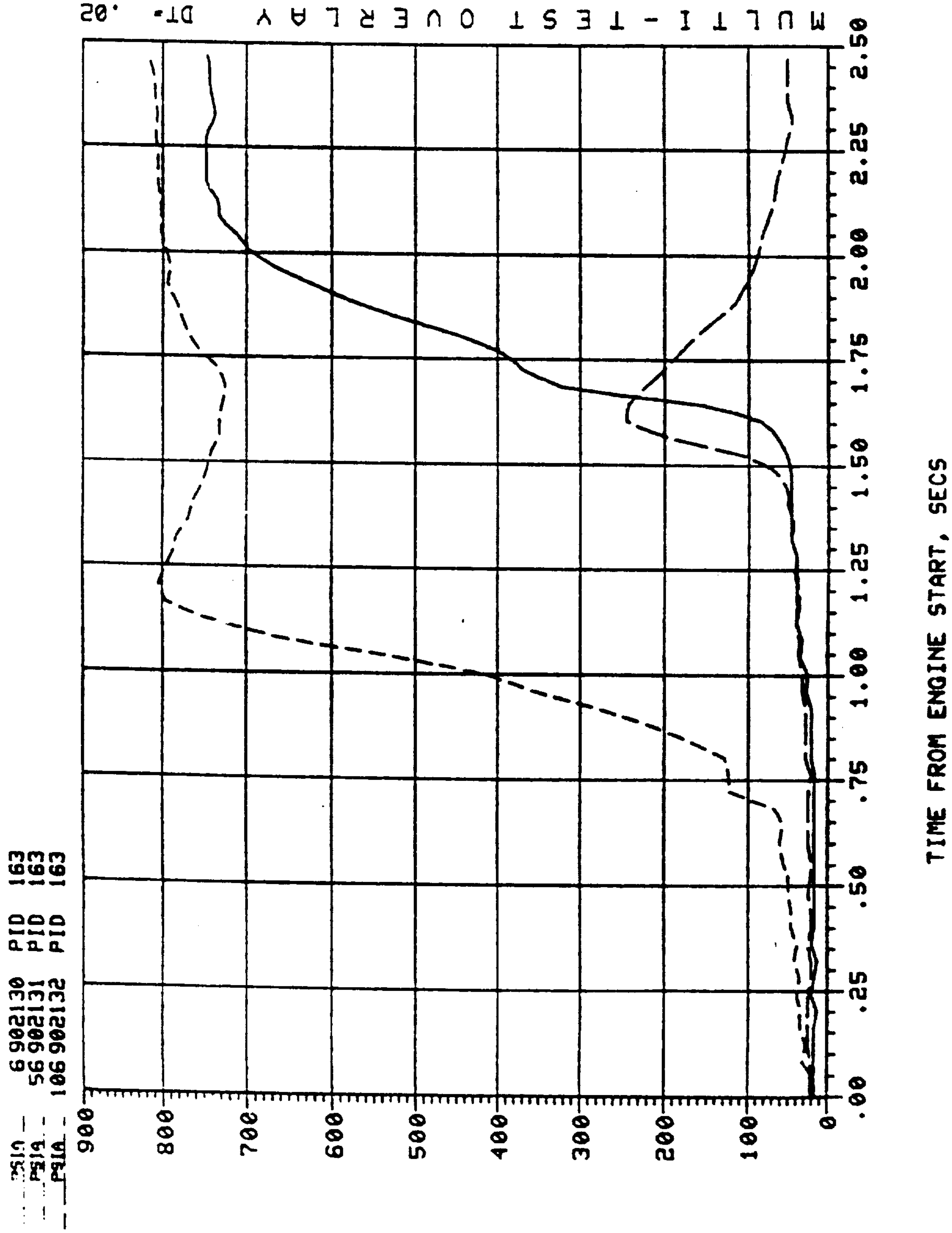


Figure-11: Main Chamber Pressure

ATTACHMENT 10

SSME FLIGHT AND FACILITY MEASUREMENTS

KEY TO ATTACHMENT 10

Column 1 - Parameter Identification Number

Column 2 - Measurement System Identification Number

FIELD NO. 1 (FIRST CHARACTER)

A - GROUND TEST ARTICLE
E - MAIN ENGINE
F - FACILITY
G - GSE
T - ET
V - ORBITER

FIELD NO. 2 (SECOND & THIRD CHARACTERS)

07 - AERODYNAMIC/THERMODYNAMICS
08 - STRUCTURAL DYNAMICS
09 - THERMAL PROTECTION SYSTEM (TPS)
35 - AFT FUSELAGE
38 - PURGE AND VENT
41 - MAIN PROPULSION
48 - ET DTI
49 - SSME GTI
58 - HYDRAULIC
79 - FLIGHT CONTROL

FIELD NO. 3 (FOURTH CHARACTER)

C - CURRENT
D - VIBRATION
G - FORCE/STRESS/STRAIN
H - POSITION
K - STIMULUS
M - MULTI- DATA
P - PRESSURE
Q - QUANTITY
R - RATE
T - TEMPERATURE
V - VOLTAGE
W - TIME
X - DISCREET EVENT
Y - ACOUSTICS

FIELD NO. 4 (FIFTH THRU EIGHTH CHARACTER)

0001 - 8999 OFI MEASUREMENTS
9000 - 9999 DFI MEASUREMENTS
0001 - 9999 GTI/DTI MEASUREMENTS
(NUMBERED SEQUENTIALLY FOR FIELDS ONE AND TWO)

FIELD NO. 5 (NINTH CHARACTER)

DATA TYPE			DATA ROUTING
ANALOG	EVENT	DIGITAL	(MAY BE MULTIPLE)
A	E	O	OFI/DFI
		(O)	EIU 60KG (ALL SSME DATA WORDS)
C	X		FLIGHT CRITICAL MDM
		B	EIU 1 MEGABIT TO SATS
M	M		GROUND TEST
K	K		GTM OR STIMULI ON FLT CRIT MDM
H	W		GROUND TEST HARDWIRE
F			CONTINUOUS SIGNAL
	N		GND DECODER MEAS VIA FLT CRIT MDM
		P	PARENT WORD

FIELD NO. 6 (TENTH CHARACTER, IF USED)

*IDENTIFIES TWO ACQUISITION REQUIREMENTS FOR ONE TRANSDUCER/SIGNAL CONDITIONER.

T IDENTIFIES A PCM MEASUREMENT THAT IS DECOMMUTATED FOR RECORDING BY A SYSTEM OTHER THAN PCM.

Column 3 - Measurement Units

Column 4 - Name of Measurement

SSME Flight Measurements (1 of 3)

•• TITLES UTILITY 020289 Vd6.02 ••

SSME EADS DATA FOR STS30R ME-1 60KB   ENGINE 2027 CONTROLLER F23

FULL NAME ——— DAT1:FLT029.C13/G
TEST NUMBER —— 0290001
TEST STAND ——— 6
CUTOFF TIME —— 515.32
NUMBER OF PIDS — 130
FILE FORMAT ——— D

PID	MSID	UNITS	TITLE	
TIME		SECONDS	TIME IN SECONDS	
4	E41M1005P•		HARD FAIL ID	ME-1
5	E41M1078P		HARD FAIL TST NO1	ME-1
6	E41M1079P		HARD FAIL TST NO2	ME-1
7	E41M1080P		HARD FAIL TST NO3	ME-1
8	E41U1095D	UNITS	MIX RATIO .	ME-1
12	E41T1020D	DEGR	PBP DS TMP AVG	ME-1
15	E41T1019D	DEGR	HPFP IN TMP AVG	ME-1
17	E41P1067D	PSIA	MCC CLNT DS PR A	ME-1
18	E41T1070D	DEGR	MCC CLNT DS TMP B	ME-1
21	E41T1120D	DEGR	MCC OXID INJ TEMP	ME-1
24	E41P1066D	PSIA	MCC HG INJ PR A	ME-1
30	E41R1073D	RPM	LPOP SPEED B	ME-1
32	E41R1072D	RPM	LPFP SPEED A	ME-1
34	E41P1068D	PSIA	HX DS PR B	ME-1
36	E41H1024D	PCT	MFV ACT POS A	ME-1
38	E41H1025D	PCT	MOV ACT POS A	ME-1
40	E41H1028D	PCT	OPOV ACT POS A	ME-1
42	E41H1027D	PCT	FPOV ACT POS A	ME-1
45	E41H1026D	PCT	CCV ACT POS A	ME-1
46	E41H1062D	PCT	LOX BLD VLV POS B	ME-1
47	E41H1061D	PCT	FUEL BLD VLV POS	ME-1
48	E41P1069D	PSIA	CON INT PR A/B	ME-1
49	E41T1071D	DEGR	CON INT TMP A/B	ME-1
50	E41V1074D	VAC	CON BUS 1 VOLTAGE	ME-1
51	E41V1075D	VAC	CON BUS 2 VOLTAGE	ME-1
52	E41P1029D	PSIA	HPFP DS PR A	ME-1
53	E41P1008D	PSIA	HPFP CLNT LNR A	ME-1
54	E41P1009D	PSIA	HPFP CLNT LNR B	ME-1
58	E41P1031D	PSIA	FPB PC A	ME-1
59	E41P1033D	PSIA	PBP DS PR B	ME-1
63	E41P1023D	PSIA	MCC PC AVG	ME-1
78	E41V1118D	VDC	+36 OE VOLTAGE A	ME-1
79	E41V1119D	VDC	+36 OE VOLTAGE B	ME-1
86	E41P1018D	PSIA	HPFP IN PR AVG	ME-1
90	E41P1030D	PSIA	HPOP DS PR A	ME-1
91	E41P1051D	PSIA	HPOT S/C PR A	ME-1
92	E41P1053D	PSIA	HPOT S/C PR B	ME-1
94	E41T1125D	DEGR	PBP DS TMP B	ME-1
96	E41R1022D	GAL/MIN	LOX FLOW AVG	ME-1
100	E41R1021D	GAL/MIN	FUEL FLOW AVG	ME-1
104	E41M1121P		FASCOS STATUS WD	ME-1
129	E41P1035D	PSIA	MCC PC A2	ME-1
130	E41P1036D	PSIA	MCC PC A1	ME-1
131	E41R1037D	GAL/MIN	FUEL FLOW AVG	ME-1
132	E41R1038D	GAL/MIN	LOX FLOW AVG	ME-1
133	E41R1050D	GAL/MIN	FUEL FLOW A1	ME-1
136	E41H1040D	PCT	MFV ACT POS A	ME-1
137	E41H1084D	PCT	MFV ACT POS B (R	ME-1
138	E41H1041D	PCT	MOV ACT POS A	ME-1

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SSME Flight Measurements (2 of 3)

139	E41H1085D	PCT	MOV ACT POS B (R	ME-1
140	E41H1044D	PCT	OPOV ACT POS A	ME-1
141	E41H1088D	PCT	OPOV ACT POS B (R	ME-1
142	E41H1043D	PCT	FPOV ACT POS A	ME-1
143	E41H1087D	PCT	FPOV ACT POS B (R	ME-1
145	E41H1042D	PCT	CCV ACT POS A	ME-1
146	E41H1086D	PCT	CCV ACT POS B (R	ME-1
147	E41P1048D	PSIA	HYD SYS PR B	ME-1
148	E41P1106D	PSIA	FPB PRG PR A	ME-1
149	E41P1059D	PSIA	OPB PRG PR B	ME-1
152	E41P1045D	PSIA	HPFP DS PR A	ME-1
154	E41M1097P		DST REG 2A	ME-1
155	E41M1099P		DST REG 2B	ME-1
156	E41M1096P		DST REG 1A	ME-1
157	E41M1098P		DST REG 1B	ME-1
158	E41P1047D	PSIA	FPB PC A	ME-1
159	E41P1049D	PSIA	PBP DS PR B	ME-1
161	E41P1124D	PSIA	MCC PC B2	ME-1
162	E41P1052D	PSIA	MCC PC B1	ME-1
163	E41P1039D	PSIA	MCC PC AVG	ME-1
171	E41H1117D	PCT	OPOV CMD LIMIT	ME-1
172	E41H1060D	PCT	MFV COMMAND	ME-1
173	E41H1113D	PCT	MOV COMMAND	ME-1
174	E41H1114D	PCT	CCV COMMAND	ME-1
175	E41H1115D	PCT	FPOV COMMAND	ME-1
176	E41H1116D	PCT	OPOV COMMAND	ME-1
190	E41P1046D	PSIA	HPOP DS PR A	ME-1
200	E41P1016D	PSIA	MCC PC A AVG	ME-1
201	E41P1017D	PSIA	MCC PC B AVG	ME-1
203	E41P1092D	PSIA	HPFP INLET PR A	ME-1
204	E41P1127D	PSIA	HPFP INLET PR B	ME-1
209	E41P1064D	PSIA	HPOP INLET PR A	ME-1
210	E41P1065D	PSIA	HPOP INLET PR B	ME-1
211	E41P1014D	PSIA	HPOP ISP PR A	ME-1
212	E41P1015D	PSIA	HPOP ISP PR B	ME-1
214	E41P1054D	PSIA	HYD SYS PR B	ME-1
219	E41P1057D	PSIA	FUEL PRG PR A	ME-1
220	E41P1058D	PSIA	FUEL PRG PR B	ME-1
221	E41P1055D	PSIA	POGO PRCHG PR A	ME-1
222	E41P1056D	PSIA	POGO PRCHG PR B	ME-1
223	E41P1107D	PSIA	EM SHTDN PR A	ME-1
224	E41P1108D	PSIA	EM SHTDN PR B	ME-1
225	E41T1093D	DEGR	HPFP INLET TMP A	ME-1
226	E41T1128D	DEGR	HPFP INLET TMP B	ME-1
231	E41T1010D	DEGR	HPFT DS TMP A	ME-1
232	E41T1011D	DEGR	HPFT DS TMP B	ME-1
233	E41T1012D	DEGR	HPOT DS TMP A	ME-1
234	E41T1013D	DEGR	HPOT DS TMP B	ME-1
237	E41T1111D	DEGR	MFV HYD TMP A	ME-1
238	E41T1112D	DEGR	MFV HYD TMP B	ME-1
239	E41T1109D	DEGR	MOV HYD TMP A	ME-1
240	E41T1110D	DEGR	MOV HYD TMP B	ME-1
251	E41R1102D	GAL/MIN	FUEL FLOW A2	ME-1
253	E41R1103D	GAL/MIN	FUEL FLOW B2	ME-1
258	E41R1034D	GAL/MIN	FUEL FLOW A1	ME-1
260	E41R1006D	RPM	HPFP SPEED A	ME-1
261	E41R1007D	RPM	HPFP SPEED B	ME-1
264	E41M1082D	ND	HARD FAIL PARVAL2	ME-1
265	E41M1083D	ND	HARD FAIL PARVAL3	ME-1
266	E41H1063D	PCT	POGO RIV POS A	ME-1
267	E41R1123D	LBM/S	FUEL MASS FLOW	ME-1
268	E41H1104D	PCT	AFV POS A	ME-1
269	E41H1105D	PCT	AFV POS B	ME-1

SSME Flight Measurements (3 of 3)

270	E41Q1122D	LBM/FT3	FUEL DENSITY	ME-1
271	E41Q1101D	UNITS	CALCULATED KF	ME-1
272	E41R1126D	LBM/S	LOX MASS FLOW (SO	ME-1
273	E41Q1100D	UNITS	CALC C2	ME-1
280	E41M1076D	ND	VEH CMD 1	ME-1
281	E41M1077D	ND	VEH CMD 2	ME-1
286	E41W1004D	S	TIME REFERENCE	ME-1
287	E41P1094D	PSIA	PC CNTL REF	ME-1
288	E41J1090D	ND	INHIBIT COUNT	ME-1
289	E41J1091D	ND	FID COUNT	ME-1
291	E41M1001P*		ID WORD 1	ME-1
292	E41M1002P*		ID WORD 2	ME-1
293	E41M1003P*		ENGINE STATUS WD	ME-1
294	E41M1081D	ND	HARD FAIL PARVAL1	ME-1
301	E41R1089D	GAL/MIN	FUEL FLOW B1	ME-1
7516	E41U1032D	PCT	SPARE	ME-1

SSME Facility Measurements (1 of 2)

•• TITLES UTILITY 020289 Vd6.02 ••

SSME EADS DATA FOR STS30R ME-1 OD   ENGINE 2027 CONTROLLER F23

FULL NAME ——— DAT1:FLT029.F13/G
TEST NUMBER ——— 0290001
TEST STAND ——— 6
CUTOFF TIME ——— 515.32
NUMBER OF PIDS — 66
FILE FORMAT ——— D

PID	MSID	UNITS	TITLE
TIME		SECONDS	TIME IN SECONDS
553	E41T1153A	DEGF	MFV DS SKIN TEMP 1 ME-1
554	E41T1154A	DEGF	MFV DS SKIN TEMP 1 ME-1
821	V41P1100C	PSIA	ENG FL IN PR 1 ME-1
835	V41P1160A	PSIA	FL PRESS INT PR ME-1
858	V41P1130C	PSIA	ENG OX IN PR 1 ME-1
879	V41T1171A	DEGF	GOX PRESS OUT.T ME-1
937	V41P1154A	PSIA	HELIUM REGA OUT PR ME-1
938	V41P1153A	PSIA	HELIUM REGB OUT PR ME-1
1021	V41T1101C	DEGF	ENG FL IN T ME-1
1035	V41T1161A	DEGF	GH2 PRESS INT T ME-1
1058	V41T1131C	DEGF	ENG OX IN T ME-1
1145	V58T1131A	DEGF	HYD SYS IF RT LN T ME-1
1147	V58T1130A	DEGF	HYD SYS IF PR LN T ME-1
1420	E41T1155A	DEGF	AFV DS SKIN TEMP 1 ME-1
1421	E41T1156A	DEGF	AFV DS SKIN TEMP 2 ME-1
1552	V58H1100A	DEG	GIM ACT Y POS ME-1
1558	V58H1150A	DEG	GIM ACT Z POS ME-1
1895	E41T1152A	DEGF	OPOV GOX S L SK T2 ME-1
1896	E41T1151A	DEGF	OPOV GOX S L SK T1 ME-1
1912	E41T1150A	DEGF	CONTROLLER PS TEMP ME-1
7001	V41X1109E	EVENT	LH2 RECRC VLV OPEN ME-1
7002	V41X1110E	EVENT	LH2 RECRC VLV CLOS ME-1
7003	V41X1661E	EVENT	GH2 PRESS 1 ON/OFF ME-1
7004	V41X1596E	EVENT	GO2 PRESS 1 ON/OFF ME-1
7005	V41X1105E	EVENT	LH2 PREVALV CLOSED ME-1
7006	V41X1135E	EVENT	LOX PREVALV CLOSED ME-1
7007	V41X1614E	EVENT	PNEU CROSSOVR OPEN
7010	V41X1104X	EVENT	LH2 PREVALVE OPEN ME-1
7011	V41X1134X	EVENT	LOX PREVALVE OPEN ME-1
7021	V41R1115A	RPM	LH2 RECIRC PUMP S ME-1
7023	V41P1490A	PSIA	GH2 DISCONNECT PR
7024	V41P1590A	PSIA	GOX DISCONNECT PR
7027	V41P1600A	PSIA	PNEU VLV HE SUPPLY
7028	V41P1605A	PSIA	PNEU VLV HE RG OUT
7029	V41P1650A	PSIA	PNEU ACCUM PRESS
7031	V41P1150C	PSIA	HE SUPPLY BOTL PR ME-1
7033	V58P0137A	PSIA	HYD SYS CRC PMP PR ME-1
7035	V95U0163C	FT/S2	TOTAL LOAD FACTOR
7041	V41P1564A	PSID	LH2 SYS DELTA P
7042	V41P1464A	PSID	LOX SYS DELTA P
7043	V41P1433C	PSIA	LH2 MANIFOLD PR
7044	V41P1533C	PSIA	LOX MANIFOLD PR
7045	V41T1428A	DEGF	LH2 MANIFOLD T
7046	V41T1527A	DEGF	LOX MANIFOLD T A
7047	V41T1528A	DEGF	LOX MANIFOLD T B
7051	V41T1151A	DEGF	AFT FSLG HE SPLY T ME-1
7052	V41T1152A	DEGF	MID FSLG HE SPLY T ME-1
7053	V41T1601A	DEGF	PNEU VLV HE SUP T
7055	V09T1702A	DEGF	AFT FSLG FLR BTM T

SSME Facility Measurements (2 of 2)

7056	V09T1720A	DEGF	RH AFT FSLG SIDE T
7057	V09T1724A	DEGF	LH AFT FSLG SIDE T
7060	V58T2140A	DEGF	H ACCUM SYS RTN , ME-1
7061	V58T0183A	DEGF	HYD LOX ET R ACT T ME-1
7065	V58P0114C	PSIA	HYD SYS SUP PR A ME-1
7066	V58P0116C	PSIA	HYD SYS SUP PR C ME-1
7070	V58P0616A	PSIA	HYD ACM SYS RTN PR ME-1
7075	V58P0115A	PSIA	HYD SYS SUP PR B ME-1
7091	T41T1705A	DEGF	LH2 ULLAGE TEMP
7092	T41T1755A	DEGF	LO2 ULLAGE TEMP
7093	T41P1700C	PSIA	LH2 ULLAGE PRES 1
7094	T41P1701C	PSIA	LH2 ULLAGE PRES 2
7095	T41P1702C	PSIA	LH2 ULLAGE PRES 3
7096	T41P1750C	PSIG	LO2 ULLAGE PRES 1
7097	T41P1751C	PSIG	LO2 ULLAGE PRES 2
7098	T41P1752C	PSIG	LO2 ULLAGE PRES 3

ATTACHMENT 11

PRELIMINARY SAFD HARDWARE DESCRIPTION

PRELIMINARY SAFD HARDWARE DEFINITION

The preliminary SAFD hardware configuration consists of eight major subassemblies: 1) interface panel, 2) control panel, 3) mass data storage system, 4) time code generator, 5) optic isolation system, 6) command processor, 7) performance monitor channels interface (PMCI), and 8) uninteruptable power supply. Preliminary information on each major subassembly is provided in the following sections.

1. **Interface Panel.** The preliminary layout of the interface panel consists of five main areas. The first area is the power interface, which includes the main AC power input, circuit breaker, facility power I/O, and auxiliary power output. The second area of the interface panel is the analog input interface. The third area of the interface panel is the PMCI interface, which includes the receiver inputs, transmit outputs, and vehicle data table (VDT) outputs. The forth area of the interface panel is the facility clock interface. The fifth area of the interface panel is the peripheral interface, which includes the printer, monitor, mass storage, keyboard, mouse, and modem inputs and outputs.

2. **Control Panel.** The preliminary layout of the control panel consists of three main areas: Power Status, Algorithm Status, and Algorithm Response.

3. **Mass Data Storage System.** Hard disk drives contain the operating system files, algorithm files, and the SAFD data generated by the command processor during SSME hot-fire testing. Floppy disk drives are available for loading and unloading data and files. A tape system is available to backup the hard disk drives. Specific details of each data storage device have not yet been defined.

4. **Time Code Generator.** In normal operation, the time code generator receives the facility IRIG-B signal. This signal is passed to the command processor where it is used to time stamp the VDT and analog data. If the IRIG-B signal is unavailable, the time code generator independently issues a time stamp signal.

5. **Optic Isolation System.** The optical isolator isolates the SAFD system from facility electrical signals that potentially could damage the command processor.

6. **Command Processor.** The command processor is the heart of the SAFD system. It contains the controller cards for all if the peripherals, the analog to digital converter card(s), and the central processing unit(s) which process the engine and facility data and issues commands. The A/D converters will accept 64 single ended or 32 differential -5 to +5 volt discrete analog signals.

Several candidate systems are being evaluated. The leading candidates are shown in Table A11-1.

7. **Performance Monitor Channel Interface.** The PMCI acts as a front end processor for the SSME Vehicle Data Tables (VDT). The main function of the PMCI is to convert the SSME Channel A and B VDT serial inputs to parallel outputs. After the 128 words have been converted to parallel data they are buffered onto the command processor.

The VDT is obtained by inserting coaxial "T's" into the data lines between the VEEI buffer (located on the test stand) and the CADS (located in the block house). The transmit cards in the PMCI are used to perform PMCI loop back tests. This is done by disconnecting the SSME VDT receiver input cables from the SAFD and installing short coaxial connectors between the transmit outputs and receiver inputs.

The receiver inputs receive the 128 word SSME Channel A and B Vehicle Data Table's every 40 ms.

8. **Uninteruptable Power Supply.** The SAFD power (117 volts, 30 amps maximum) is provided by the facility through the UPS. The UPS will supply approximately 15 seconds of reserve power incase the facility power fails. This allows for safe system shutdown by the SAFD operator.

TABLE A11-1 SAFD CANDIDATE HARDWARE FEATURES

	INTEL-SBC 386	SUN 3/470	SUN 4/370	VAX 3500	MicroVAX 3800
CPU	80386	68030	SPARC	KA650	
CPU MIPS	7.5	7.0	16.0	2.7	3.8
BUS TYPE	multibus-II	VME	VME	Q	Q
BUS THROUGHPUT (Mbyte/sec)	40.0	3.0	2.7	3.3	3.3
MULTI-TASKING	yes	yes	yes	yes	yes
MULTI-PROCESSING	yes	yes	yes	no	no
OPERATING SYS.	RMX-3	UNIX	UNIX	VMX	VMX
A/D THROUGHPUT (KHz)	100	100	100	200	200
A/D RESOLUTION (bits)	12	12 or 16	12 or 16	12	12
VDT THROUGHPUT (Mbyte/sec)		>5	>5	2.6	2.6

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15. Supplementary Notes

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16. Abstract

The functional framework of a failure detection algorithm for the Space Shuttle Main Engine (SSME) is developed. The basic algorithm is based only on existing SSME measurements. Supplemental measurements, expected to enhance failure detection effectiveness, are identified. To support the algorithm development, a figure of merit is defined to estimate the likelihood of SSME criticality 1 failure modes and the failure modes are ranked in order of likelihood of occurrence. Nine classes of failure detection strategies are evaluated and promising features are extracted as the basis for the failure detection algorithm. The failure detection algorithm provides early warning capabilities for a wide variety of SSME failure modes. Preliminary algorithm evaluation, using data from three SSME failures representing three different failure types, demonstrated indications of imminent catastrophic failure well in advance of redline cutoff in all three cases.

17. Key Words (Suggested by Author(s)): Health monitoring; Rocket engine diagnostics; Rocket engine fault detection; Health monitoring system hardware architecture	18. Distribution Statement: Unclassified – Unlimited; Subject Category 20

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