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CONTRACT NAS3-25279
REUSABLE ROCKET ENGINE TURBOPUMP
HEALTH MONITORING SYSTEM

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FINAL REPORT

PREPARED FOR
NASA-LEWIS RESEARCH CENTER
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ABSTRACT

The final technical report for contract NAS3-25279, Reusable Rocket Engine Turbopump Health Monitoring System, is presented. The work Breakdown Structure is correlated to the nature of the actual tasks performed. Task 1, degradation mechanisms, and Task 2, sensor identification/selection resulted in a list of degradation modes and a list of sensors that are utilized in the diagnosis of these degradation modes. The sensor list is divided into primary and secondary indicators of the corresponding degradation modes. The signal conditioning requirements are discussed, describing the methods of producing the SSME post-hot-fire test data to be utilized by the Health Monitoring System.

Development of the diagnostic logic and algorithms is also presented. The knowledge engineering approach, as utilized, includes the knowledge acquisition effort, characterization of the expert's problem solving strategy, conceptually defining the form of the applicable knowledge base, and rule base, and identifying an appropriate inferencing mechanism for the problem domain. The resulting logic flow graphs detail the diagnosis/prognosis procedure as followed by the experts. The nature and content of required support data and databases is also presented. The distinction between deep and shallow types of knowledge is identified. Computer coding of the Health Monitoring System is shown to follow the logical inferencing of the logic flow graphs/algorithms. Coding is performed using both the conventional programming language "C", and an expert system development tool. The computer code was delivered to LeRC as part of this program. Finally, an HMS development plan is presented, detailing suggested HMS enhancements to increase its functionality and robustness.

(1739C)

INTRODUCTION

The final technical report for contract NAS3-25279, Reusable Rocket Engine Turbopump Health Monitoring System, will follow the same descriptive format as the monthly reports. Each task of the program will be discussed in a sequential manner as it was satisfied during the program effort. Tasks 1 and 2 provided the list of sensors and the failure modes that were used in the diagnostic system along with a methodology for determining failed sensor characteristics. Initial efforts in Task 3 concentrated on developing a set of logic flow graphs that captured the domain experts heuristic knowledge of how turbopump diagnostics are performed. The final activity of Task 3, algorithm development, was completed in conjunction with Task 4, data processing. Data sampling and processing procedures that are performed on all SSME test and flight data were reviewed and evaluated for use in this program. This information was then used in the final development of the system algorithms.

Once the algorithms had been developed, they were then coded as a functional whole comprising the diagnostic system for this program. The coding constituted a portion of the activity in Task 5. Two methods of coding the algorithms were used. One set is coded in the "C" language with another set in an expert system shell called G2. Both systems capture the same knowledge and provide the same diagnostic capability. The technical activity for Task 5, and for the entire program, cumulated in an HMS conceptual design and development plan. The design and development plan gives an overview of the system that has been developed and presents a detailed procedure for expanding the existing diagnostic system to include multiple failure modes, prognostics, and life prediction.

Health Monitoring System Development

Initial activity for Task 1, degradation mechanism, and Task 2, sensor identification/selection, started with a review by turbomachinery personnel of the life-limiting components that had previously been generated in a 1983 study, Reusable Rocket Engine Turbopump Condition Monitoring, NAS3-23349.

Specific HPOTP life-limiting component degradations that were discussed in this study were modified to reflect current pump design and engine hot fire test experience that had been gathered since 1983. In conjunction with the degradation mode identification, updates to the sensor technology as given in the 1983 study were made to incorporate experience gained. After the updates had been completed, a preliminary listing of life-limiting component degradation modes and sensor technologies was established. Discussions of defective sensor detection, Task 1: Sensor Methodology, are given along with the discussion of algorithm development.

Further discussions with the domain experts finalized the list of failure modes and sensors. Appendix A includes a list of the failure modes, Table 1, and Primary Identification (PID) Numbers, Table 2, that were used in this program. The PID numbers are the SSME flight and facility instrumentation identifiers. Redline measurements are identified, and where appropriate, are broken into primary and secondary listings. Those measurements listed as primary are the first line indicators of a particular failure mode. Secondary measurements are those that the turbopump experts review in conjunction with the primary measures to aid in the interpretation of turbopump performance.

It is not to be inferred that information derived from the measurements listed with a particular failure mode give an unequivocable indication that the associated turbopump component has failed. The redline measurements are certainly used in this fashion; however, several of the other components do not have direct measures associated with them and inferences must be made. An example is ball bearing wear. Here, accelerometers are sources of dynamic data which contain certain operating frequencies that are indicators of bearing performance. These frequencies provide a screening measure from which the turbopump experts deduce what has happened during the test with regard to the bearing. The topic of additional and advanced sensor requirements is addressed in the HMS Development Plan.

The second subtask within Task 2 was signal conditioning requirements. Appendix B gives a detailed description of the signal conditioning requirements for this program. Since the sensors used for this diagnostic system are the same as those used on existing SSME turbopumps, the data processing follows the same procedures and policies that are followed by Rocketdyne in the data reduction of all SSME test and flight data. For this reason, Appendix B not only prescribes the signal conditioning requirements but also specifies the data processing requirements and identifies the data sampling rate, Task 4. To briefly summarize Appendix B, the digital tapes are read by a Perkin-Elmer computer system, converted into 32 bit packed binary floating point representations, and stored on a 9-track tape. Rocketdyne generated computer programs are then used to selectively extract data and perform a variety of manipulations. These results are then made available as time-history plots of sensor values as well as stored on magnetic tape as sensor data vs. time.

The analog recording and processing system, which includes data from accelerometers and strain gauges, stores the data in continuously varying analog voltage form on FM tapes. A FFT data reduction technique is applied to the data resulting in Fourier Coefficients characterizing the signals in the frequency domain. Further processing typically includes the generation of power spectral density plots, giving the square of acceleration divided by frequency vibration sensed at varying frequencies, including the resonant peaks corresponding to the vibration modes present within the signal. This data can be made available as x-y point values, the format for plotting stored on magnetic tape. The HMS diagnostic system utilizes both of the tapes generated by the digital and the analog recording methodology.

Having identified the failure modes and sensors that would be used for this system the process of logic and algorithm development began. A knowledge engineering approach was utilized. The domain experts, high pressure oxidizer turbopump specialists, were queried as to how they review the time history plots of sensor data that are generated from the x-y time history plots discussed above. The manual review of these plots is the normal procedure for both successful tests and premature shutoff. By analyzing these plots, the experts can determine the operating characteristics of the engine components. The function of the knowledge engineer is to compile logic flow graphs of this review and analysis methodology. A complete listing of all of the logic flow graphs developed in this program is given in Appendix C.

Figure 1 of Appendix C is one such logic graph. In this instance there was a successful test, and the normal post-test data review procedures were followed. During the review process it was found that the turbine discharge temperature was higher than expected. The temperature had not reached the red line limit but had exceeded the expected operating levels. The expected levels are determined from data stored in the test/flight data base, which is considered an experiential or shallow knowledge base. This data base has within it all past histories of relevant engine operating conditions and serves the purposes of table lookup.

The HMS System also provides for a deep knowledge base. This knowledge base is comprised of analytical models of the SSME engine and the oxidizer turbopump. When there is insufficient or missing data within the shallow knowledge base, calls to this deep knowledge are made and the necessary information provided. For the case presented in Figure 1, it was necessary to access a FORTRAN coded procedure that utilizes first principals of thermodynamics and fluid flow to compute values for which there are no direct sensor measurements and to generate flow characterization coefficients.

As can be seen, both the deep and shallow knowledge bases are resident within the system and assume an active role only when needed in the logic flow. At each node in the logic tree the expert trys to determine the cause of the anomaly. If successful the search ends, else there is a logical progression to the next node. By logically exhausting all possible alternatives, it was concluded, for this case, that there was a turbine tip seal problem.

Algorithm development followed the definition of the logic flow graphs. Each box or node of the logic graphs represents the heuristics which the domain expert uses in performing pump analysis. Since they follow in a sequential manner they readily lend themselves to a procedural approach. The process of developing the algorithms therefore involved assigning numerical values to each decision point and defining a methodology for the logical progression through the graph.

Several methods were employed to assign the numerical values. Data values that are constants were entered as assigned variables. Where sensor data was missing, analytical models were used to provide the necessary information. This method was discussed above relative to flow coefficients. The final method made use of database values or table look up. The limits of this program did not permit establishing a relational database for values, such as assembly information. However, the algorithms are so structured that future activity will easily permit the incorporation of database values through program calls. This is discussed further in the HMS development plan.

In addition to providing for the analysis of sensor data, a methodology was also established for detecting and handling faulty sensor values. Appendix D is a replication of several algorithmic approaches for validating sensor input that appeared in Monthly Status Report 4, 22 March 1988. This report discusses both hard and soft sensor failures as well as an advanced technique based upon diagnostic expectations. The HMS Development Plan discusses how these techniques can be implemented in the next generation turbopump diagnostic system. There are several methodologies for information validation that are currently employed by the domain experts when reviewing the sensor data. Where applicable and practical these have been incorporated into this program. Coherence techniques utilize redundant channels of the same measurement to compare for similarity. Measured values are also compared to limit values, or end points, that a properly functioning sensor is capable of providing. The same measured values can be recorded prior to engine start and after engine shutdown for computation of differentials and drift. Finally, the values can be compared to what the fundamental laws of physics would dictate are possible, as in the case of mass and energy continuity. This methodology is a portion of the function of the deep knowledge base within the knowledge system. In developing the algorithms those procedures just discussed that could be coded were incorporated into the diagnostics of this program.

The technical activities in Task 5 were the coding of the algorithms and the creation of an HMS Development Plan. Rocketdyne made the decision to develop a functional, prototype system to demonstrate the diagnostic capabilities of the system for its interim program review at NASA Lewis Research Center. The system was developed using the "C" programming language. This language was chosen because the source and executable code are deliverable and usable by the customer without the need for extra software purchases, and the data driven, forward chaining nature of the diagnostic system was readily implemented in a common procedural language such as "C". As program development continued, the demonstration system evolved into a completely functional, diagnostic system. This system is considered to be a deliverable item within this program and will be demonstrated at the final program review. Five data files will also be delivered, one for each of the failure modes that have been observed during turbopump operation. These data files will be used to demonstrate the capabilities of the system. Two failure modes, primary turbine seal and primary oxidizer seal wear, have never been observed during operation of the current HPOTP design and, therefore, data files do not exist for them.

In addition to the Rocketdyne computer code, program team member University of Alabama at Huntsville is using the information provided by Rocketdyne to develop, in a parallel effort, a comparable diagnostic system using the expert system development tool G2. This system will also be delivered as a part of this program. By having the diagnostic capability represented in two different formats, conventional language and expert system shell, trades can be made as to the direction for future development efforts.

An HMS Development Plan was created and delivered as part of Monthly Report 13, 16 January 1989. This plan is included as Appendix E. It presents a descriptive methodology for expanding the system, particularly the logic flow graphs and ensuing code, created during this program. Areas for inclusion in subsequent programs would include: multiple failures and failure propogation; transient analyses; power level changes and throttling; an expansion of the deep knowledge base; and database identification and development. Since each of these areas is formidable, a phased development program was proposed. Figure 2 of the Development Plan is a pictorial representation of the envisioned expert system. By utilizing the same development procedures as used in this contract the system presented in the conceptual design can be systematically defined, modeled, and developed.

CONCLUSION

A Health Monitoring System for the SSME HPOTP was defined, modeled, and developed. The system captures the knowledge that the domain experts utilize in performing post test/flight data analysis. The knowledge was encoded as part of a knowledge based system that automates this analysis procedure. The system was demonstrated during an interim program review by processing data files containing SSME HPOTP hot-fire test results. In addition to developing the diagnostic system, a Development Plan was created that identifies areas for future effort and prescribes a sequential procedure for accomplishing these objectives. The completion of this program is a first step in the development of a universal pump health monitoring system.

APPENDIX A: TABLE 1

Degradation modes and corresponding PID numbers

Primary Turbine Seal Wear
 Primary Measurement: 990
 Secondary Measurements: 2, 233, 234, 1190, 63

Secondary Turbine Seal Wear
 Primary Measurement: 91, 92 (red lines)
 Secondary Measurements: 2, 233, 234, 990, 937, 1100, 63

Turbine Interstage Seal / Tip Seals Wear and Erosion
 Primary Measurement: 233, 234 (red lines)
 Secondary Measurements: 2, 8, 2176, 63, 231, 232, 334
 1949, 1994, 1996, 1998, 1952, 1961, 1962

Intermediate (purge) Seal Wear
 Primary Measurement: 211, 212 (red lines)
 Secondary Measurements: 233, 234, 937, 1100, 1188, 1190

Primary Oxidizer Seal Wear
 Primary Measurements: 951, 952, 953
 Secondary Measurements: 2, 937, 1100, 1187

Pump Impeller / Turning Vane Cavitation Erosion
 Primary Measurement: 2
 Secondary Measurements: 8, 2176, 63, 90, 190, 334

Ball Bearing Wear
 Primary Measurements: 1949, 1994, 1996, 1998, 1952, 1961, 1962

APPENDIX A: TABLE 2

PID Number Description

2	HPOTP Shaft Speed (accelerometer)
8	Mixture Ratio (Indirect, Flight calc)
2176	Mixture Ratio (Facility, PID number varies)
63	MCC Pc
287	Pc Reference (commanded)
3001	Power Level (Based on PID 63, PID Number Varies)
90, 190, 334	HPOP Discharge Pressure
91, 92	Secondary Turbine Seal Drain Pressure
211, 212	Intermediate Seal Purge Pressure
231, 232	HPFT Discharge Temperature
233, 234	HPOT Discharge Temperature
937	Intermediate Seal He Purge Pressure, Upstream of PCA Orifice
1100	Intermediate Seal He Purge Drain Temp
951, 952, 953	Primary Oxidizer Seal Drain Pressure
990	Primary Turbine Seal Drain Pressure
1187	Primary Oxidizer Seal Drain Temperature
1188	HPOT Secondary Seal Drain Temperature
1190	HPOT Primary Seal Drain Temperature
1949, 1994, 1996, 1998	PBP Radial Accelerometers
1952, 1961, 1962	Turbine Radial Accelerometers

APPENDIX B

DATA PROCESSING AND SIGNAL CONDITIONING

During operation of the SSME, 85 engine parameters are monitored by the SSME controller. At 40ms intervals (100ms intervals during engine preparation and post-fire phases), the controller sends a block of 128 digital values known as a vehicle data table (VDT) consisting of the 85 digitized measurements, 12 calculated parameters, and 31 redundant parameters and miscellaneous control words. The numeric values of the VDT are passed from the engine through the Vehicle Engine Electrical Interface (VEEI). During flight, the shuttles General Purpose Computer (GPC) acts as a data acquisition system. The 128 word VDTs are stored in the onboard continuous-loop recorders and are telemetered to NASA's own computer system which, in turn, may be accessed by Rocketdyne through electronic tie-ins.

During hot-fire engine testing, the Command and Data Simulator (CAD) takes the place of the GPC as the data acquisition system. The VDTs are passed through to a 9 track 1600 bpi magnetic tape recorder. In addition to the CADs system, the Facility Recording System also operates during hot-fire testing. This system samples 300 parameters at 20ms intervals. The 300 parameters consist of test facility measurements and osme engine parameters along with a number of redundant measurements. The Facility Recording System performs limited redline checking (in addition to that done by the SSME controller) for possible engine shutdown. The data is stored on a second 9-track magnetic tape in raw measurement form, i.e. milivolt values and raw counts. The digital tapes are read by a Perkin-Elmer computer system, converted into 32 bit packed binary floating point representation, and stored on a 9-track tape. Computer programs are then used to selectively extract data and perform a variety of manipulations. Results can be make available in several forms including time-history plots of sensor values and magnetic tapes of sensor data vs. time. Figure 1 is a diagram of this signal processing procedure.

Separate from the digital recording system is an analog recording system in which the data from certain measurements, including that from accelerometers and strain gauges, are stored in contimuously-varying analog voltage form on Frequency Modulated (FM) tapes. Rocketdyne's processing of this data consists of converting the analog signals into 10240 digital signals per second. A FFT data reduction technique is applied to the data resulting in Fourier coefficients characterizing the signals in the frequency domain. The sensor measurements, in this form, are stored on 1 GByte, 12 inch optical disks. Further processing typically includes the generation of Power Spectral Density (PSD) plots, giving the square of acceleration divided by frequency versus frequency. These plots show the magnitude of vibration sensed at varying frequencies, including the resonant peaks corresponding to the vibration modes present within the signal, and can also aid in the identification and categorization of unrecognized peaks. Other output formats include plots of frequency spectrum vibration trends over the duration of a test, and RMS acceleration values over time. This data can be made available as x-y point values, the format for plotting, stored on 9 track 1600 bpi magnetic tape. See figure 2 for a diagram of the analog signal conditioning and processing.

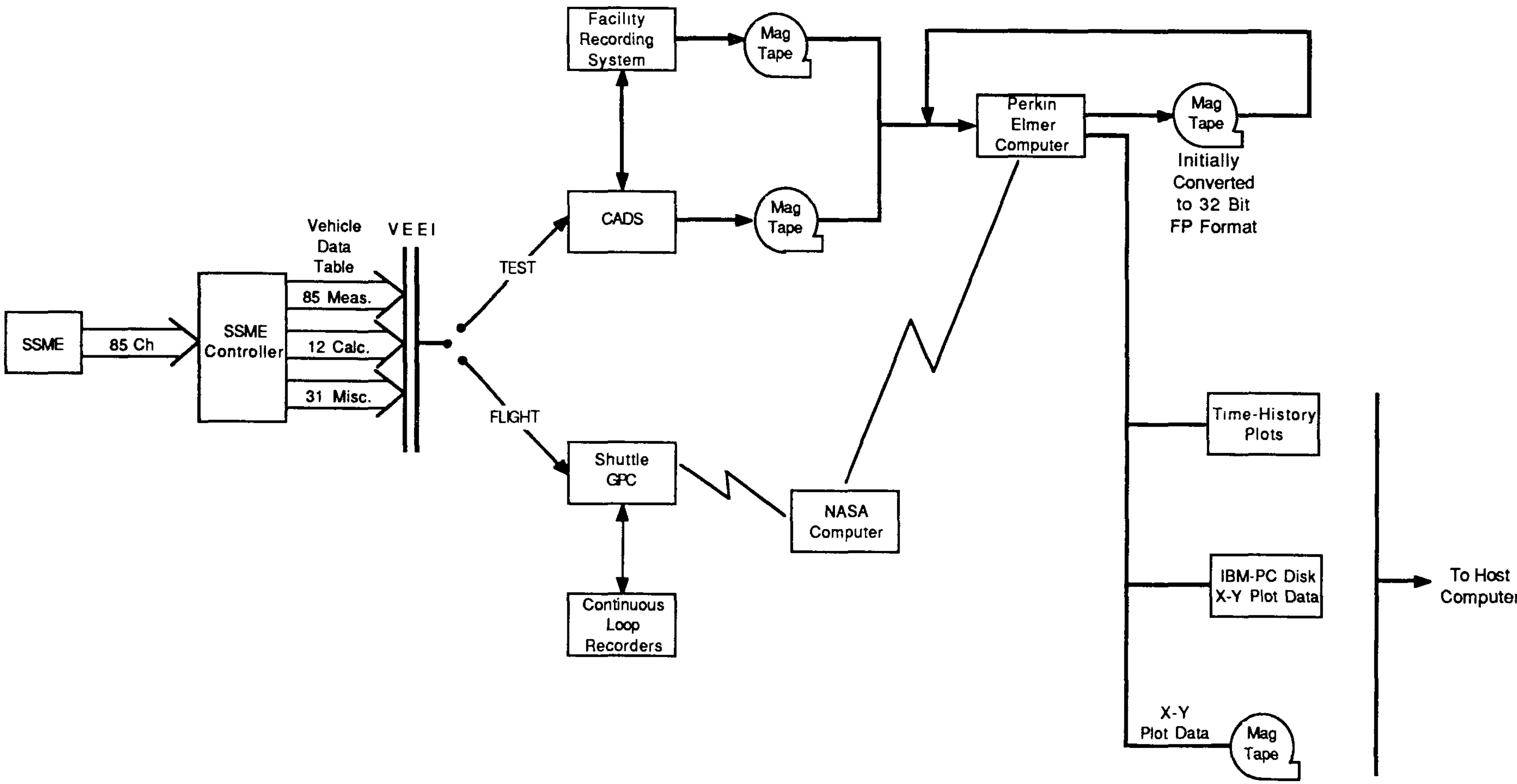


Figure 1: Data Processing and Signal Conditioning of Digitally Recorded SSME Sensor Data

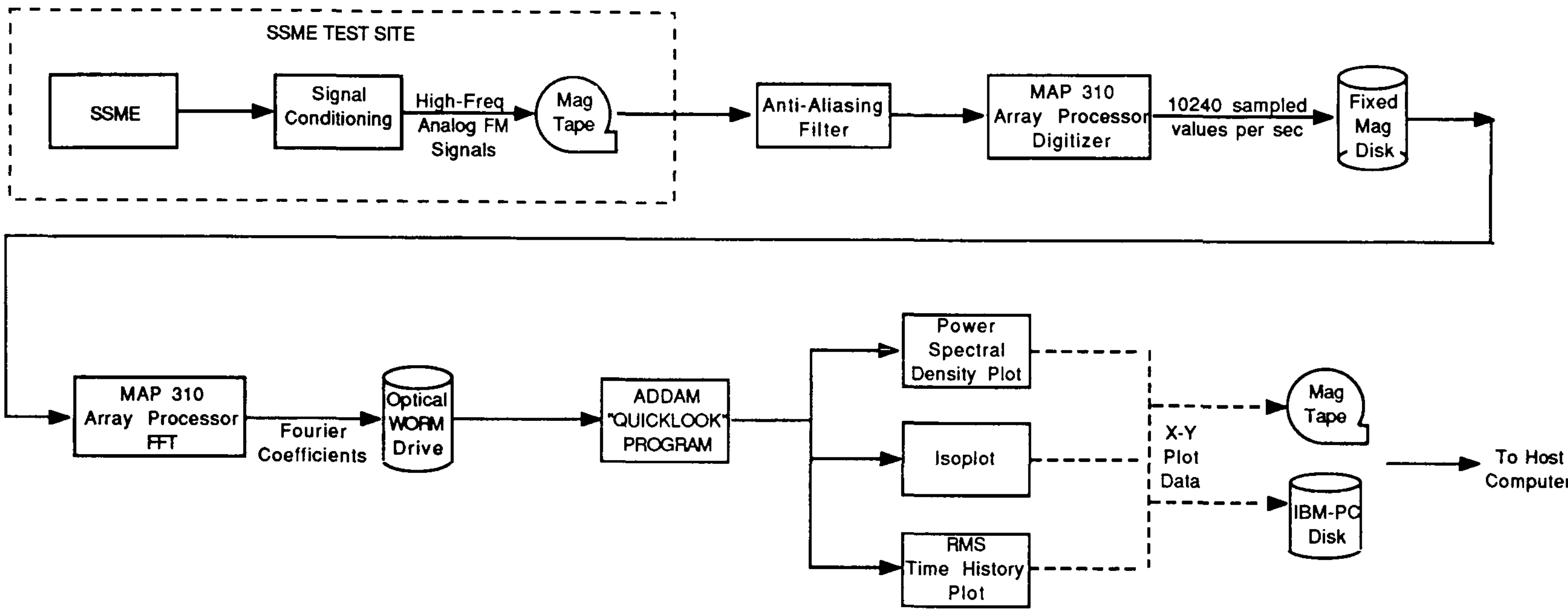
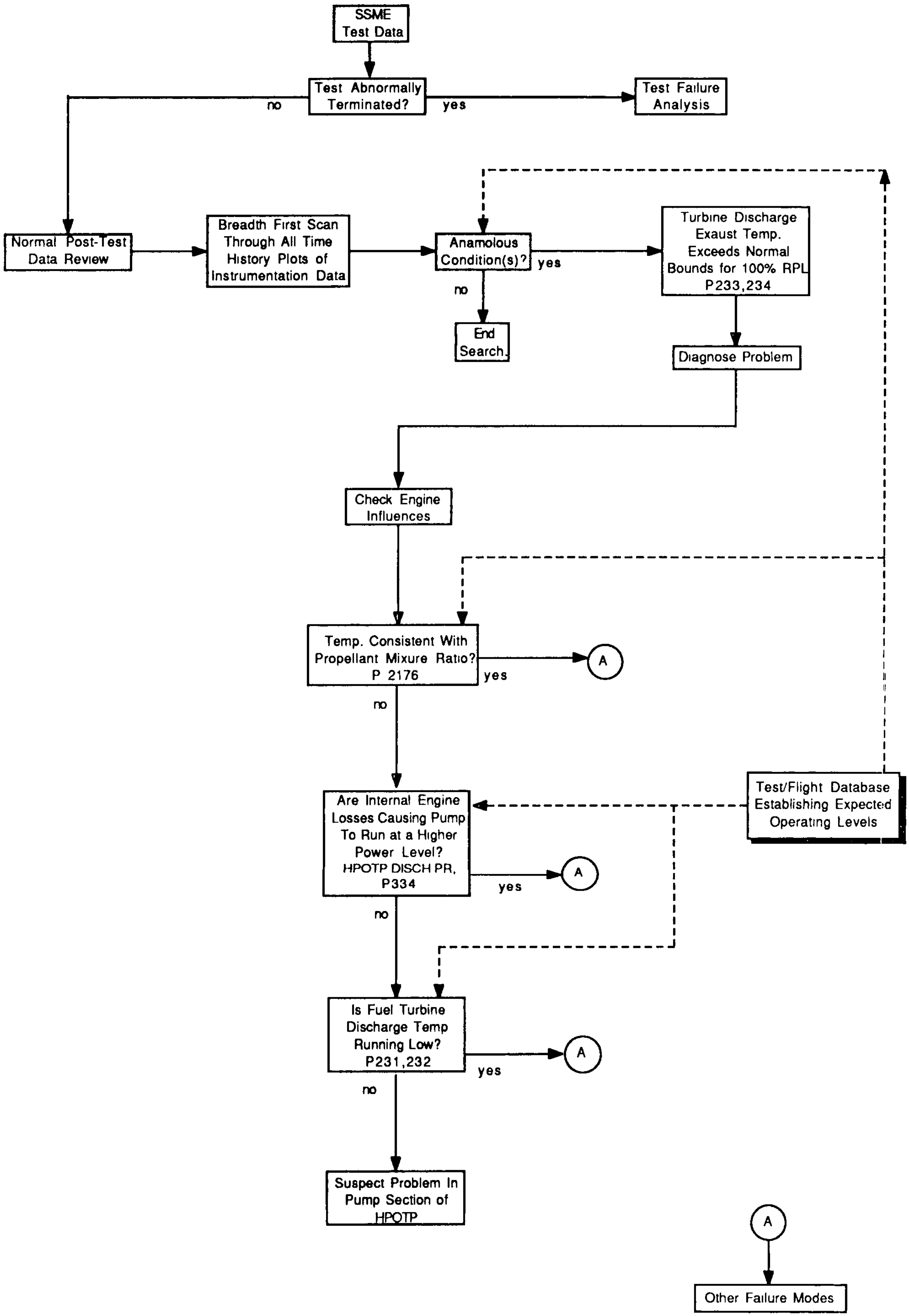
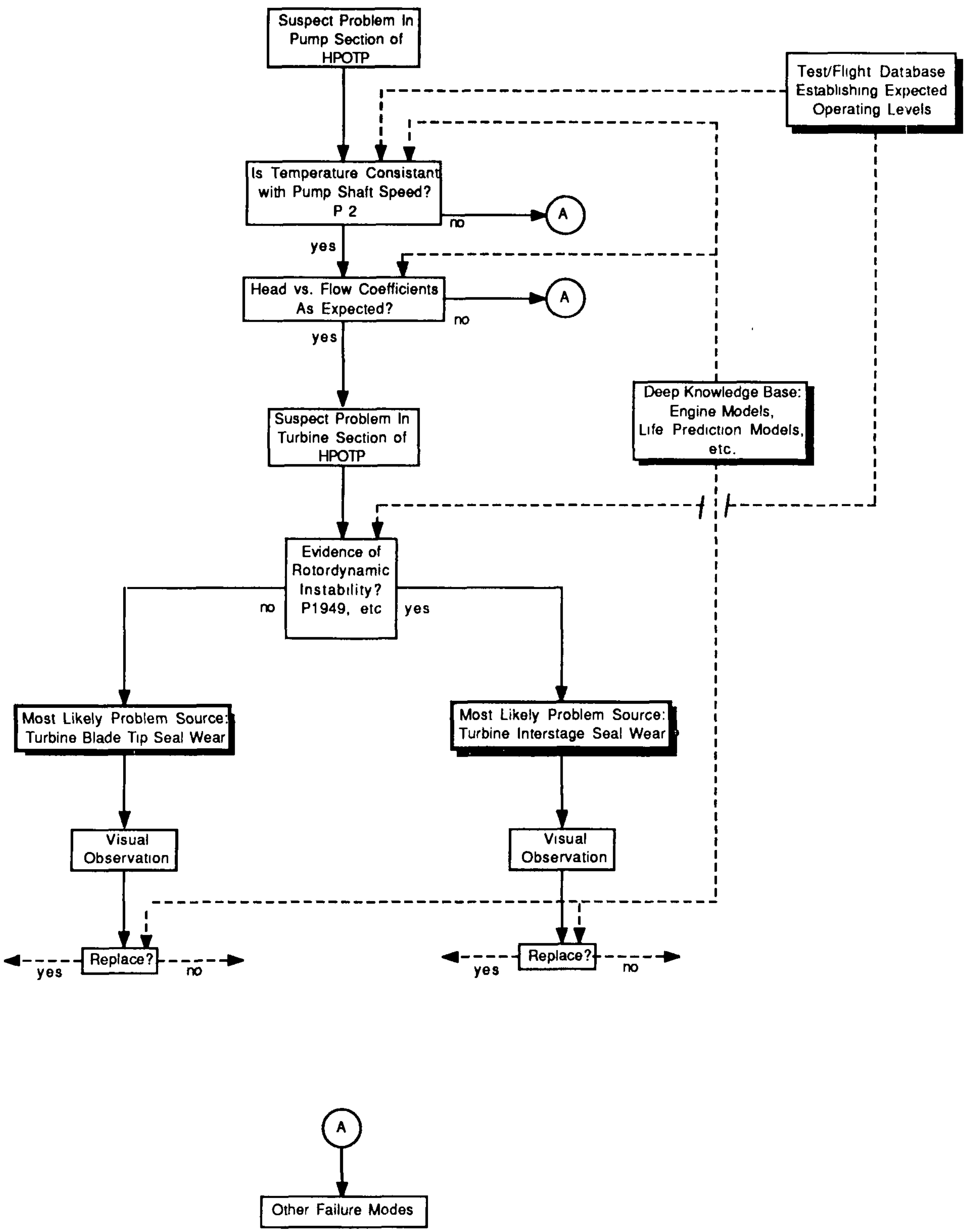


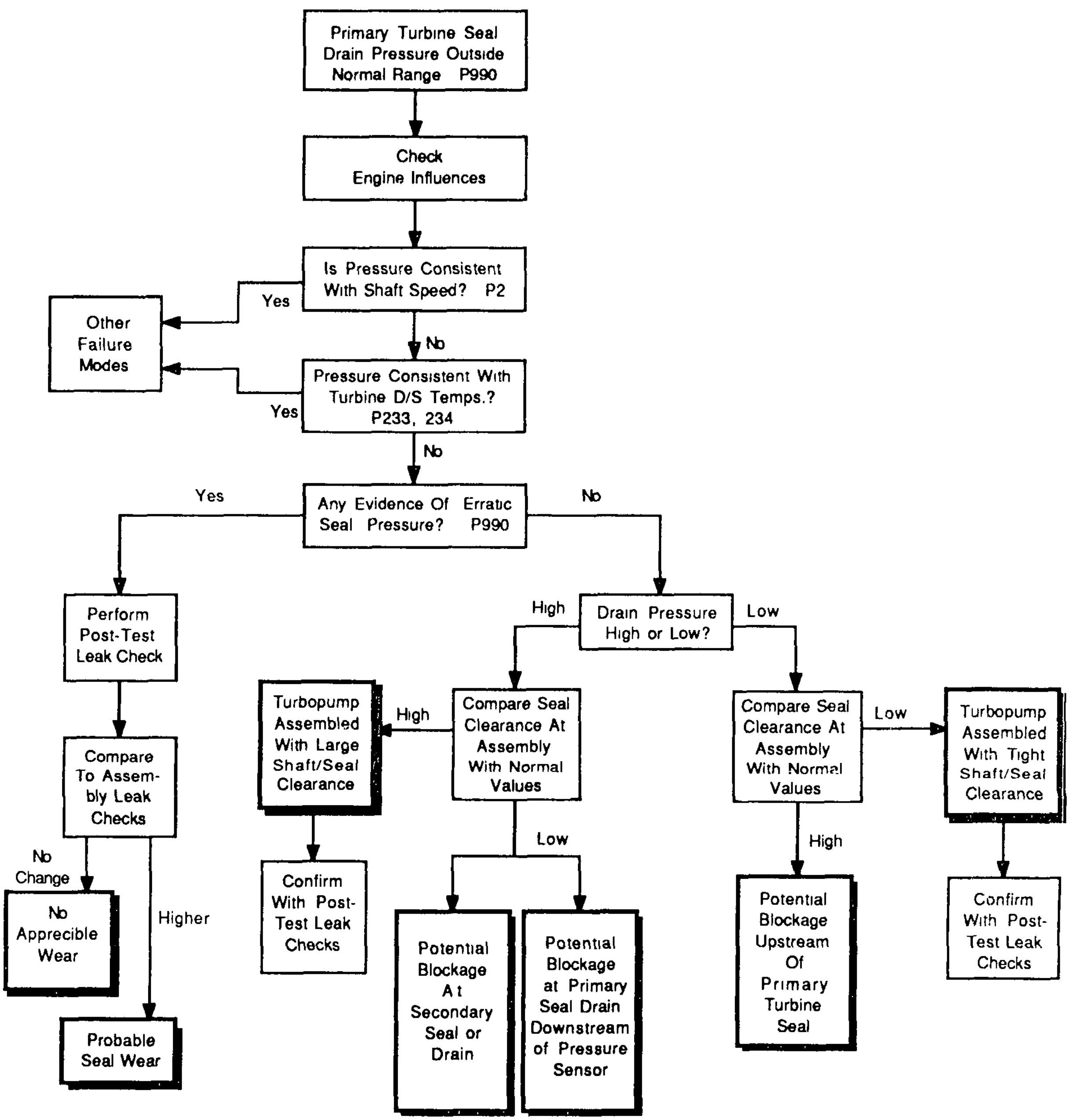
Figure 2: Processing and Signal Conditioning of SSME High-Frequency Analog Test Data

mode 3
3-8-89

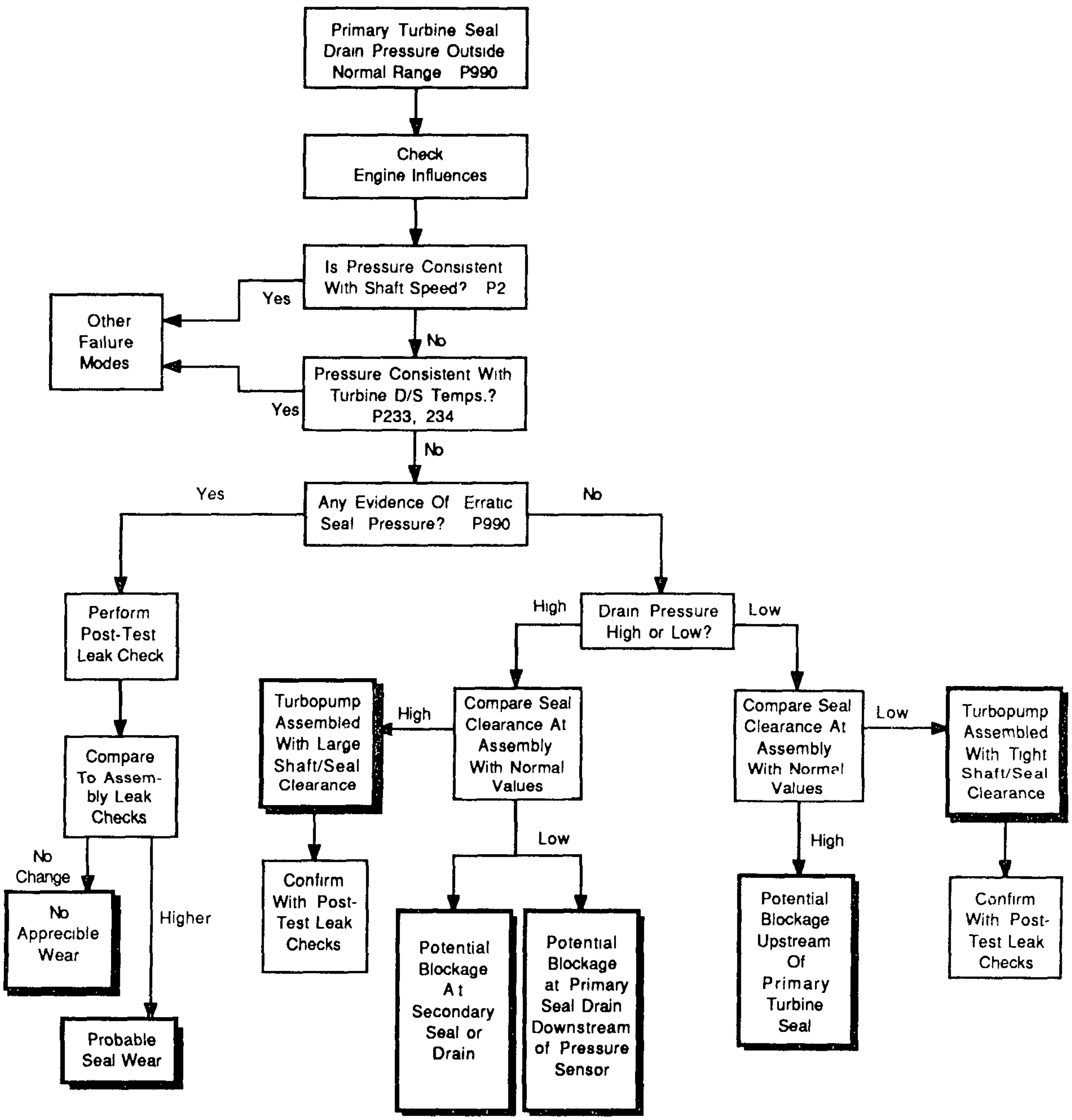
APPENDIX C




Suspect Problem In Pump Section of HPOTP
Test/Flight Database Establishing Expected Operating Levels
Is Temperature Consistant with Pump Shaft Speed? P 2
no
A
yes
Head vs. Flow Coefficients As Expected?
no
A
yes
Deep Knowledge Base: Engine Models, Life Prediction Models, etc.
Suspect Problem In Turbine Section of HPOTP
Evidence of Rotordynamic Instability? P1949, etc
no
yes
Most Likely Problem Source: Turbine Blade Tip Seal Wear
Most Likely Problem Source: Turbine Interstage Seal Wear
Visual Observation
Visual Observation
yes
Replace?
no
yes
Replace?
no
A
Other Failure Modes

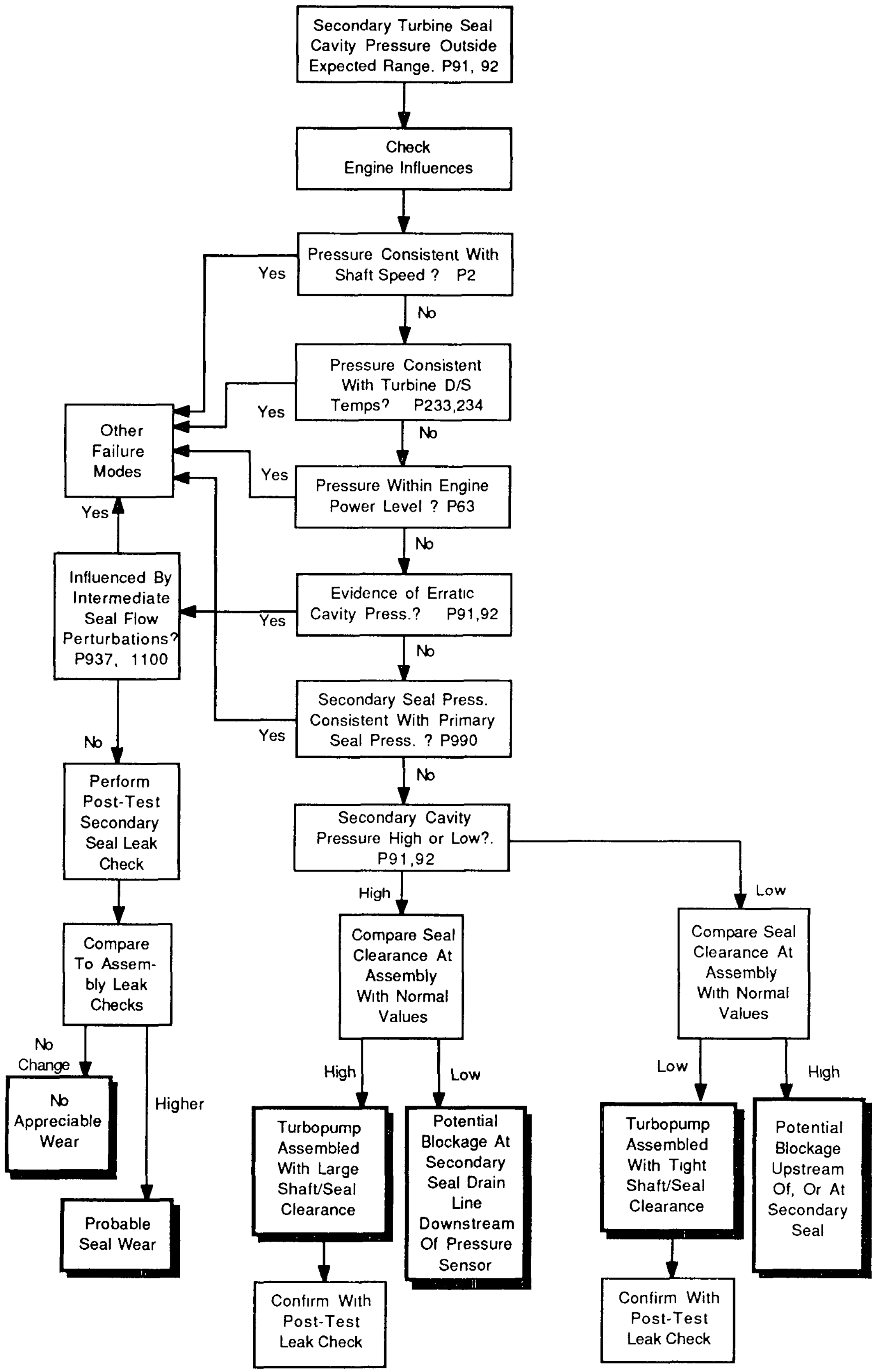

Primary Turbine Seal Drain Pressure Outside Normal Range P990
Check Engine Influences
Is Pressure Consistent With Shaft Speed? P2
Yes
Other Failure Modes
No
Pressure Consistent With Turbine D/S Temps.? P233, 234
Yes
No
Any Evidence Of Erratic Seal Pressure? P990
Yes
No
Perform Post-Test Leak Check
Compare To Assembly Leak Checks
No Change
No Apprecible Wear
Higher
Probable Seal Wear
Drain Pressure High or Low?
High
Low
Compare Seal Clearance At Assembly With Normal Values
High
Turbopump Assembled With Large Shaft/Seal Clearance
Confirm With Post-Test Leak Checks
Low
Potential Blockage At Secondary Seal or Drain
Potential Blockage at Primary Seal Drain Downstream of Pressure Sensor
Compare Seal Clearance At Assembly With Normal Values
Low
Turbopump Assembled With Tight Shaft/Seal Clearance
Confirm With Post-Test Leak Checks
High
Potential Blockage Upstream Of Primary Turbine Seal

mode 1
3-8-89

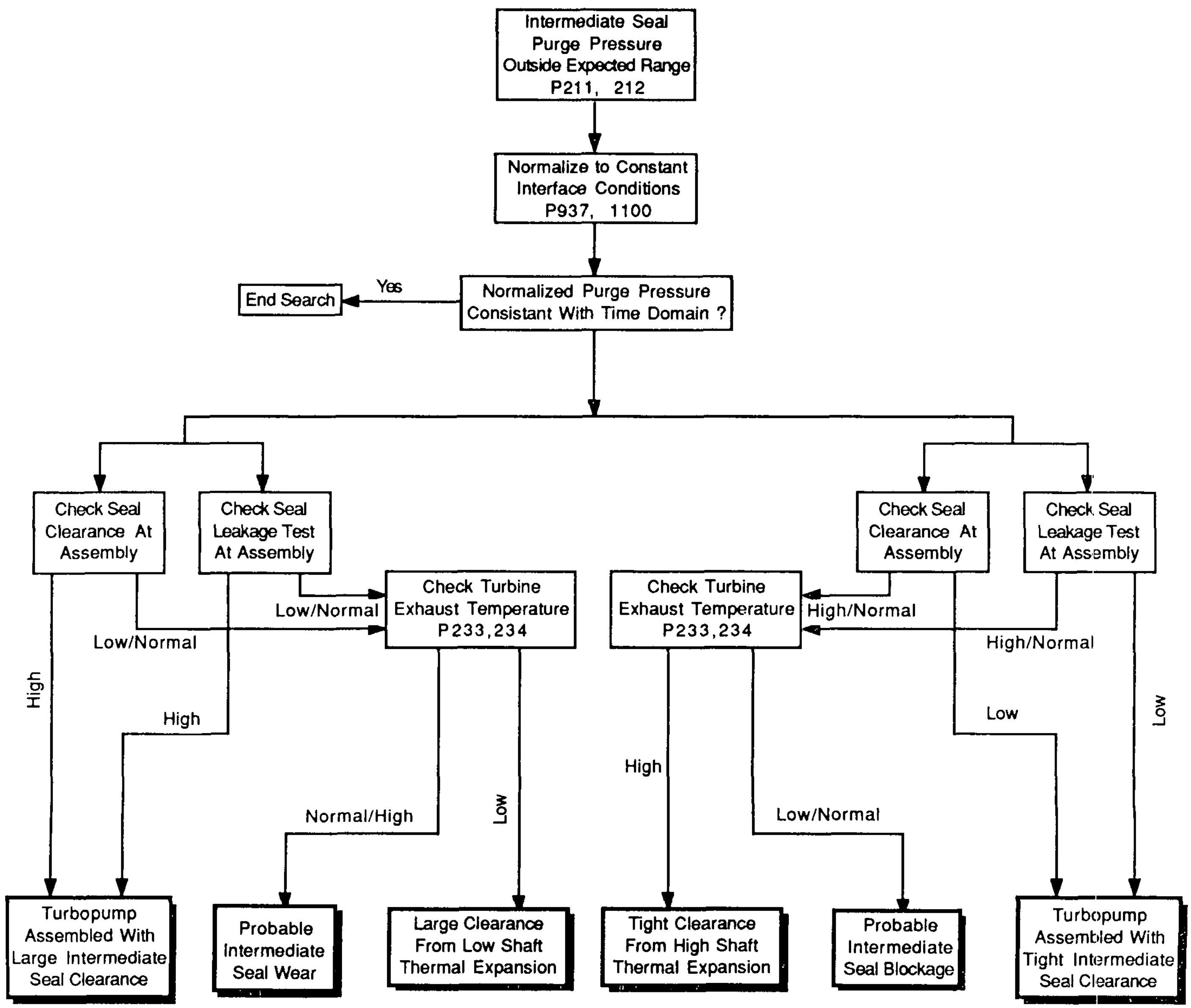


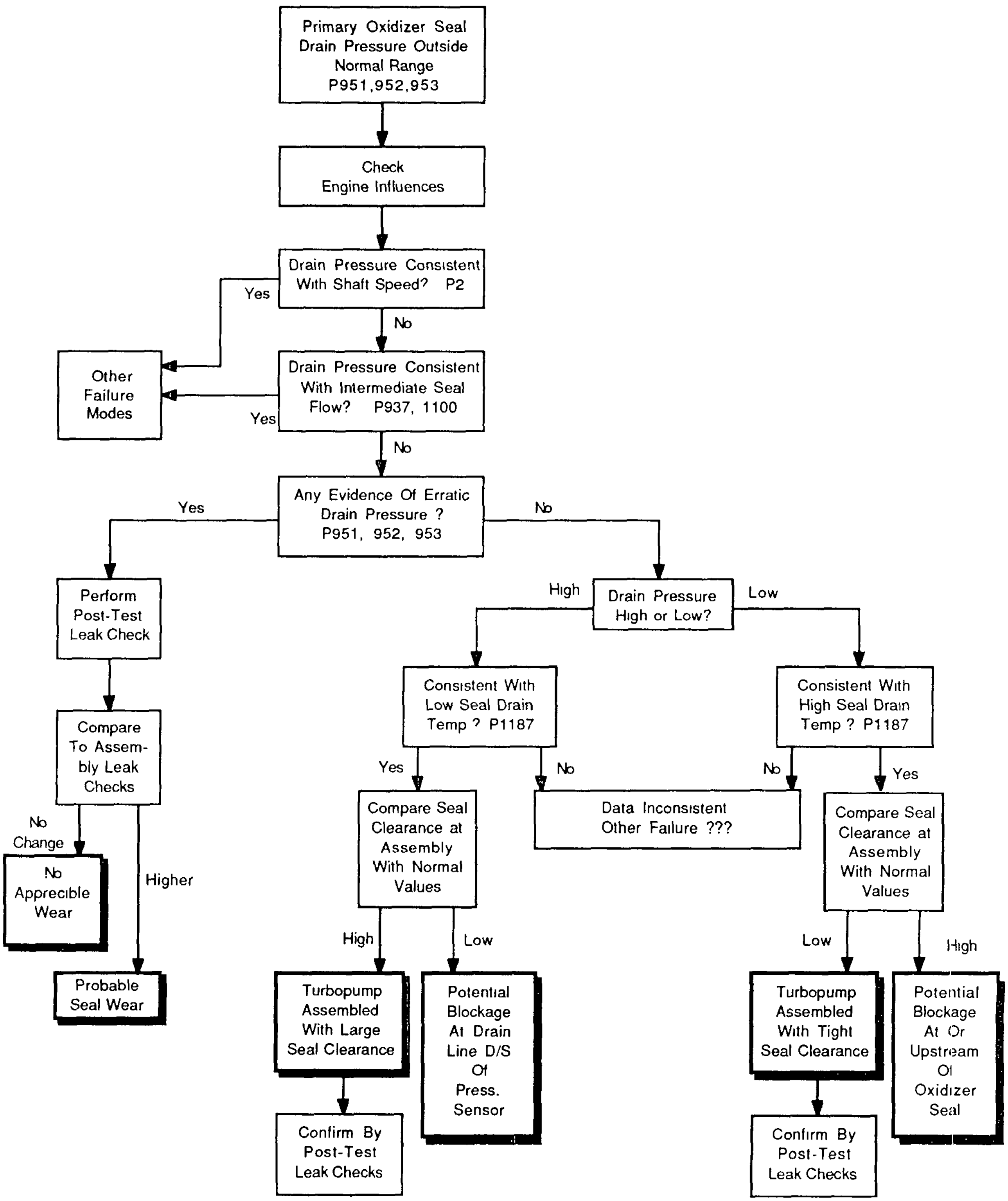
Primary Turbine Seal Drain Pressure Outside Normal Range P990
Check Engine Influences
Is Pressure Consistent With Shaft Speed? P2
Yes
Other Failure Modes
No
Pressure Consistent With Turbine D/S Temps.? P233, 234
Yes
No
Any Evidence Of Erratic Seal Pressure? P990
Yes
No
Perform Post-Test Leak Check
Compare To Assembly Leak Checks
No Change
No Appreciable Wear
Higher
Probable Seal Wear
Drain Pressure High or Low?
High
Low
Compare Seal Clearance At Assembly With Normal Values
High
Turbopump Assembled With Large Shaft/Seal Clearance
Confirm With Post-Test Leak Checks
Low
Potential Blockage At Secondary Seal or Drain
Potential Blockage at Primary Seal Drain Downstream of Pressure Sensor
Compare Seal Clearance At Assembly With Normal Values
Low
Turbopump Assembled With Tight Shaft/Seal Clearance
Confirm With Post-Test Leak Checks
High
Potential Blockage Upstream Of Primary Turbine Seal

mode 2

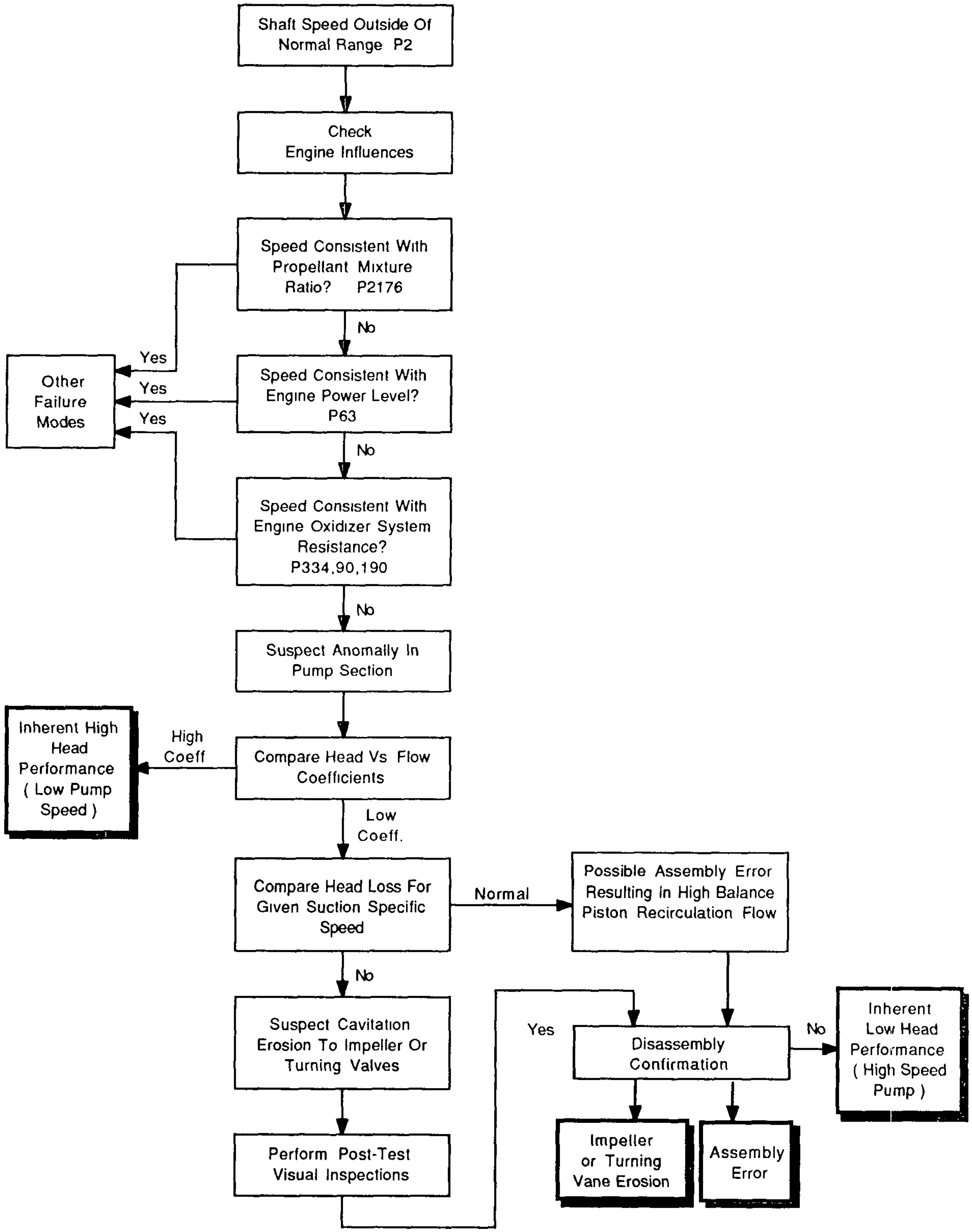


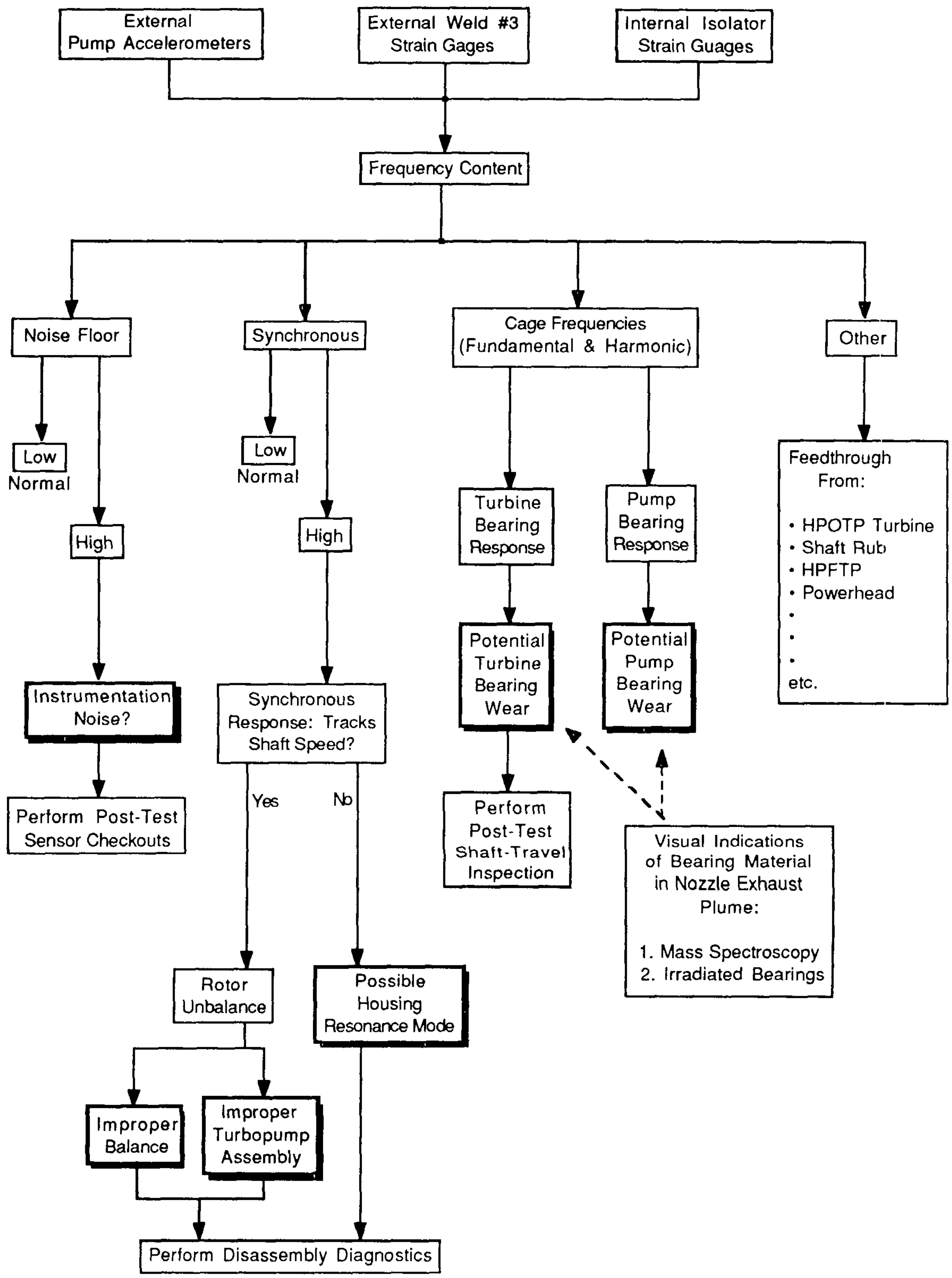
Secondary Turbine Seal Cavity Pressure Outside Expected Range. P91, 92
Check Engine Influences
Pressure Consistent With Shaft Speed ? P2
Yes
No
Pressure Consistent With Turbine D/S Temps? P233,234
Yes
No
Other Failure Modes
Yes
Pressure Within Engine Power Level ? P63
No
Yes
Influenced By Intermediate Seal Flow Perturbations? P937, 1100
Evidence of Erratic Cavity Press.? P91,92
Yes
No
Secondary Seal Press. Consistent With Primary Seal Press. ? P990
Yes
No
No
Perform Post-Test Secondary Seal Leak Check
Secondary Cavity Pressure High or Low?. P91,92
High
Low
Compare To Assembly Leak Checks
Compare Seal Clearance At Assembly With Normal Values
Compare Seal Clearance At Assembly With Normal Values
No Change
Higher
High
Low
Low
High
No Appreciable Wear
Turbopump Assembled With Large Shaft/Seal Clearance
Potential Blockage At Secondary Seal Drain Line Downstream Of Pressure Sensor
Turbopump Assembled With Tight Shaft/Seal Clearance
Potential Blockage Upstream Of, Or At Secondary Seal
Probable Seal Wear
Confirm With Post-Test Leak Check
Confirm With Post-Test Leak Check


Intermediate Seal Purge Pressure Outside Expected Range P211, 212
Normalize to Constant Interface Conditions P937, 1100
Normalized Purge Pressure Consistant With Time Domain ?
Yes
End Search
Check Seal Clearance At Assembly
Check Seal Leakage Test At Assembly
Check Seal Clearance At Assembly
Check Seal Leakage Test At Assembly
Check Turbine Exhaust Temperature P233,234
Check Turbine Exhaust Temperature P233,234
Low/Normal
Low/Normal
High/Normal
High/Normal
High
High
Low
Low
Normal/High
Low
High
Low/Normal
Turbopump Assembled With Large Intermediate Seal Clearance
Probable Intermediate Seal Wear
Large Clearance From Low Shaft Thermal Expansion
Tight Clearance From High Shaft Thermal Expansion
Probable Intermediate Seal Blockage
Turbopump Assembled With Tight Intermediate Seal Clearance


Primary Oxidizer Seal Drain Pressure Outside Normal Range P951,952,953
Check Engine Influences
Drain Pressure Consistent With Shaft Speed? P2
Yes
No
Other Failure Modes
Drain Pressure Consistent With Intermediate Seal Flow? P937, 1100
Yes
No
Any Evidence Of Erratic Drain Pressure ? P951, 952, 953
Yes
No
Perform Post-Test Leak Check
Compare To Assembly Leak Checks
No Change
No Appreciable Wear
Higher
Probable Seal Wear
Drain Pressure High or Low?
High
Low
Consistent With Low Seal Drain Temp ? P1187
Consistent With High Seal Drain Temp ? P1187
Yes
No
No
Yes
Compare Seal Clearance at Assembly With Normal Values
Data Inconsistent Other Failure ???
Compare Seal Clearance at Assembly With Normal Values
High
Low
Low
High
Turbopump Assembled With Large Seal Clearance
Potential Blockage At Drain Line D/S Of Press. Sensor
Turbopump Assembled With Tight Seal Clearance
Potential Blockage At Or Upstream Of Oxidizer Seal
Confirm By Post-Test Leak Checks
Confirm By Post-Test Leak Checks

mode 6


Shaft Speed Outside Of Normal Range P2
Check Engine Influences
Speed Consistent With Propellant Mixture Ratio? P2176
No
Yes
Other Failure Modes
Yes
Yes
Speed Consistent With Engine Power Level? P63
No
Speed Consistent With Engine Oxidizer System Resistance? P334,90,190
No
Suspect Anomally In Pump Section
Inherent High Head Performance (Low Pump Speed)
High Coeff
Compare Head Vs Flow Coefficients
Low Coeff.
Compare Head Loss For Given Suction Specific Speed
Normal
Possible Assembly Error Resulting In High Balance Piston Recirculation Flow
No
Suspect Cavitation Erosion To Impeller Or Turning Valves
Yes
Disassembly Confirmation
No
Inherent Low Head Performance (High Speed Pump)
Perform Post-Test Visual Inspections
Impeller or Turning Vane Erosion
Assembly Error


External Pump Accelerometers
External Weld #3 Strain Gages
Internal Isolator Strain Guages
Frequency Content
Noise Floor
Synchronous
Cage Frequencies (Fundamental & Harmonic)
Other
Low
Normal
High
Low
Normal
High
Turbine Bearing Response
Pump Bearing Response
Feedthrough From:
• HPOTP Turbine
• Shaft Rub
• HPFTP
• Powerhead
etc.
Potential Turbine Bearing Wear
Potential Pump Bearing Wear
Instrumentation Noise?
Synchronous Response: Tracks Shaft Speed?
Yes
No
Perform Post-Test Sensor Checkouts
Perform Post-Test Shaft-Travel Inspection
Visual Indications of Bearing Material in Nozzle Exhaust Plume:
1. Mass Spectroscopy
2. Irradiated Bearings
Rotor Unbalance
Possible Housing Resonance Mode
Improper Balance
Improper Turbopump Assembly
Perform Disassembly Diagnostics

Appendix D

I. Introduction

Any diagnostic expert system that relies on data obtained from physical sensors must take measures to ensure that the sensors themselves are functioning correctly and providing valid data. A number of techniques are available for the detection of both large (out-of-range or large bias) and soft (small bias or drift) errors in the HPOTP sensor instrumentation.

II. Hard Failures

Hard failures are naturally the easiest to detect. The simplest method assumes that each sensor has a plausible range of operation bounded by a minimum output value (r_{min}) and a maximum output value (r_{max}). If the sensor output becomes lower than r_{min} then it has probably failed by going "open." If the sensor output becomes greater than r_{max} then the sensor has probably "shorted." In either case the failure is easily detected by examination of the sensor output, either visually or by computer analysis.

Both pretest and postest calibration checks are currently done to detect hard failures. This test applies a known quantity of a sensed variable (e.g., pressure, temperature, torque) to a sensor of the appropriate type. The output voltage of the sensor is then compared to a nominal curve of sensor output voltage versus the sensed variable. If the tested output voltage is off the curve by more than a given maximum tolerance then the sensor is malfunctioning. If the data from these tests is recorded and available then a computer program can easily detect such failures.

For redundant sensor information, consisting of output from three or more identical sensors (e.g., boost pump discharge pressure is measured by four identical sensor channels), voting can be used to detect hard failures and in some cases soft failures. The standard voting procedure detects a marked deviation in one (or a minority) of the three (or more) signals by assuming that the output from the majority of sensors is correct. Another method of combining redundant sensors is "auctioneering" which simply ignores the lowest or highest sensor output[1]. Again these methods are easily implementable in a computer algorithm. For example the following algorithm will detect and throw out a minority of redundant sensor readings that violate the range bounded by r_{min} and r_{max}:

Given:

r_{min}, r_{max} : as explained above.

n : total number of redundant sensor channels.

1. For each sensor channel S_i ($i = 1$ to n), if $S_i >= r_{min}$ AND $S_i <= r_{max}$ then mark S_i as GOOD.

2. Calculate T_g = Total number of GOOD S_i's.

3. If $T_g >= n$ DIV 2 + 1 then proceed to step 4 (DIV returns an integer quotient), otherwise the sensor value is undetermined.

4. Combine the GOOD S_i's into a single composite value S_c (e.g., take some measure of central tendency such as mean or median).

III. Soft Failures

More subtle sensor malfunctions are also algorithmically detectable. These are characterized by small bias errors or drift errors that increase relatively slowly with time. The following examples will illustrate this type of failure.

One of the existing HPOTP sensor types measures boost pump discharge pressure. Nominal output for this type of sensor during engine firing is depicted in figure 1. Figure 2 depicts output that drifts away from a steady norm, becoming more marked with time. Past experience indicates that this kind of output is caused by sensor malfunction rather than by actual behavior of the turbopump. This malfunction can be detected using the following simple algorithm:

Given:

ΔP_{max} : maximum allowable drift in average pressure.

t_1, t_2, t_3, t_4 : time points such that t_1 to t_2 establishes initial average pressure and t_3 to t_4 establishes final average pressure.

1. Calculate initial average pressure

$$\bar{P}_{init} = \frac{\sum_{i=t_1}^{t_2} P_i}{t_2 - t_1 + 1}$$

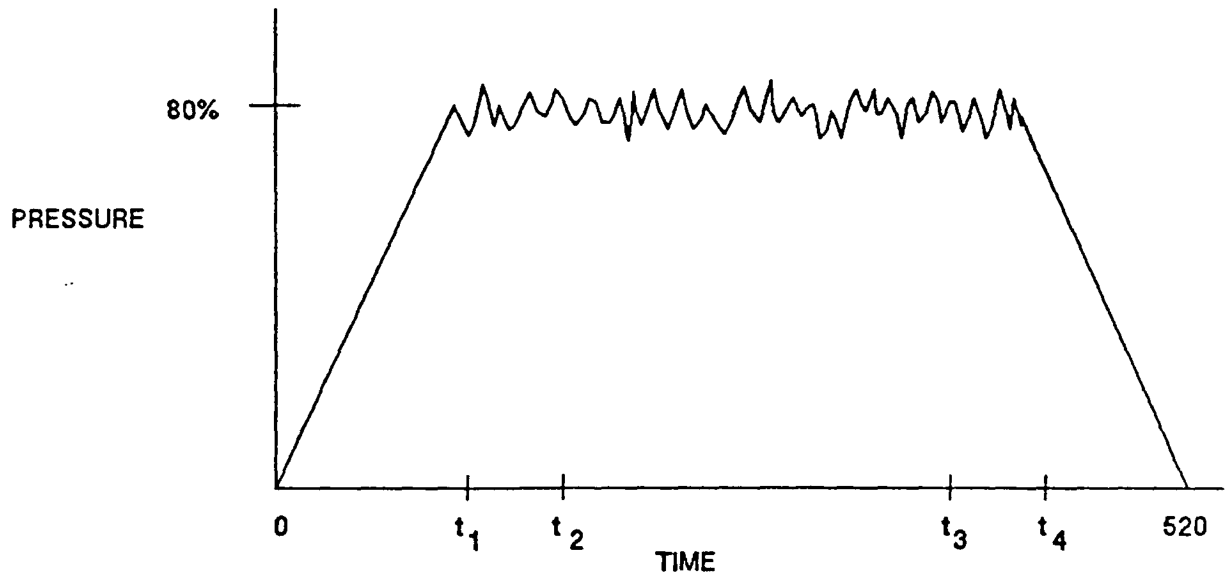


Figure 1 – Nominal Pressure Sensor Output

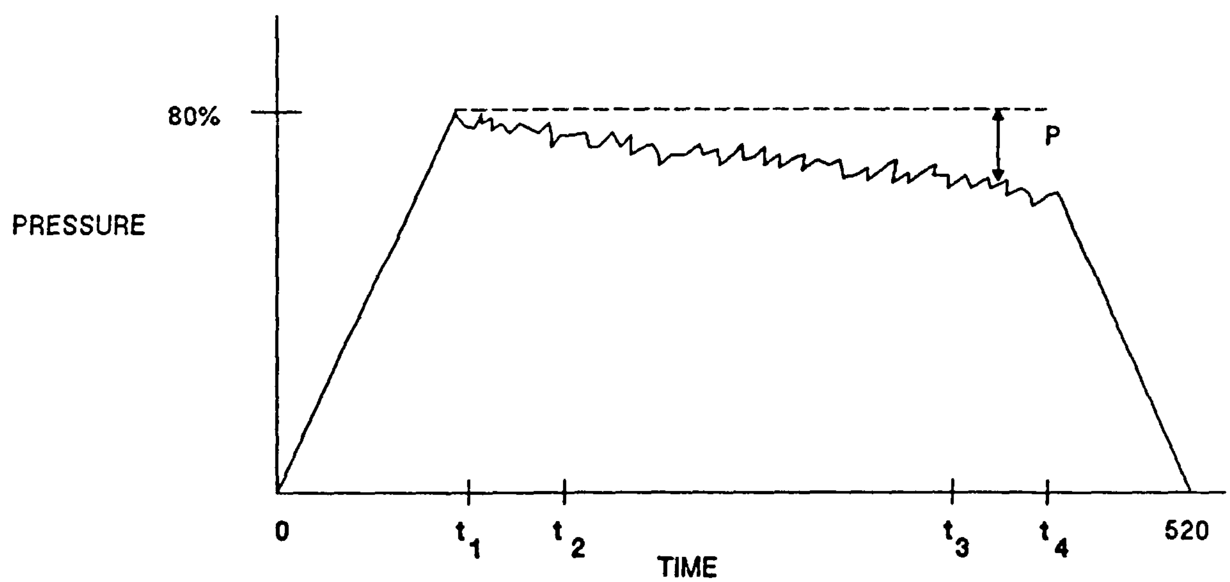


Figure 2 – Malfunctioned Pressure Sensor Output

2. Calculate final average pressure

$$\overline{P}_{final} = \frac{\sum_{i=t_3}^{t_4} P_i}{t_4 - t_3 + 1}$$

3. Calculate change in average pressure

$$\Delta P = abs(P_{final} - P_{init})$$

4. If $\Delta P > \Delta P_{max}$ then the sensor has malfunctioned, otherwise assume the sensor is correct.

The input to this algorithm is assumed to be digital in form with a high enough sampling rate to be representative of the original analog pressure reading.

Another example of soft failure detection is illustrated by the torquemeter, a proposed future sensor for the HPOTP. Again we compare nominal sensor output to anomalous output that is known to indicate sensor malfunction. Figure 3 depicts nominal AC voltage output from a torquemeter and figure 4 depicts output from a malfunctioning torquemeter. The waveform in figure 2 is missing the "B" peaks present in the nominal waveform. This difference can be detected by the following algorithm:

1. Determine initial baseline voltage V_b.

2. Determine t_A = time of occurrence of the first peak greater than V_b (an "A" peak).

3. Determine t_B = time of occurrence of the next peak after t_A greater than V_b (the "B" peak in a nominal wave).

4. Calculate $T_{AB} = t_B - t_A$.

5. Determine t_1 = time of occurrence of a peak less than V_b (a "negative" peak).

6. Determine t_2 = time of occurrence of the next peak after t_1 which is less than V_b.

7. Calculate period $P = t_2 - t_1$.

8. If $T_{AB} \approx P$ then the sensor has malfunctioned (i.e., the "B" peaks are missing so the time between successive positive peaks is close to the period length), otherwise assume the sensor is correct.

Again the input is assumed to be digital with a high enough sampling rate to capture the significant peaks in the data.

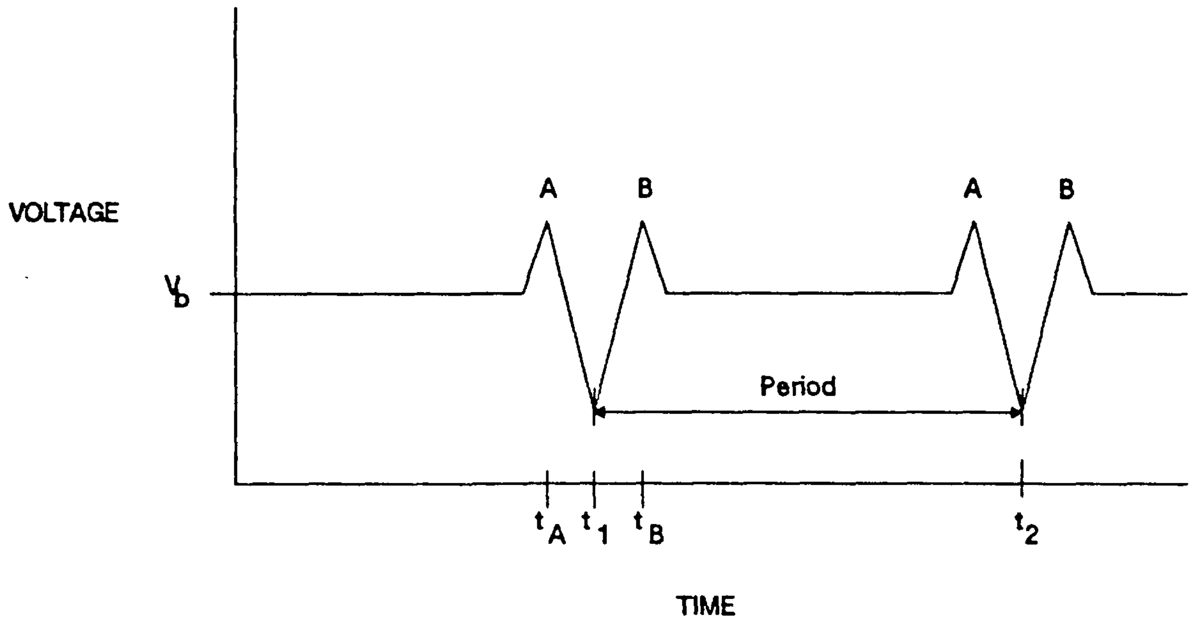


Figure 3 – Nominal Torquemeter Output

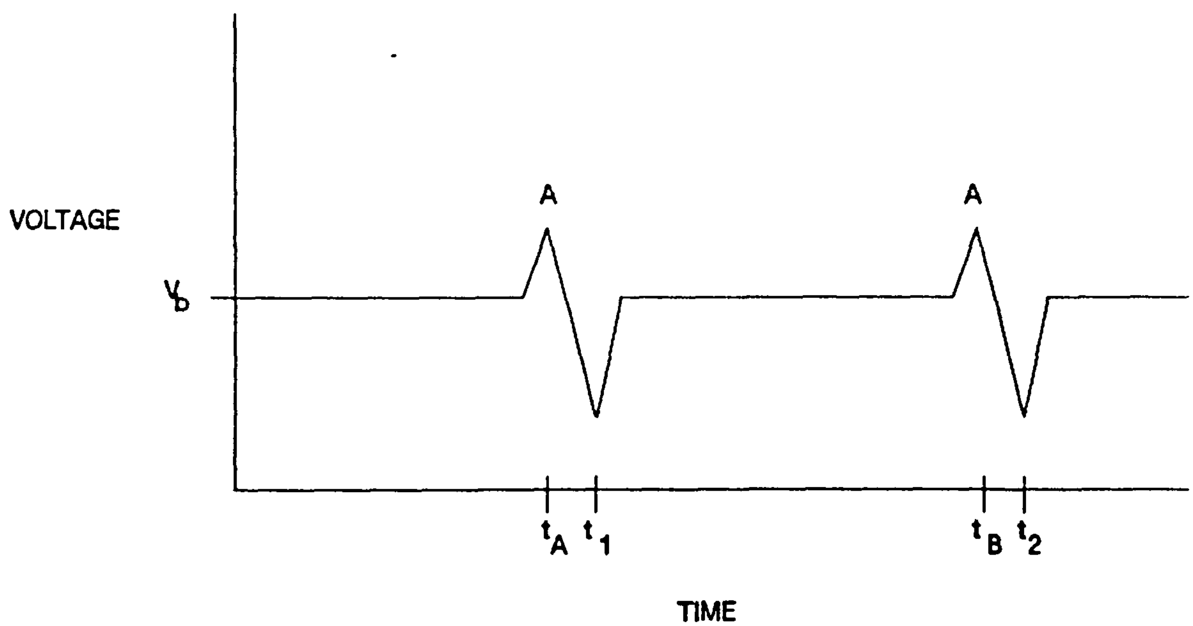


Figure 4 – Malfunctioned Torquemeter Output

These methods demonstrate the ability to detect common types of soft sensor failures through the use of simple algorithms. Many soft failures in other types of sensors can be detected using this kind of approach.

IV. An Advanced Failure Detection Method

An alternative approach to failed sensor detection relies on the idea of "diagnostic expectations"[2]. An expert in the field of turbopump diagnosis has certain expectations about the characteristics of a final answer. These expectations provide a basis for judging the validity of the derived answer. For example consider the following values for some of the HPOTP sensors:

Variable	Status
Boost Pump Discharge Pressure	Low
Boost Pump Discharge Temperature	High
Turbine Discharge Temperature	High
Shaft Speed	Normal

Here the boost pump discharge pressure and temperature are immediately suspect since temperature and pressure are normally proportional to each other and not inversely related. We surmise that one of the two sensors may be malfunctioning, but which one? On further examination we find that the turbine discharge temperature is abnormally high and the shaft speed (as measured by torquemeter) is normal. An expert might conclude that the boost pump pressure reading is probably incorrect since the high turbine temperature corroborates the high boost pump temperature and the shaft speed does not contradict this conclusion since it is not abnormally low.

A particular turbopump condition can be inferred from a certain pattern of sensor readings. In this case the sensor pattern does not fit any plausible turbopump condition, and corroboration and correlation between sensor values reveals that the boost pump pressure value is probably incorrect, meaning that the pressure sensor has failed.

The partial decision tree in figure 5 captures this line of reasoning. This kind of decision tree can be easily implemented in Prolog or in one of the expert system shell languages.

Uncertain reasoning can be incorporated by associating a certainty factor or weighting factor with each branch of the tree. Of course this is a simple and incomplete example, but it illustrates the method of expectation-based sensor validation. No doubt there are many such correlated sensor patterns among the current and proposed HPOTP instrumentation and these will be revealed by further interviews with sensor experts. This method can be used by itself to detect sensor failure, or to verify

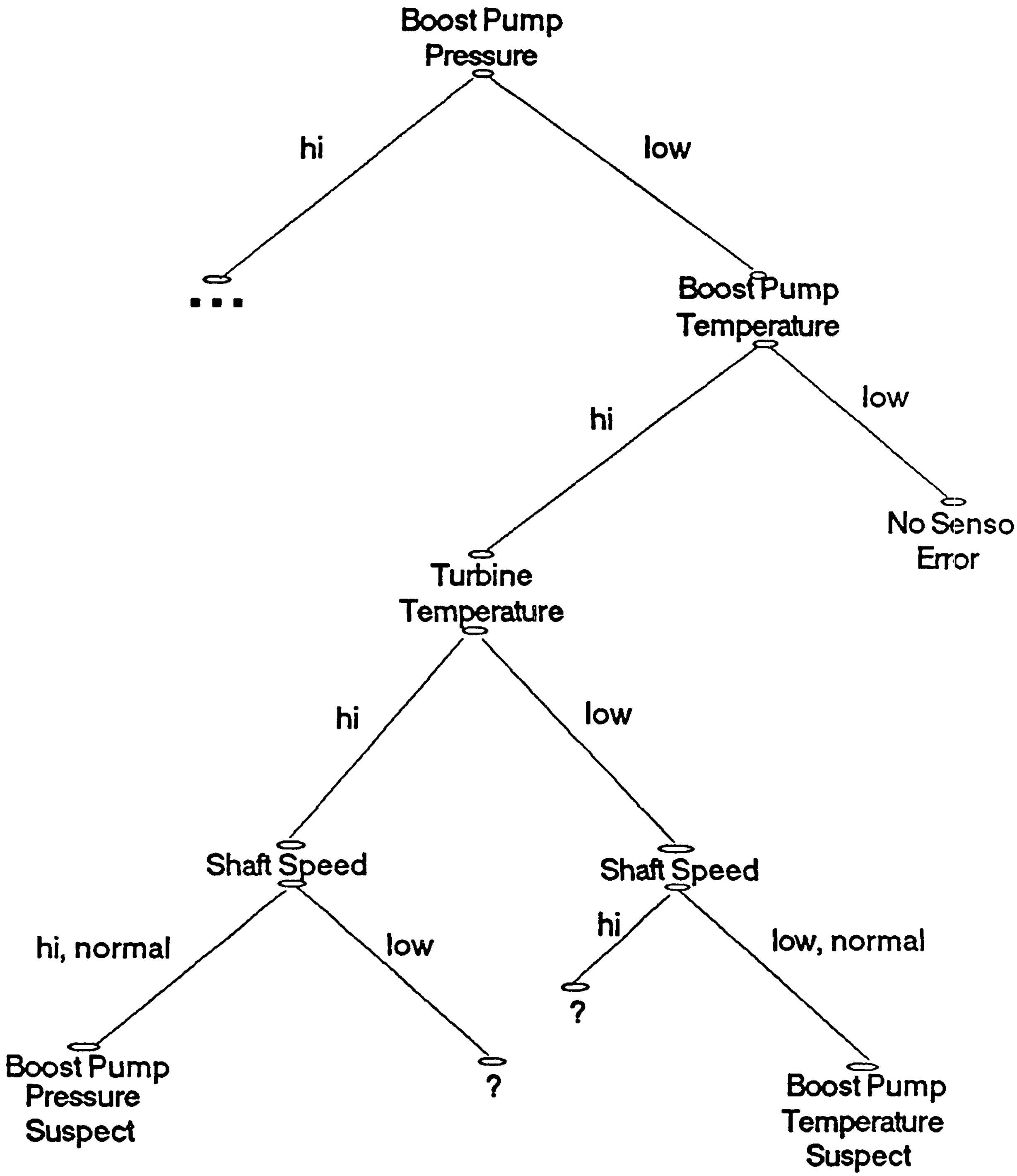


Figure 5 — Decision Tree for Sensor Validation

sensor failures that were initially detected using other methods.

V. Conclusion

Many techniques exist for the detection of both hard and soft failures in HPOTP sensors. These methods can be expressed as algorithms and thus are implementable as computer programs or expert systems. Sensor validation for the proposed HPOTP health monitoring system will be accomplished using the following methods:

1. Detection of hard failures using range checks and voting where appropriate.

2. Detection of soft failures where possible using a straightforward algorithmic approach as described in section III.

3. Verification of soft failures detected above by corroboration and correlation with other related sensor values.

4. A general expectation-based examination of sensor values to identify anomalous readings and determine which of these is caused by sensor failure.

Once sensor readings have been validated using these methods, the task of actual HPOTP fault diagnosis can proceed with confidence.

References

1. Fox, M., Lowenfeld, S., and Kleinosky, P., "Techniques for Sensor-Based Diagnosis". Carnegie-Mellon Univ., Pittsburgh PA, Report No. CMU-RI-TR-83-7, May 14, 1983.

2. Chandrasekaran, B., and Punch, W., "Data Validation During Diagnosis, A Step Beyond Traditional Sensor Validation", Expert Systems, Fall 1984.

APPENDIX E

HMS DEVELOPMENT PLAN

Development of the HMS will follow the methodologies and procedures that were used in satisfying Contract NAS3-25279: Reusable Rocket Engine Turbopump Health Monitoring System. The discussion will follow the analysis that was used for the HPOTP, as shown is Figure 1; however, the technologies embodied within approaches presented are directly transferable to any engine component or to the entire engine as a functional unit.

Initial activity in the development of any Health Monitoring System is the identification of the failure mode/sensor system couplets. For the existing SSME HPOTP, these couplets have been defined in great detail and are explicitly given in the above mentioned report. This list will be continuously reviewed to account for any changes in pump or engine design which may have an influence upon the number and type of failure modes that are to be analyzed as well as the number and type of sensors that provide information relative to the engine component. Changes in this category are expected to occur very infrequently and can only be included within the diagnostic system after extensive testing and verification by engineering test and quality assurance. However, recognizing that some changes will occur, the computer system, software diagnostics and prognostics, will be designed and developed such that any changes and/or modifications can be easily incorporated.

In the same manner, it is expected that the data processing and signal conditioning will change very little. Additional processing may be required if new or additional sensors are added to the system. The method by which this data is collected and processed is not part of the HMS; rather, the end product, the magnetic tapes, is of concern in this diagnostic system. The HMS development team can ask that the tape data be in a certain format for easier computer uptake; however, actual data collection and reduction is outside of the scope of this program.

The information provided by existing sensors may prove to be insufficient in helping identify the occurrence of certain failure modes. For such cases, alterations to the sensor complement or to sensor data processing may be specified. These alterations may include relocation of sensors nearer to the physical location of the failure mode, thereby decreasing the localized component configuration effects. An example of this type of effect is pressure drop due to flow through a length of drain manifold. In addition to sensor placement, additional sensors may be prescribed for specific measurements relative to individual failure modes. An example of this would be plume spectroscopy for wear detection. Many failure modes involve either seal wear, bearing wear, or cavitation erosion. Use of detectable compounds and isotopes embedded in key locations of likely wear can give indication of single or multiple failure modes.

Further investigation into the nature of information derivable from high frequency analog measurements (such as accelerometers and strain gages) may also be desirable. For example, it may be possible to identify a particular bearing as undergoing significant wear by specialized phase or amplitude analysis of data from various strain gages or accelerometers.

Figure 2 is a cross-sectional line drawing of the space shuttle main engine high pressure oxidizer turbopump. Surrounding the figure are the names if several HPOTP parameter sensors used for the diagnostic and prognostic functions of the Reusable Rocket Engine HMS (mentioned above). Note that aside from the accelerometers and strain gages (some of which are not present in the pump's flight configuration) and the secondary turbine seal cavity pressure, all the sensors are somewhat removed from the region of their associated failure mode. They are often located up- or down-stream of the pump at its connecting flanges. In fact, one section of the turbopump HMS deep knowledge base performs extrapolation of fluid property values from the physical region of the sensor to nearer the point of interest, such as the actual discharge region of a pump or turbine.

Once the sensor/failure mode couplets have been identified the process of defining the diagnostic and prognostic analysis logic begins. These flow graphs are the sequential logical steps by which the domain experts, eg. HPOTP diagnostic experts, analyze the time history plots of the sensor data to determine if any anomalies are present. For Contract NAS3-25279, seven flow graphs were generated, one for each of the primary failure modes of the turbopump. Each primary mode constitutes a single point, uncoupled failure which would occur during steady state operation. Changes in these graphs would need to be made only when new sensor information becomes available or when the character of the failure modes themselves change. A complete listing of these graphs was delivered to NASA Lewis Research Center during the first program review on 1 December 1988.

A major element within the HMS Development Plan would be the expansion of the logic flow graphs now in existence. There are several prominent areas in which this can occur. These include:

1. multiple failures occurring simultaneously or those generated as a result of another failure, failure mode propagation, both within the turbopump as well as those caused within the pump as a result of a failure within

another component of the engine

2. transient condition analysis, both start and shutdown

3. power level changes, throttling

4. sensor data validation and procedures to reconstruct or provide data when it is missing

5. existing analytical models, deep knowledge.

6. database identification and development

Each of these tasks is formidable by itself and as a group constitute a major development effort. As an example, the transient conditions are poorly understood and require particular attention if they are to be included within an HMS. Therefore, caution must be exercised when establishing the goal for the HMS and the time course for its development. For this reason, a sequential development program is proposed for the HMS. In the first phase, the existing logic flow graphs will be expanded to accommodate power level changes and sensor data validation and reconstruction. Also during this phase information will be gathered and assimilated relative to multi-point failures and failure mode propagation, data base development of historical engine and test data, and existing analytical models that can be used to provide information relative to the failure modes. The data base of assembly , fluid flow test, and statistical data will be accessed as part of the information used by the inference engine while the analytical models will form the deep knowledge base within the expert system. These two knowledge bases will be discussed in more detail later is this report. The second phase of the development plan will be to develop new logic flow graphs, where warranted, that account for multi-point and failure mode propagation. In addition, both the shallow and deep knowledge base will be incorporated into the expert system at this time. Also during this phase, investigation will begin of the transient cases. The third phase of the program will be to finalize all of the logic flow graphs, including those for the transient cases. With this, the logic by which engine anomalous conditions, from engine start to stop, will have been identified and developed.

As shown in the HMS Conceptual design, Figure 1, following the development of the logic flow graphs is algorithm and heuristics development. The distinction between the graphs and the algorithms/heuristics is that numerical and data values as well as all subroutine computer calls are identified in the algorithms while inferential and rule of thumb methodologies constitute the heuristics. Development here will follow the same phase format as defined above.

It is intended in this development plan that any time the program calls for the development of a logic graph or algorithm or analytical model that this will also be incorporated into the expert system to perform relevant diagnostics and prognostics.

For any given phase of the development, once algorithms/heuristics have been identified software implementation begins. Due to the anticipated size of the final HMS for any engine component or entire engine system, the host computer for the HMS must be sufficiently large, in terms of memory and processing capacity. For this reason, the computer chosen will be a work station such as a SUN 4. To facilitate the software development in terms of rule implementation, changes, modification, data entry and access, networking, and natural language structure it will also be beneficial to use an expert system development tool such as ART, KEE, or G2.

As the HMS Conceptual Design shows, Figure 3, the host computer/expert system has a multitude of components and operations. The system must be able to access large data bases, have an extensive inference engine, allow for calls to FORTRAN subroutines, have a user friendly interface, allow for fuzzy logic or reasoning under uncertainty, provide logic trees of its inference strategies, and be maintainable. The FORTRAN subroutine access is necessary since several existing Rocketdyne programs, eg. SCOTTY, SAFD, that can be utilized in this HMS, are coded in FORTRAN. The selection of the system that can best accomplish all of these objectives will be performed during the early portion of phase one. As soon as algorithms/heuristics/rules are developed they will be entered into the expert system. Proper selection of an expert system development tool (shell) will provide an environment that will promote ease in creating the expert diagnostic/prognostic system. In this manner, continuous implementation and testing will take place during all phases of the HMS program.

As can be seen in Figure 3, Oxidizer Turbopump Health Monitoring Expert System Block Diagram, the Conceptual Diagram for the expert system consists of several components. Each of these components is a part of the development plan and will be developed and incorporated during the appropriate phases discussed above. The structure of the expert system itself, the inference engine and knowledge base, is provided by the tool and shell chosen. For this reason it is not necessary to talk about developing the inference engine or knowledge representation format, but rather implementing the knowledge, facts, and rules embodied within the logic flow graphs, algorithms, and heuristics into a software system. Once the particular language of the tool is mastered, it becomes a straight forward procedure to perform the actual coding.

The function of the data base is to provide a store of knowledge about assembly data and historical data relative to a particular engine, test, and/or component. This information is resident within Rocketdyne and is collected for every engine and component that is built. Development of the data base for purposes of this program will be to structure this data into a relational or other relevant format such that it can be accessed by the inference engine on an as needed basis. It is essential that the expert system tool selected be capable of addressing large data structures.

There are several diagnostic tools available at Rocketdyne that may provide relevant information for the Health Monitoring System developed in this program. These include SAFD, SCOTTY, and ADDAMX. All of these tools are written in FORTRAN; therefore, in developing the HMS system, software procedures must be defined and developed that can access these routines when needed. This does not pose a serious development problem since most expert system development tools have a built in capability to address such programs. However, one group of analysis tools that exist at Rocketdyne that will most likely require task specific modification are the analytical models that will form the deep knowledge base within the expert system.

Several of the analytical models that will be considered for inclusion within the deep knowledge base are the power balance model, the aero-thermo model, HPOTP component analytical models, and the life prediction models. These models are now in existence at Rocketdyne and are in use on other programs; however, they have never been coordinated into a unified system. Their function within the knowledge base is to provide a second source of information and verification where there may be gaps in sensor data, to perform diagnostic analysis independent of the expert system thereby allowing for internal validity checks, and to provide the basis from which prognostic analyses are made. It is not the intention of the HMS Development Program to alter or develop these models, in terms of their constituent analysis functions, but rather to modify, if needed, their format such that they can be incorporated into the HMS. Shortfalls in analysis capability relevant to the HMS will be identified and corrective procedures suggested such that the relevant groups within Rocketdyne can begin to make needed changes and/or modifications.

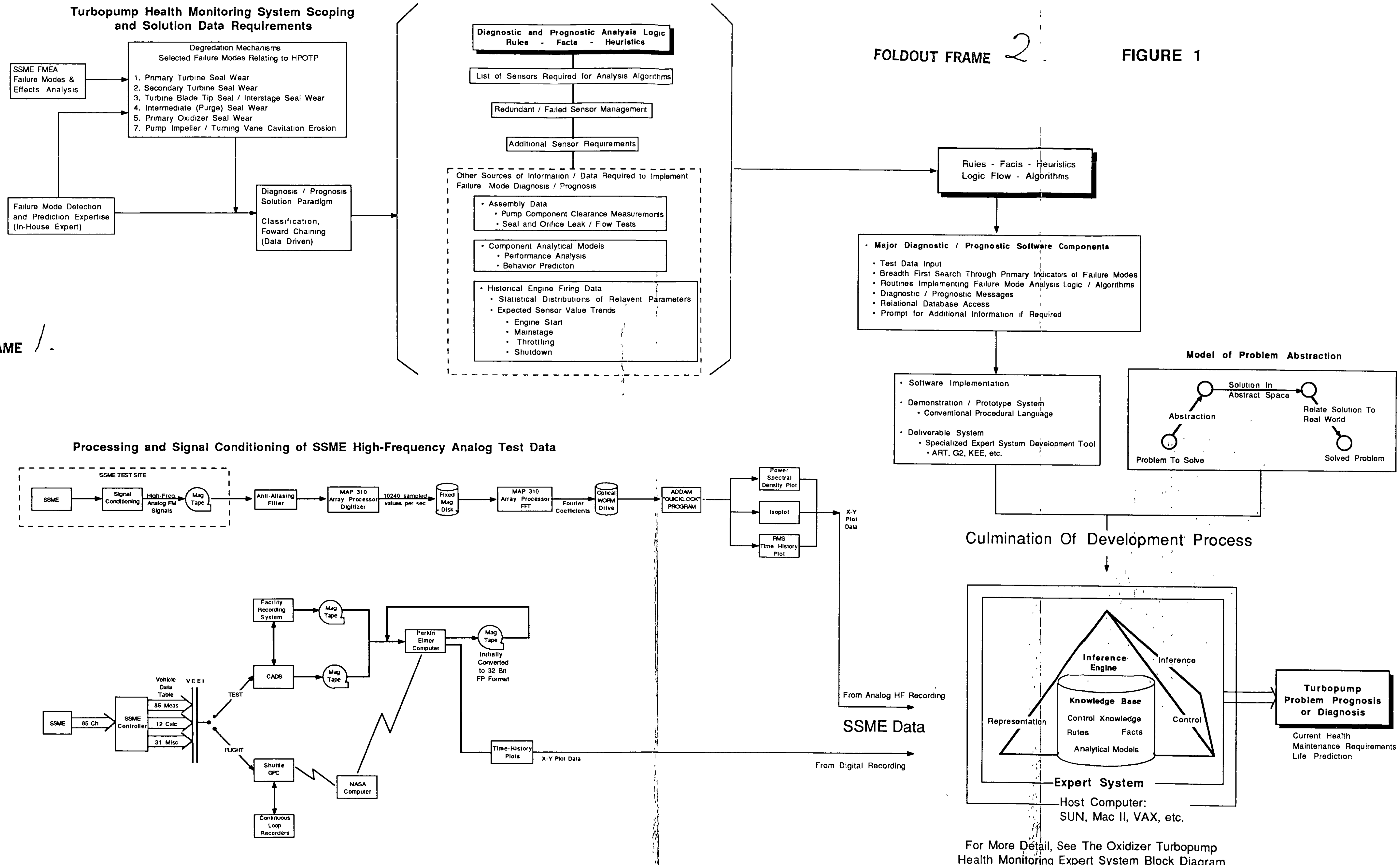
As mentioned above, as each phase of logic flow/algorithm/heuristic development progresses this knowledge is entered into the rule and control structure of the HMS. Since each phase of the HMS development process has a specific output, in terms of diagnostic and prognostic capability, it will also be possible to validate the software code in parallel with this development. The first step in the validation process will be a review of the logic graphs, desk audit, to check for inter- and intra-mode diagnostic consistency. Following this 'hand check', validation will consist of execution of the software with all relevant hot fire engine component data. Test and flight data exists for every engine and component developed under the SSME program. By methodically running this data through the program and verifying the computer output by domain experts a major step in the validation will have been accomplished. Inconsistencies will be corrected and the development will then proceed. Software validation will be an ongoing process through all phases of the program. With final Rocketdyne certification of the software, the HMS system will be demonstrated at NASA Lewis. Upon acceptance, the system will then be delivered to the Research Center. It is the intention of this development program that Rocketdyne help NASA maintain the system by incorporating any modifications or changes resulting from new capabilities and/or engine changes.

SUMMARY

An HMS conceptual design and development plan has been presented which will provide a complete HPOTP, or total engine, between flight, diagnostic and prognostic expert system. Development will follow a sequential approach whereby at each successive level of development greater analysis capability and sophistication is added to the system. The final expert system will have both a shallow and deep knowledge base, access existing diagnostic programs as needed, be capable of maintaining and addressing large databases of information, provide a user friendly interface, and be easily maintainable. Upon completion of the development process, the entire system will be delivered to the NASA Lewis Research Center.

FOLDOUT FRAME 2

FIGURE 1



FOLDOUT FRAME 1.

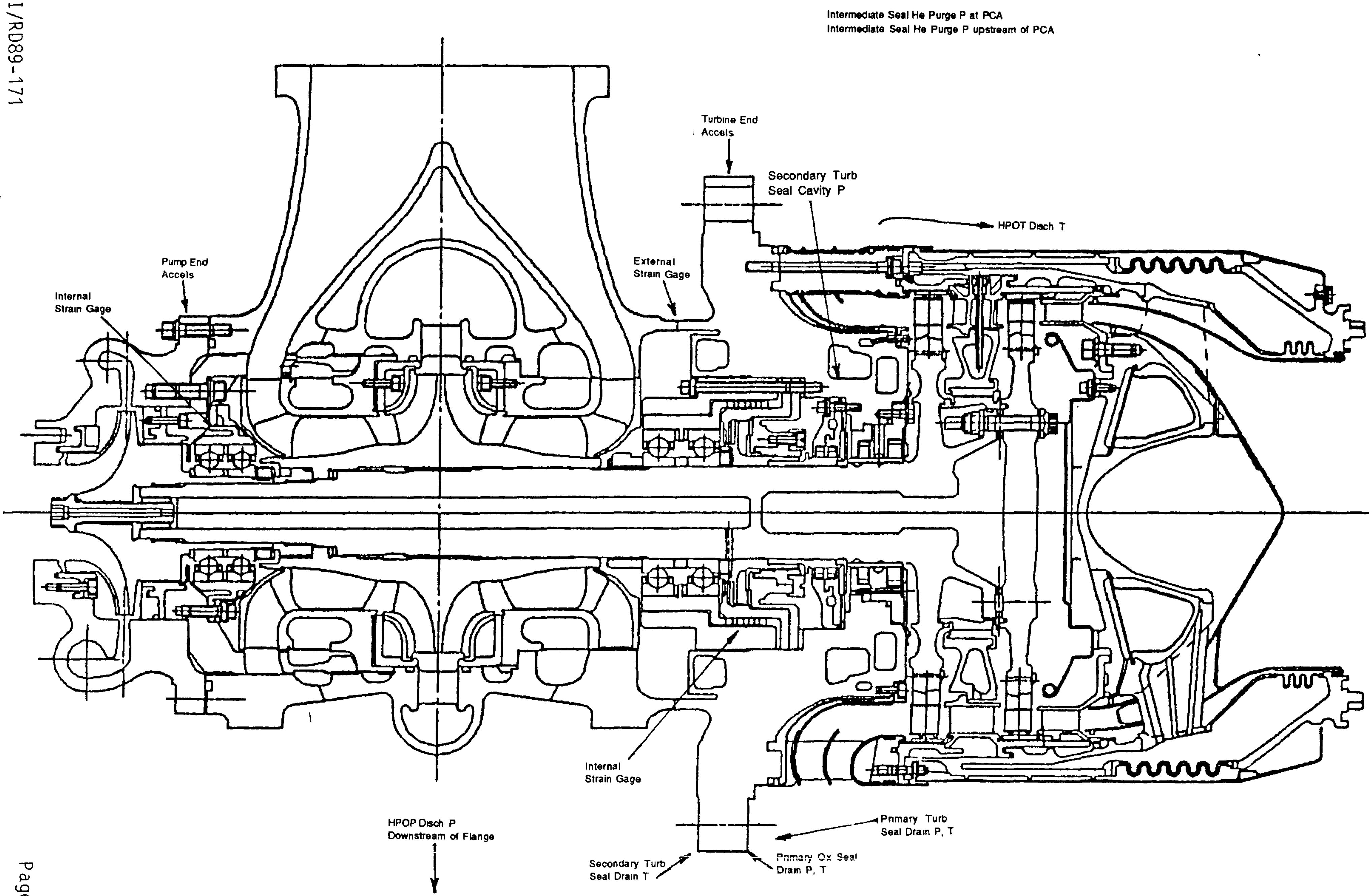

Intermediate Seal He Purge P at PCA
Intermediate Seal He Purge P upstream of PCA
Turbine End Accels
Secondary Turb Seal Cavity P
HPOT Disch T
Pump End Accels
External Strain Gage
Internal Strain Gage
Internal Strain Gage
HPOP Disch P Downstream of Flange
Primary Turb Seal Drain P, T
Secondary Turb Seal Drain T
Primary Ox Seal Drain P, T

FIGURE 2

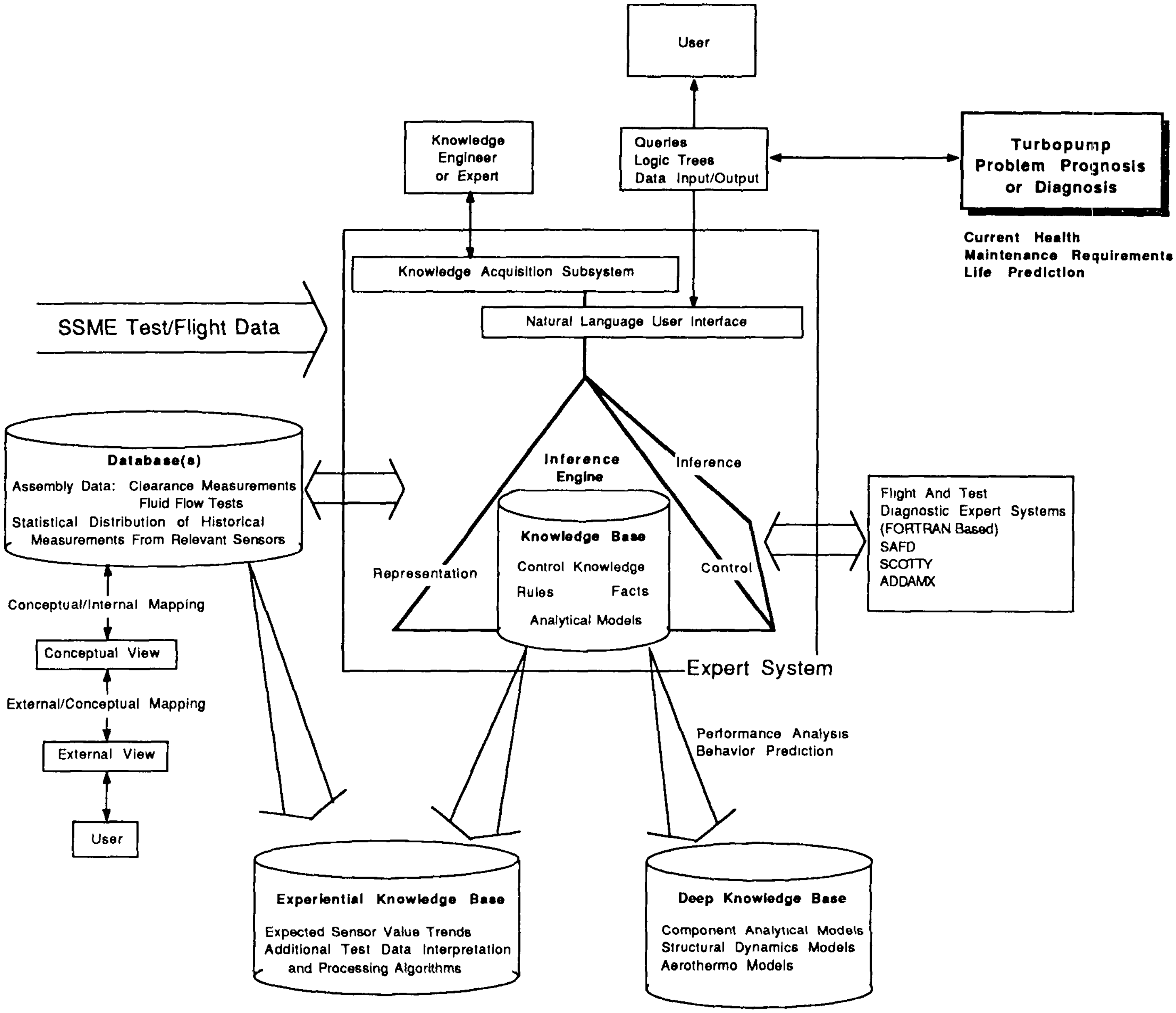


FIGURE 3
Oxidizer Turbopump Health Monitoring Expert System Block Diagram