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Paper Session I-C - Propulsion Advisory Tool

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1.0 ABSTRACT

The data recording, display, and playback capabilities currently available for propulsion system engineers in the launch control room at the Kennedy Space Center lack the fidelity required to perform complex real time data analysis associated with Orbiter main propulsion system health management and anomaly resolution. During the hydrogen leak investigations (summer and fall of '90) on Space Shuttles Columbia and Atlantis, the deficiencies of the system became obvious. The troubleshooting team was hampered in drawing conclusions because they couldn't perform real-time data analysis and by the cumbersome time consuming procedures required to do specific comparisons of present data with past data.

The Propulsion Advisory Tool (PAT) was created to fill this need. It is a joint software development project at the Kennedy Space Center between NASA, Lockheed Sanders, Lockheed Space Operations Company, Rockwell International Launch Support Services, and Rockwell International Aerospace Simulations and Systems Test Center. For clarity herein, Lockheed companies will be referred to as "Lockheed" and all Rockwell divisions will be referred to as "Rockwell." PAT provides propulsion engineers with a monitor and record only (no command capability) sub-system to augment the existing capabilities for monitoring the shuttle cryogenic propellant loading system in the launch control room. The propellant loading system is comprised of the ground storage facility, shuttle Main Propulsion System (MPS), Space Shuttle Main Engines (SSME), and the External Tank (ET). The data supplied to the engineers is displayed in an easy to understand graphic format that can be stored for future reference. These capabilities are coupled with the Rockwell designed Knowledge Based Reasoning Tool (Expert System) for early detection and resolution of anomalies and potentially anomalous trends.

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2.0 WHY CREATE PAT

For some time, a subsystem to enhance vehicle health management and anomaly resolution for the Space Shuttle's Main Propulsion System (MPS) at the Kennedy Space Center has been needed. The data recording display and playback capabilities currently available lack the fidelity required to perform the complex real time data analysis associated with Orbiter MPS health management and anomaly resolution. This lack of fidelity in the current launch control room equipment is partly due to the age of the equipment, but is also due to a lack of flexibility in the software and hardware configuration. This stems from the strict configuration control required for the launch control room's Command, Control, and Monitor Subsystem (CCMS).

To perform the data analysis during the hydrogen leak investigations, teams of engineers at each space center scotch-taped yards of strip chart data to walls in an attempt to understand what was happening as the liquid hydrogen (LH2) system was fueled. The inability to perform real-time data analysis coupled with the cumbersome time consuming procedures required to perform specific comparisons of present data with past data hampered the troubleshooting team in drawing conclusions.

The current Space Shuttle loading software is written in the Ground Operations Aerospace Language (GOAL) which was developed in the mid 1970's specifically for use in controlling shuttle ground checkout and launch. The language was ideal because hardware system engineers also served as programmers. GOAL, however, is a simple language and not well suited to perform complex analysis routines. It cannot adequately meet today's need for expert systems. Today, most engineers are well trained (at the university level) in using software for analysis and advances in UNIX based systems are providing the mechanisms to apply real-time expert systems.

3.0 PAT OBJECTIVES

Under the direction of the National Aeronautics and Space Administration at the Kennedy Space Center (KSC), a team was formed to develop a UNIX based computer system that would go beyond the current methods of shuttle main propulsion system analysis. To this end, Rockwell International Space Systems Division, Lockheed Space Operations Company, and Lockheed Sanders are building such a tool. The scope of the PAT project spans the entire shuttle propulsion loading system from the ground facility, shuttle Orbiter, ET, to the main engines. Three media will be covered: hydrogen, oxygen, and helium. Presently the tool excludes analysis of the solid rocket boosters and the orbital maneuvering system (OMS).

3.1 OBJECTIVES FOR 1993

NASA funding for the project began in June, 1993. The primary focus for that year was the LO₂ loading subsystem. Rockwell has completed an anti-geyser knowledge base and a basic LO₂ loading system model. Lockheed has completed the data handling, graphics package, and user displays for the LO₂ portion of the MPS, ET, SSME, and facility. Previous Lockheed work on the hydrogen and helium subsystems was also incorporated into PAT. This PAT prototype is now on line and supporting the Space Transportation System (STS) during propellant loading.

Although work by both companies has been proceeding separately, merging the two products onto one SPARC 10 SUN workstation has been the end goal from the beginning. Integration will take place at a future time.

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The work of Rockwell and Lockheed has been developed as stand-alone products, but interface requirements were established at the onset of the FY93 project. The RI and LSOC products will be fully integrated and loaded onto a single SPARC 10 SUN workstation during future efforts.

3.2 OBJECTIVES FOR 1994

The project will continue into FY 1994. The Rockwell knowledge base software will be integrated with the Lockheed developed software and mounted on a common computer. MPS valve electrical functionality will be added to the knowledge base. Under development is a neural net model of the Orbiter LO₂ flowpath in order to determine fluid conditions in non instrumented areas. On the Lockheed side, the SSME's basic diagram will be incorporated into the system and debugging will be done.

4.0 TECHNICAL DESCRIPTION AND CAPABILITIES

The PAT capabilities can be divided into three distinct areas - user interface, data handling, and knowledge base. To the observer, the user interface and data handling are the most visible portions of the PAT. They provide data storage, graphics packages, and system schematics.

The knowledge base reasoning tool is designed to operate in the background, constantly monitoring system performance for anomalous trends or hardware failures. Capabilities are also being developed for system electrical analysis at the direction of the user.

4.1 USER INTERFACE AND DATA HANDLING

PAT substantially increases the amount of data available to the engineer for real time or historical comparison, while decreasing the amount of time required to access and use that data. This accomplishment is made possible since it is a separate, monitor only system. As mentioned before, this very unique feature is also its major advantage - it gives the system its flexibility. Since PAT's hardware and software do not have to be qualified to flight hardware control standards, it is much easier to make changes and upgrades. PAT is very responsive to new requirements as new problems arise. Also, a system that isn't responsible for command and control can devote a greater percent of its hardware and software hierarchy to fast efficient operation, rather than many levels of rote redundancy with guaranteed operation and failure modes. Thus, PAT performs very complex functions in a reasonable amount of time.

PAT puts the most pertinent data available at the engineer's fingertips. Approximately 14,000 discrete and analog sensor measurements are recorded on hard disk during a typical load. Data can be rapidly manipulated, compressed and assembled into higher order information that inherently enhances the relationship of the different pieces of information. This provides the potential to allow a full understanding of the more complex problems in the absolute shortest amount of time. It also allows the subsystem engineer to assemble the clearest management presentation of the cause and effect of an anomaly. This is very important to systems engineering as many of the decisions are made under very critical time constraints.

Many different tools have been developed to simplify data evaluation. Some of the most valuable are real-time plotting (also known as real-time strip charts) capability, redline exceedence prediction using curve fitting techniques, and graphics enhancement. Real-time plotting capability is essential to be able to graphically monitor numerous measurements in real-time. PAT has the capability to monitor several measurements at once in graphic form plotted against advancing countdown time (CDT) and Greenwich Mean Time (GMT). This allows a mixture of pressures and temperatures (analog) and valve position indicator's (discretes) to be

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viewed simultaneously in real-time. However, the heart of PAT's graphic capabilities are the LO₂ and LH₂ system schematics. An example of the LH₂ schematic is shown in Figure one.

Many times after a measurement trend has been established it is critical to know when that trend will result in a particular limit being exceeded. PAT is developing the capability to predict limit redline exceedance for any measurement. This is accomplished by plotting available data for a measurement, selecting the applicable curve fit option, and entering the redline value. The cursor is then dragged over the pertinent data, PAT calculates the slope, extends the curve into the future, and displays the time remaining until the limit is exceeded. When run in conjunction with the real-time plotting capability, the "time to exceedance" will be automatically adjusted as the new data becomes available.

From the very start of the project, basic graphing techniques have proven very useful. Thus it comes as no surprise that as the project has matured, several enhancements have been added to PAT. Split graphs were added to allow easy comparison of extremely active data. The capability to enlarge a plot to full screen size was added. This allows maximum on screen resolution of plotted data and maximizes the hard copy plot area. A third addition, the ability to select different colors for measurement plots allows continuity to be easily maintained between various hard copies and also makes the plots easier to read. Another aid to simplify plot analysis are labels. They may be attached to lines on graphs to allow easy highlight of key points as well as identifying curves for black and white (standard copier) reproduction. A mark may be set on a graph to measure the delta value and delta time between that mark and any cursor position. This enhancement is valuable when identifying a measurement rate of change versus a significant event, or when comparing historical data.

4.2 KNOWLEDGE BASE REASONING TOOL

The development and implementation of the PAT knowledge base applies a hybrid artificial intelligence approach, utilizing commercial off the shelf (COTS) tools. The knowledge base takes advantage of three types of technologies, consisting of rule based, model based and neural networks. The primary software tool is Gensym's G2 expert system tool. NASA NETS was also used for the neural network implementation. "C" code was developed to link the knowledge base modules as well as other modules like data acquisition and the user interface. Database hooks are built into the code to allow access to many specific databases. The heuristic knowledge in which the knowledge base is formulated was primarily generated from the expertise of Rockwell, NASA, and LSOC MPS engineers.

4.2.1 METHODOLOGY

A hybrid Artificial Intelligence approach to this problem was taken because of the complexity and diversity of the actual MPS system that was being represented. Selection of this technology was based on the type of knowledge to be represented and actual functionality of the MPS. The expert system G2 by Gensym was used for the rule and model base development.

Rule based technology consists of approximately seventy percent of the heuristic knowledge in the system. The rule base focuses on limit checking, diagnosis formulation, control of the hybrid knowledge base, I/O to other functional modules (data acquisition, user interface). It also allows for user interrogation and easy maintenance.

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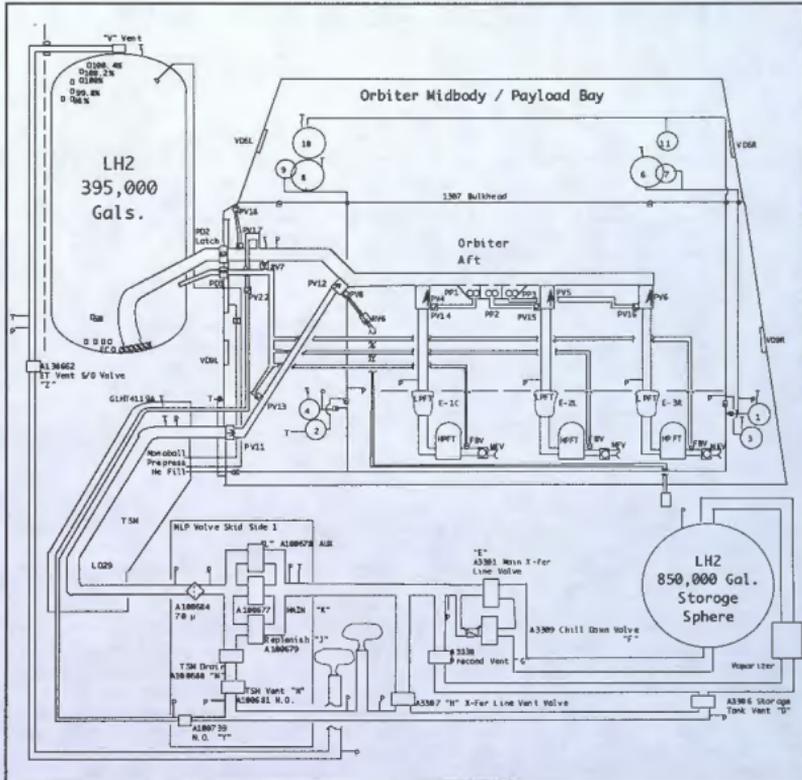


Figure 1 LH2 System Schematic

The rule base is designed to be hierarchical in nature and breaks the knowledge (represented as rules) into rule groups. These rule groups coincide with related areas of knowledge for the MPS. The current anti-geyser PAT rule groups include: LO₂ Quality, Configuration, Valve Positions, Overboard Bleed Valve Rules, TSM Engine Bleed, Preburner Temperature, and Phase Control. The overall architecture of PAT allows for expansion beyond LO₂ anti-geyser in a similar fashion, utilizing rule groups and hierarchical rule firing structures. Reference Figure 2.

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a rule	
Options	invocable via backward chaining, invocable via forward chaining, may cause data seeking, may cause forward chaining
Notes	OK
Names	none
Tracing and breakpoints	default
if pv19_op_ind = 0 and pv19_ci_ind_a = 0 and pv19_ci_ind_b = 0 and tsm_eng_bld_press < 15.0 and tem_eng_bld_press > 5.0 and tsm-pressure-status is not-changing and pv19-mess-reported is false then inform system that "[gmtime(gmt)] PV19 Problem 6A) The ball valve is most likely fully open with the open ind. failed off OFF and both the closed ind. working correctly&red" and conclude that pv19-mess-reported is true	
Scan interval	none
Focal classes	none
Focal objects	none
Categories	pv19_questionable
Rule priority	6
Depth first backward chaining precedence	1
Timeout for rule completion	use default

Figure 2 A Rule Table with Sample Rule

The PAT rule base is designed to respond in near real time (less than one second) to any anomaly it may detect. To accomplish this goal a top level rule group is used to monitor critical parameters while the more detailed rules that deal with a specific problem are deactivated until they are needed. This type of top level rule firing scheme allows the rule base to function with very little overhead until a problem arises.

The model base technology is focused on the flow path and the physical connectivity of the MPS LO₂ plumbing. The MPS is comprised of valves, sensors, pipes, etc. forming a very complex plumbing system. At any single time this system can be in one of many configurations. Hazardous situations can arise depending on the configuration and phase of the propellant loading system. To represent this type of configuration knowledge, models were built of nominal, off-nominal, and potential problem configurations. These models are used while the system is running to give current configuration status. The models were developed using the functional connectivity features of the G2 expert system. Reference Figure 3.

The Neural Network portion of the hybrid knowledge base was primarily used to predict changes in specific parameters based on their signature recognition. Prediction characterizations are communicated to the rule base and proper action within the rule base is taken based on the prediction validity. This portion of the knowledge base is the least developed of the three technologies used in the overall knowledge base. Expanded work with parameter prediction and also fluid condition interpretation of non instrumented areas is planned for FY '94. The NASA NETS tool was used to develop the preliminary neural network application.

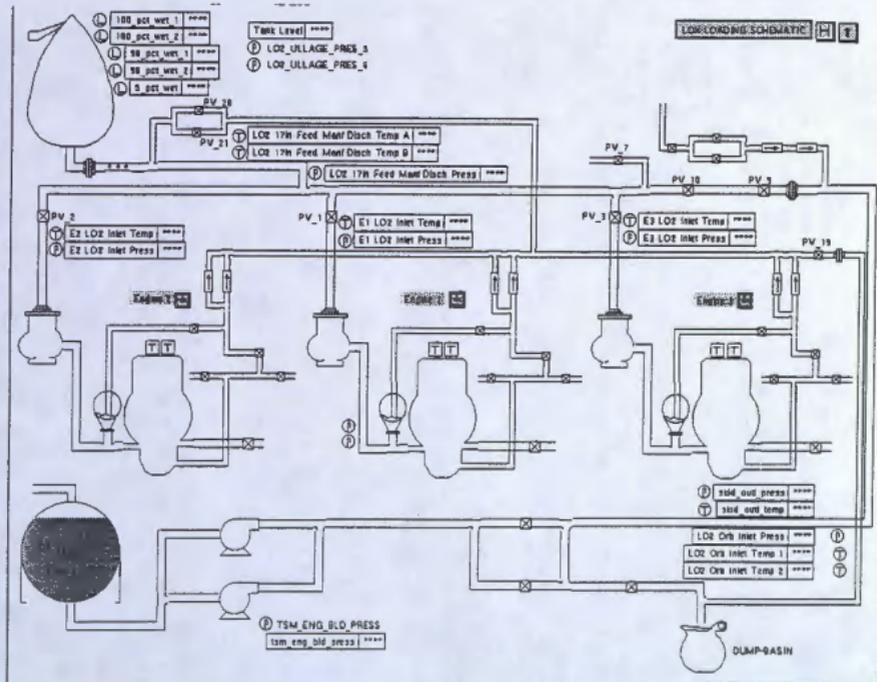


FIGURE 3
FLIGHT ELEMENT MODEL - FUNCTIONAL CONNECTIVITY

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4.2.2 KNOWLEDGE CAPTURE

Knowledge base heuristics were developed through interactive work with MPS experts. Existing MPS documentation was used but the majority of the information was developed from the MPS engineers knowledge. This knowledge was undocumented and stored only in the MPS engineers head. The process of extracting knowledge started with the MPS engineers writing pertinent information down in English and representative flow charts. This information along, with information generated from refinement meetings and demonstrations, was then represented in the knowledge base. The refined PAT knowledge base code was then reviewed before operational testing began. The knowledge base code review was made simpler because of the use of G2, which uses English as the rule base representation language. Through many iterations and reviews this was developed into the current PAT knowledge base.

Actual Space Shuttle flight data is used to test the PAT knowledge base. Much of this data is nominal so error injection capabilities were developed to thoroughly check out the knowledge base. Off nominal cases were developed and the system was tested for all cases the knowledge base was designed to handle. Current testing includes error injection as well as concurrent operational testing during actual Shuttle propellant loading. Through many iterations and reviews this was developed into the current PAT knowledge base.

5.0 PAT HARDWARE

PAT's system hardware consists of a Sun Sparc 10 workstation with 128 Mbytes RAM. It operates at approximately 90 MIPs. Two magnetic hard drives provide a total memory capacity of 3.4 Gbytes. This amount of memory provides enough data storage capacity for comparison of real-time data to multiple previous launches. This allows for real time manipulation of all pertinent data available for historical comparison. Since the data is stored as shared memory, it is available to both the user and knowledge base at the same time with no impact on system performance. Both the user and the expert system can perform analysis of the propellant loading system in a near real time mode.

The original design for data storage called for unlimited storage capacity through the use of optical disk platters, but the optical disks proved unreliable and were dropped from the system.

PAT's color monitor has a resolution of 1280 x 1024. This allows complex data to be presented in detail while not causing operator fatigue. It will also support the addition of on screen operational television (OTV) if the decision is made to add this function to PAT. Digital OTV display and recording capability is currently being developed for the Lockheed Propulsion System Advisor.

The system configuration for output is a Lockheed Calcomp thermal color printer. This provides high quality resolution graphics that allow eight to ten curves to be printed on one chart without losing the context of the data being presented. This is possible due to both the resolution of the printer and its color capabilities. The printer also provides a screen dump. Cost per copy is reasonable and the print time is approximately 45 seconds.

6.0 CONCLUSIONS

Since its inception, the concept of PAT has been widely supported within the propulsion engineering community at the Kennedy Space Center. The project has been under way for nearly a year, with the Fiscal Year 1993 objectives complete. NASA will continue to fund the project through Fiscal Year 1994.

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To sum it up, PAT:

- Provides a common data source that:
 - Displays and records real-time data
 - Produces historical displays for real-time comparison with current loading data
 - Evaluates incoming (or stored) data to provide monitor functions of the following parameters:
 - Gaseous helium leak rate in SCIM
 - Gaseous helium in pounds mass on board
 - Change in Gaseous helium pounds mass delta during decay checks
 - H2 leak rate in SCIM
 - Propellant quality in all MPS subsystems
- Evaluates incoming data to determine system health and potential anomalies
- Knowledge was "captured" from MPS engineering experts
- Provides color print/graphics capability to produce near real-time charts for data analysis and presentation to the mission management team during Space Shuttle countdowns
- Utilizes all available instrumentation coupled with algorithms and equations to calculate an estimated propellant quality in all sections of the MPS hydrogen subsystem
- Can store wind speed, direction, and relative humidity for correlation with 17-inch disconnect leak detector data

PAT allows a clearer and quicker understanding of any potential anomaly. Since it can be tailored to a particular problem it will take maximum advantage of the data generated during any leak isolation effort. This may reduce the amount of testing required to reach a conclusion. It also allows systems engineering to prepare a clear and concise management summary of the cause and effect of an anomaly.

Since the system is not currently certified, conclusions must be backed up using CCMS. This is a worthwhile trade off since it is easy to verify a piece of data, once the big picture is clearly understood. In keeping the system "advisory" the configuration control can be managed by hands on personnel allowing ease of change to adapt to a particular problem and unencumbered influx of new technology when available.

Final system configuration identification, debug, and verification to an acceptable confidence level will be performed iteratively by Rockwell / LSOC MPS and software engineering at the Kennedy Space Center. In addition, the computer engineering specialists at Lockheed Sanders Advanced Engineering Technology Division and Rockwell's Advanced Simulations and Systems Test Center will provide technical expertise. This iterative approach will provide ample opportunity to correct the course of the program to ensure it achieves the desired goal. PAT's on-site development guarantees both the completeness of the system and actual operability (not just experimental laboratory equipment). The participation of both technologists and users encourages the application of the correct technology to the pertinent problems. Plans are still in work to complete a knowledge representation of the entire propulsion loading system. The hydrogen and helium subsystems remain to be represented. Flight and GSE valve electrical functionality modeling are on the agenda.

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To conclude, PAT development has been very rapid and cost effective. The initial software and hardware configurations were developed under a Lockheed Internal Research and Development program. Six weeks after the start of the program, PAT had been delivered to KSC. Within six months, the system was on-line, collecting and analyzing data. Since that early start, the continuous iterative approach to development has produced a viable system that has proved its worth. For the next phase of the project, the Space Shuttle Main Engines will be added to the system and debugging will be done. To date, the total cost for three delivered systems, including all hardware and software has been under \$550,000.