

SPACE SHUTTLE MAIN ENGINE ANOMALY DATA AND  
INDUCTIVE KNOWLEDGE BASED SYSTEMS:  
AUTOMATED CORPORATE EXPERTISE

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Abstract

Since 1984, a low-level effort has been underway at Rocketdyne, manufacturer of the Space Shuttle Main Engine (SSME), to automate much of the analysis procedure conducted after test firings. Previously published articles in corporate publications, international conference proceedings, and the international trade press have contained the context of and justification for this effort [4, 8, 9], and technical issues regarding the integration of large data bases with the run-time component of the knowledge-base system [2]. In this paper, progress is reported in building the full system, known as SCOTTY, after a noted 23rd century rocket propulsion expert.

The progress is on two fronts. The first is an organizational or philosophical one: the automated analysis of SSME tests is a complex process, but only part of it typically involves an expert. That is, this expert knowledge-based system is called only when required; there are many more mundane tasks which may interface to an expert, but do not require heuristic technical expertise. Don't make your technical expert also serve as the program manager!

The second front of progress is a technical one. Since the very inception of the program, it has been strongly believed that the intrinsic nature of SSME test analysis and character of inductive-based expert system building tools (ESBTs) represent an excellent match of problem and tool. It was, in fact, the driving consideration for the 1984 recommendation given to management, along with the critical feature of being software-compatible with existing systems, i.e., the tool must be able to generate Fortran code. The intuition has been justified by the relative ease with which a significant source of corporate diagnostic and analytical expertise has been transformed to examples and thence to effective production rules. The source of this expertise is in completed SSME anomaly forms, one for each of the 1400+ tests conducted since 1975. The latter transformation from examples to production rules is accomplished automatically with a powerful inductive ESBT, ExTran 7 from Intelligent Terminals Ltd. [1], running on a Concurrent Computer Corporation 3260 super-minicomputer. The engineering staff responsible for building (and eventually maintaining) SCOTTY has consistently used examples as input -- a single rule has yet to be written. The knowledge-acquisition "bottleneck" is thus much wider than for most previously-reported expert systems.

The moderate expansion of the former low-level efforts in constructing an automated test analysis procedure for the SSME will be discussed in this paper. The topics will cover qualitative and quantitative details of the above organizational and technical issues, as well as various possible extensions being considered. These include:

- the integration of a large-scale relational data base system [3] and example generation at the knowledge acquisition component of ExTran 7,
- a graphics interface for experts and end-user engineers,
- increased efficiency from exploiting concurrency in problem and machine,
- potential extension of a tuned and limited subset of the system to flight engines,
- application of the system for training purposes of many newly-hired engineers,
- incorporation of design and monitoring tasks into an automated system,
- technology transfer to other engines and Rocketdyne programs,
- an anomaly description language, and
- the essential qualities of good software engineering practices for building expert knowledge-based systems.

### Introduction

Every time a Space Shuttle Main Engine (SSME) is test fired, hundreds of measurements are taken from a wide variety of sensors. Many more values are also calculated. All of these data values, when combined with previous performance of the engine and its components, are used by the engineering staff at Rocketdyne to determine the future tests. These outcomes can vary from all requirements being met, to a few minor events, to a rare significant event. As the SSME is the world's most complex reusable liquid-fuel (oxygen and hydrogen) rocket engine, Rocketdyne and NASA, the customer, consistently insist that a thorough investigation of each test firing be performed by our most highly-trained staff. This emphasis on quality is heightened even further as a result of the Challenger tragedy, ensuring that the next scheduled shuttle flight, Discovery in June of 1988, will be the safest that is humanly possible. The recent increase in the SSME testing schedule, to about twelve per month, is witness of this concern.

To continue its virtually perfect record of supporting shuttle flights, Rocketdyne is always looking for ways, both technical and organizational, to improve the quality of our product while working within customer guidelines. One of the major methods involves making the most accurate diagnosis, analysis, and recommendation possible for the the next engine test or shuttle flight. To perform this task, reliance has been on maximal use of sophisticated tools and the expertise of an engineering staff. This staff has accumulated experience dating back to 1975 and covering 1400+ SSME firings, plus numerous other ones from the Apollo F-1 and J-2 engines to those on the Atlas.

In addition to gaining incalculable experience over the years, the engineering staff has also been gaining an increase in another quality -- age. Like most other aerospace companies, Rocketdyne has a significant gap between staff with 20-30 years of experience and those with 5-10 years. Although the young

engineers are bright and motivated, they are keenly aware they do not possess the wealth of background of our older senior staff. These staff engineers are approaching or at retirement age, but their replacements have considerably less rocket engine experience. Hence, Rocketdyne is confronted with a significant dilemma: how to improve the quality of SSME test analysis in the face of diminishing senior staff. Several options to solve this dilemma were discussed in [4]. It was decided to use a combination of staff, results from previous SSME tests, and automated tools to address the problem and begin to build a prototype for automated corporate expertise.

Rocketdyne is far from alone in being confronted with the above problems. Indeed, the corporation has ample "company" in deciding to use a type of automated tool know as expert systems, part of the artificial intelligence technology. In fact, there is considerable concern that, once again, this field is in danger of being "over-hyped" [6]. And the company is certainly not the first to decide to concentrate initially on a diagnosis type application, a type currently of considerable importance in industry despite being "old-hat" to the AI research community. So what is unique about SCOTTY, our automated system? There are two unusual aspects.

One such aspect is the incorporation of SCOTTY as "another", albeit advanced, software tool which must:

- live in a distributed corporate environment,
- talk to large data bases,
- be maintained by existing engineering staff,
- run with color graphics terminals,
- execute on standard computers,
- be amenable to parallel processing hardware, and
- meet corporate-wide software engineering development and quality guidelines.

The other unusual aspect is a technical one which increases the ease with which SCOTTY can be constructed. By use of a type of ESBT known as inductive or example-based, the historical expertise now reposing in the anomaly sheets for the hundreds of SSME tests can be transformed into examples, and thence automatically into production rules. These rules will, in turn, drive SCOTTY during normal day-to-day operation in future years.

### SCOTTY History

In 1984, the author was hired by Rocketdyne to assist in the construction of an automated tool for SSME test analysis. Within two months, a proof-of-concept model for a High Pressure Oxidizer Turbo Pump (HPOTP) had been built. This involved recommendation of an inductive ESBT, Expert Ease by Intelligent Terminals, Ltd (ITL) in Glasgow, Scotland, and the first such PC-based ESBT commercially available. The tool was purchased and used, after minimal training time, by a mechanical engineer, to diagnose HPOTP anomalies, by specifying 42 examples and nine attributes. A 48 rule subsystem was automatically generated by Expert Ease. No rules were required of the engineer. This prototype and the problem context, rationale, and solution were described in an early paper [4]. A desirable tentative system configuration is shown in Figure 1.

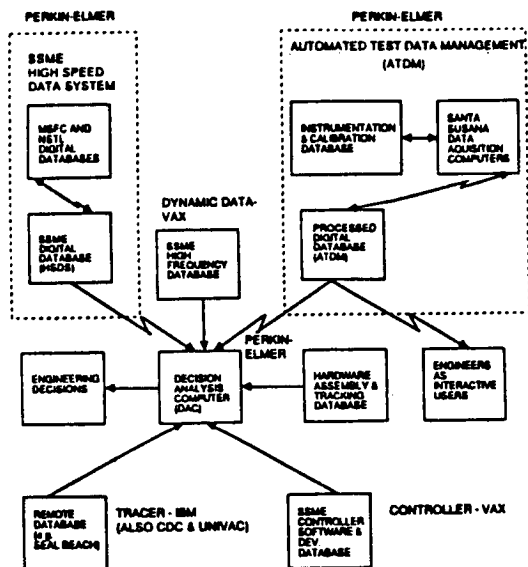


Figure 1. SCOTTY:  
Final System Configuration

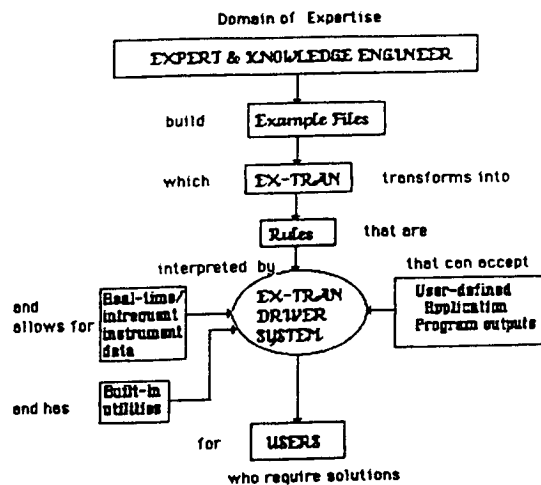


Figure 2. Building Expert Systems  
with ExTran

During 1985 and 1986, the system (now named SCOTTY) underwent several extensions. From a tool viewpoint, a more powerful ESBT became available. ExTran 7, an industrial strength Fortran-based inductive ESBT from ITL which runs on a wide variety of machines from PCs to workstations to super-minis to mainframes, was recommended. A process for using ExTran is given in Figure 2. ITL ported the product to the available Concurrent Computer Corporation 3260 super-mini at minimal cost. The HPOTP examples were immediately transported to ExTran and the resulting module was now a true, albeit simple, knowledge base system (KBS) utilizing "Why", "How", and "What if" type questions, history files, external interfaces, and all the other features usually associated with a KBS.

Conceptually, SCOTTY was extended in several directions during this same time period. It was demonstrated that multiple problems could be run concurrently on the multiple processor Concurrent 3260. Graphics routines (PLOT-10 and GKS libraries) were tied to ExTran with a minimum interface. In-house statistical routines were easily linked to SCOTTY. Small Fortran routines were written to access SSME test files and output attribute values for input to SCOTTY sub-problems. Additional SSME component modules were specified. Figure 3 contains the early version of a structure chart. A major extension was the run-time interface between ExTran and the large data base management system DMS/32 supplied by Concurrent (then known as Perkin-Elmer). These are all described extensively in a paper presented in 1986 [2].

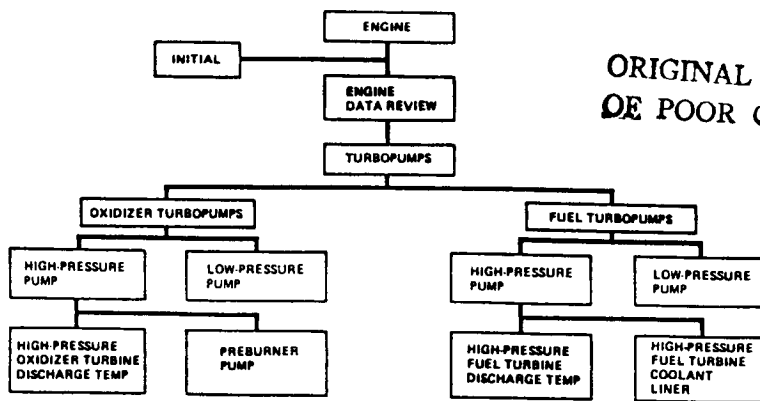


Figure 3. SCOTTY Structure Chart, Version .84

Current Status

SCOTTY now exists at a stage between a research prototype and a production model, using the taxonomy of Waterman [6]. It is not being used in production now -- additional resources would permit this to occur sooner. SCOTTY consists of far more than "just" an expert system, as is clearly shown in figure 4, but rather is one component in a fairly extensive software system. This reflects the strong belief that viable expert systems are most likely to succeed in a hybrid and integrated environment, where they must communicate easily with other standard existing and future sub-systems.

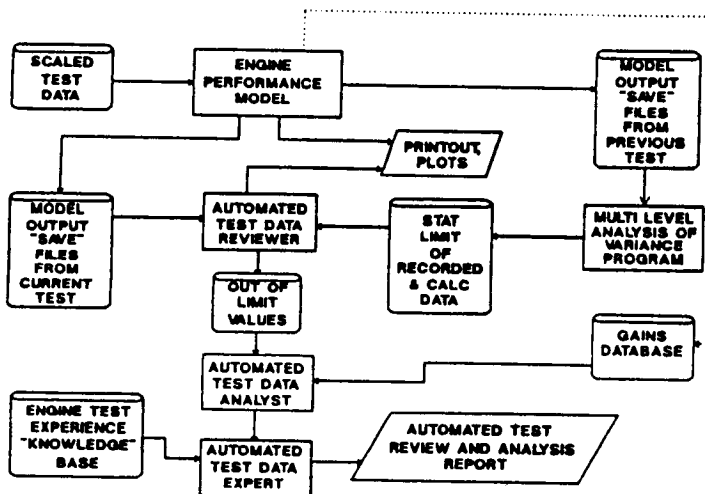


Figure 4. Context of SCOTTY (Automated Test Data Expert)

An updated structure chart reflects the understanding that SSME test analysis involves several levels of expertise, from relatively mechanical but comprehensive data review to component and system level diagnostic and analytical experts. See Figure 5. For many routine tests, the expert system is not required.

This is no stranger than the human equivalent case of calling on resources only when needed. The program manager decides when he/she must draw on the rare and expensive human expert. Do not make the mistake of having your senior technical specialist trying to "double" as program manager. These two entities have different types of expertise.

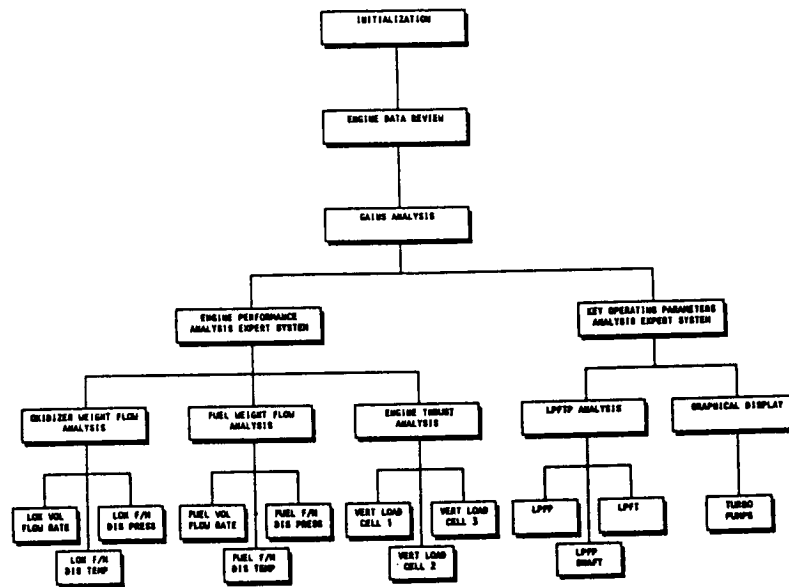


Figure 5. SCOTTY Structure Chart, Version .9X

SCOTTY, as of mid 1987, consists of 18 ExTran modules comprising 3200 lines of code (LOC) in Fortran. Supporting code required 5000 LOC. The ExTran generated code was derived automatically from approximately 260 examples. No rules have been written by hand to date -- all 700 rules were induced.

### Extensions in Progress

Development is continuing on a number of fronts for SCOTTY. Three are highlighted here: graphics, anomaly data, and a new extension to ExTran.

As SCOTTY matures, the level of effort devoted to its development has increased. The first efforts were done solely on Rocketdyne internal R&D funds. Currently, funding efforts have been underway for some time with a customer for making the system a production one more quickly. Recently hired engineers and computer scientists have been active in extending the structure, leaving the knowledge content to acknowledged experts. A SSME instrumentation chart, now taped to the walls of hundreds of Rocketdyne engineering offices, is being converted to a dynamic color computer graphics form. See Figure 6 for a sample, purposefully simple, display of a Low Pressure Fuel TurboPump (LPFTP). This graphics subsystem will have capabilities to zoom, highlight problem areas (according to actual test data measurements), and depict flow. This is not CAD/CAM, although there are a few common themes, nor is it extensive CFD modeling

of the National Aerospace Plane (NASP) using multi-million dollar CRAY 2s. It is a practical and feasible use of moderate color resolution on the readily available super-mini and terminals. Engineers on the floor, as would be expected, are very pleased to see in graphical form what they have hitherto had to dig out of static tables and plots.

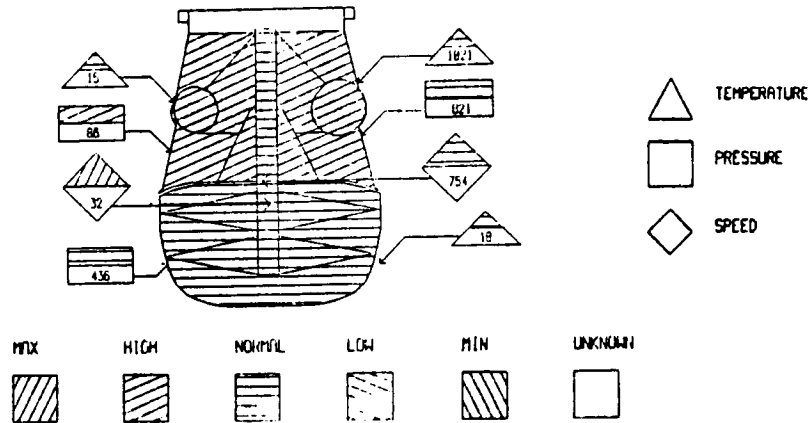


Figure 6. Simple Graphic Display for a LPFTP

Anomaly data is a key to the success of SCOTTY. It provides a starting point for converting much of the SSME testing expertise repository into machine readable form. Serious efforts are underway to use this source to augment the experience now encapsulated in the heads of senior engineering staff. Each anomaly sheet consists of three major fields: problem (symptoms), analysis (causes), and recommendations. See Figure 7 for a (dummy) sample. Zero or more anomalies are recorded for each test, usually very minor ones. By carefully reviewing each anomaly and any back-up plots/tables, it is possible to convert each one into an example format consisting of a set of attribute-values and decisions. Anomalies for the first several tests tried are converted rather slowly, as new attributes are frequently added. However, as experience in the conversion process is gained, and the rate of growth of new attributes slows, the rate of the anomaly to example format conversion increases significantly.

ENGINE	SCME ANOMALY SUMMARY	TEST
ANOMALY	ANALYSIS	ACTION TAKEN FOR NEXT TEST
FPB PC (PIDS 58, 158 AND 410) - FACILITY MEASUREMENT DEVIATES FROM CADS DURING MAINSTAGE AND OFFSET REMAINS AFTER C/O	<ul style="list-style-type: none"> <li>• FACILITY AND CADS MEASUREMENTS SHOW NO OFFSET AT E/S</li> <li>• CADS MEASUREMENT IS NORMAL</li> <li>• OFFSET INCREASES DURING 1LST</li> <li>• OFFSET PRESENT AFTER C/O</li> <li>• SENSOR CHECKOUT OK</li> <li>• PID IS INFORMATION ONLY</li> <li>• OK TO TEST</li> </ul>	<ul style="list-style-type: none"> <li>• CONTINUE TO MONITOR</li> </ul>
		UCR REQUIRED
		NO

Figure 7. Sample Anomaly Data

The third extension underway is the intention to use a new feature of ExTran which is the result of a joint project between ITL and Concurrent with roots in the earlier work at Rocketdyne [2]. This feature extends the interface between ExTran and a data base system to the knowledge acquisition component of the former, as well as the run-time interface discussed in [2]. See Figures 8, 9, and 10. The effort of this joint project is known as Reliance-Expert, and is scheduled to undergo beta test at Rocketdyne. It would permit the anomaly data to be transformed to records in a relational DBMS. This would make this valuable data available for a wide variety of uses. One of the uses would be to serve as an "expert" for historical knowledge of SCOTTY, as it can now be transformed automatically into examples and then to rules. So, once again, the knowledge acquisition bottleneck becomes less and less of an issue, as it will be possible to go directly from anomaly records in a DBMS to production rules in an expert system.

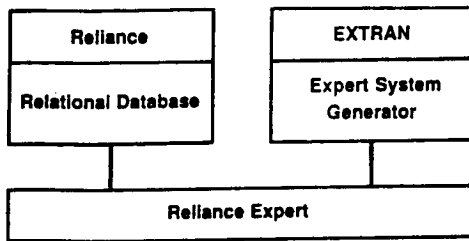


Figure 8. Reliance Expert Structure

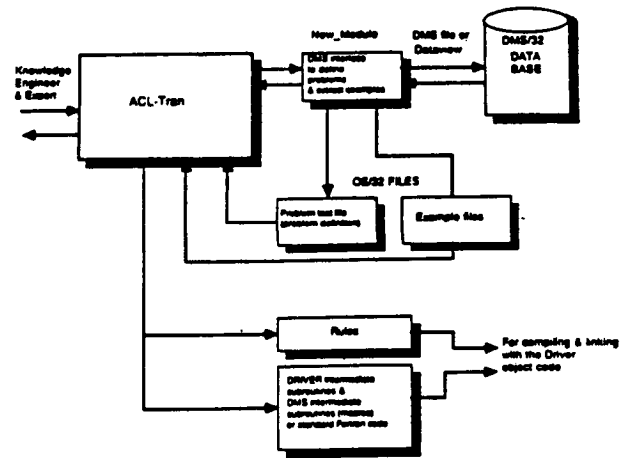
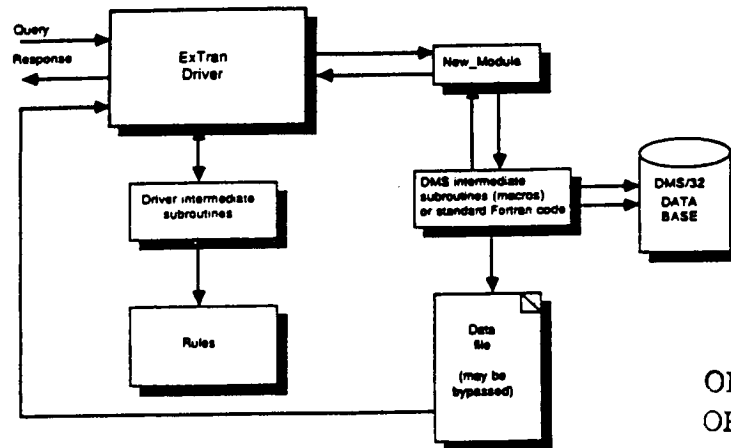


Figure 9. Reliance Expert Development Phase



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Figure 10. Reliance Expert Run-time Phase



## Future Development Issues

Further in the future are several concerns. There is an interest in each as a potential contributor to improving the quality of SSME test analysis. Obviously, Rocketdyne is keenly concerned also about technology transfer to other types of engines, in addition to the SSME. The company is deeply committed to the Advanced Launch System (ALS), Space Station power, National Aerspace Plane (NASP), Orbital Transfer Vehicles (OTV), and other propulsion and energy systems.

These further-reaching concerns are concentrated both in application and technical areas. On the application side, Rocketdyne would like to investigate the potential of extending SCOTTY to handle a limited subset of the measurement data for flight engines. The incorporation of monitoring and design tasks is also of high interest. An obvious application is to enlarge the context of SCOTTY to include new hire training on SSME test analysis.

On the tool side, the issue of dealing with uncertain and/or noisy example data is significant. Real engineering problems involve uncertain and incomplete information. Indeed, a noted nuclear engineer, Dr. Billy Koen at the University of Texas in Austin, has gone so far as to define the engineering method as "the use of heuristics to cause the best change in a poorly understood or uncertain situation within the available resources" [5]. This feature exists on several commercial tools, but only in a pre-release form for ExTran, as of this date. The possibility of using abductive reasoning for diagnosis also appears to hold some promise [7].

## Conclusions

Since 1984, a low-level effort has been underway at Rocketdyne, manufacturer of the Space Shuttle Main Engine (SSME), to automate much of the analysis procedure conducted after test firings. In this paper, we reported on progress in building the full system, known as SCOTTY, after a noted 23rd century rocket propulsion expert.

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#### References:

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