FAULT DIAGNOSIS
in
MOBILE MINING EQUIPMENT

By

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Abstract

The development of decision support systems for equipment diagnosis has been found to be an iterative process whereby functionality and knowledge are continually added to a prototype until satisfactory performance is achieved. In order to reduce both the dependency on compiled knowledge sources and the number of prototype stages necessary to develop diagnostic decision support systems, this thesis examines, adapts and applies a set theoretical approach to mechanism diagnosis first developed in the field of Artificial Intelligence. The approach does not require the development of computational models to simulate equipment behaviour.

The set theoretical approach was applied to the development of a diagnostic decision support system for a semi-automated Atlas Copco Wagner ST-8B Load-Haul-Dump vehicle. Hypothesis sets were generated for the vehicle's hydraulic circuit and Deutz FL-413-FW diesel engine. A high level of diagnostic resolution was achieved for the hydraulic circuit, but limited resolution was achieved for the diesel engine. This was postulated to be due to the ratio of observable system outputs to input sub-systems, and the number of least repairable units making up each system.

Manual knowledge acquisition was undertaken in an underground mine to refine the diagnostic knowledge developed from the hypothesis sets and to add knowledge to discriminate between competing failure hypotheses. Heuristic failure likelihoods were used to rank hypotheses in order of frequency of occurrence. The knowledge base was implemented as a hypertext decision support system using HyperText Mark-up Language (HTML). The resulting decision support system is platform independent, upgradeable and able to be maintained by site personnel. The system is currently installed at surface level and at 1800 level at INCO Limited's Stobie Mine in Sudbury, Ontario.

The thesis makes a number of original contributions, the first two of which are of generic significance. It is the first work to apply set theoretical concepts to structural models of mobile

mining equipment in order to diagnose faults. A number of modifications are advanced to the conventional trace-back analysis technique for generating contributor and normality sets, and heuristic guidelines are provided for estimating the costs and benefits of developing, implementing and maintaining diagnostic decision support systems. It is also the first work to formalise a decision support system in HTML and to suggest the application of company-wide internets ("intranets") to disseminate maintenance knowledge within mines.

Résumé

Le développement des systèmes d'aide à la décision pour le diagnostic des équipements apparaît comme un processus itératif où la fonctionnalité et la connaissance sont continuellement ajoutées à un prototype jusqu'à ce qu'un résultat satisfaisant soit atteint. C'est pour réduire la dépendance par rapport à la compilation des sources de connaissance, de même que le nombre des états prototypes nécessaires au développement d'un système d'aide à la décision, que cette thèse examine une approche basée sur la théorie des ensembles, l'adapte et l'applique au diagnostic des mécanismes, dont les premiers développements sont dûs à l'Intelligence artificielle. L'approche présentée ici ne nécessite pas le développement de modèles mathématiques pour simuler le comportement des équipements.

Nous avons appliqué l'approche de la théorie des ensembles au développement d'un système d'aide à la décision à un chargeur-transporteur Atlas Copco Wagner ST-8B semi-automatique. Nous avons généré des ensembles d'hypothèses pour le circuit hydraulique et le moteur diesel Deutz FL-413-FW du véhicule. Un haut niveau de résolution diagnostique a été atteint pour le circuit hydraulique, mais pour le moteur diesel, la résolution était limitée. On est parti du postulat qu'un tel résultat était dû au rapport entre les sorties observables du système et les entrées du sous-système, ainsi qu'au nombre d'unités les moins réparables composant chacun des systèmes.

L'acquisition des connaissances manuelles a été entreprise dans une mine sous-terraine, avec un double objectif: raffiner la connaissance diagnostique développée à partir des ensembles d'hypothèses, et ajouter une connaissance capable d'établir une distinction entre les hypothèses d'échec concurrentes. Les possibilités d'échec heuristique ont servi à classer les hypothèses par ordre de fréquence décroissante. L'implémentation de la base de connaissance s'est faite sous forme de système d'aide à la décision hypertext, en utilisant le langage HyperText Mark-Up Language (HTML). Le système d'aide à la décision qui en résulte est indépendant du système d'operation, il est expansible, et son entretien peut être fait par le personnel du site. Ce système est actuellement installé au niveau de surface et au niveau 1800 de la mine Stobie d'INCO Limited, à Sudbury, Ontario.

Cette thèse fait plusieurs contributions originales, le deux premières étant d'ordre générique. C'est en effet la première étude à appliquer les concepts de la théorie des ensembles à des modèles structuraux d'équipement mobile minier pour le diagnostic des erreurs. Un certain nombre de modifications sont également proposées en regard des techniques d'analyse conventionnelles de "recherche-arrière" pour générer des ensembles contributeurs et normaux. Enfin, on fournit des guides heuristiques capables de faire l'estimation des coûts et des bénéfices relatifs au développement, à l'implémentation et à l'entretien des systèmes d'aide à la décision. C'est le premier travail qui formalise un système d'aide à la décision en langage HTML et qui suggère l'application de réseaux ("intranets") à travers la compagnie pour la propagation de la connaissance de l'entretien minier.

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List of Acronyms

ABB	Asea Brown Boveri AB.
AI	Artificial Intelligence
APS	Advanced Product Services (Caterpillar Inc.)
ASCII	American National Standard Code for Information Interchange
ATMS	Assumption-Based Truth Maintenance System
BS	British Standard
CANMET	Canadian Minerals and Energy Technology Organization
CBM	Condition-Based Maintenance
CGI	Common Gateway Interface
CIM	Canadian Institute for Mining, Metallurgy and Petroleum
DPM	Diesel Particulate Matter
DSS	Decision Support System
EA	Equivalent Annuity
ECM	Engine Control Module (Caterpillar Inc.)
ECS	Electronic Check System (Mannesmann Demag Inc.)
GDE	General Diagnostic Engine
GPM	Gallons Per Minute
HPCO	High Pressure Carry Over
HTML	HyperText Markup Language
HWL	Hard Wired Logic
IMSS	Intelligent Maintenance Support System
IRR	Internal Rate of Return
IRV	Instantaneous Rotational Velocity
KBS	Knowledge-Based System
LHD	Load-Haul-Dump (Vehicle)
LRU	Least Repairable Unit
MCV	Main Control Valve

MMS	Maintenance Management System
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NCSA	National Center for Supercomputing Applications (USA)
NSERC	National Sciences and Engineering Research Council of Canada
NPFC	Number of Possible Fault Combinations
NPV	Net Present Value
NRC	National Research Council of Canada
NW	Net Worth
OEM	Original Equipment Manufacturer
O&K	Orenstein and Koppel AG.
PLC	Programmable Logic Controller
PSI	Pounds Per Square Inch
RI	Resolution Index
RPM	Revolutions Per Minute
SAHR	Spring Applied, Hydraulic Release (Wagner Mining Equip. Inc.)
SGML	Standardized General Markup Language
SIS	Service Information System (Caterpillar Inc.)
SQL	Structured Query Language
TBF	Time Between Failures
TEKES	Technology Development Centre of Finland
TTR	Time To Repair
URL	Uniform Resource Locator
USBM	United States Bureau of Mines
VIMS	Vital Information Monitoring System (Caterpillar Inc.)
VSM	Vital Signs Monitoring (Marethon LeTourneau Ltd.)
WWW	World Wide Web

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"Felix qui potuit rerum cognoiscere causus."

(Virgil, Georgics 2.490).

1. Introduction

1.1 Mobile Mining Equipment Productivity

The productivity of mobile mining equipment such as drills, shovels, trucks and load-haul-dump vehicles is a complex function of machine design, operating environment, operator care and skill, mine planning and equipment availability. Mobile mining equipment is generally operated under severe conditions that often stress a machine's electrical, hydraulic and mechanical components to the limit of their designed capabilities [Kohler and Sottile, 1993]. This poses significant challenges to equipment manufacturers and mine maintenance departments, both of whom are charged with maintaining high levels of equipment availability.

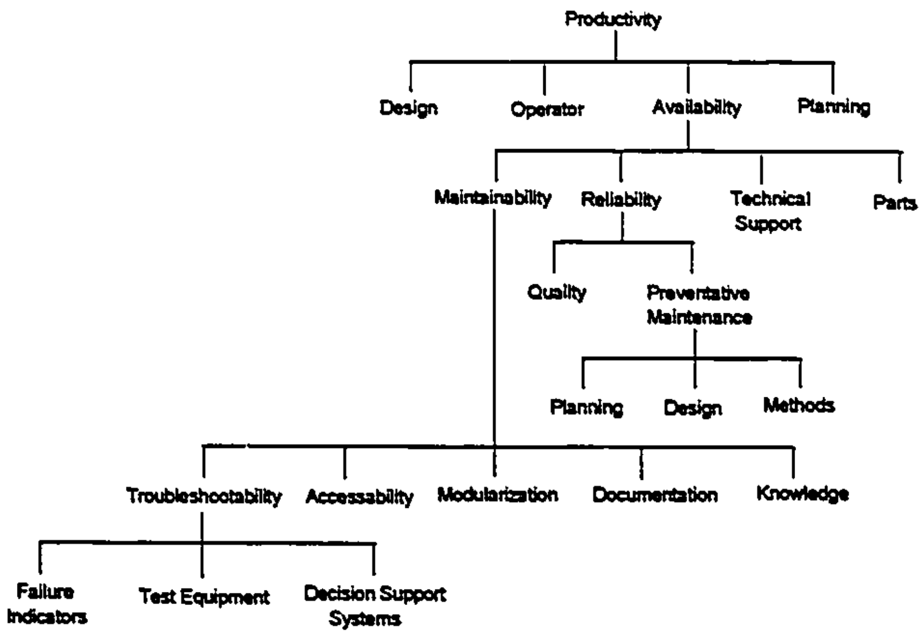

Figure 1.1 Factors Influencing Equipment Availability and Productivity [Nilsson and Ouellette, 1992]

Availability is defined as the fraction of scheduled time that an item of plant is able to produce its end product at or above a minimum acceptable level [Smith, 1993]. Availability is a function of parts availability, technical support, machine reliability and machine maintainability (see Figure

1.1). Reliability is defined as the ability of a machine to perform a required function under given environmental and operational conditions for a stated period of time [British Standard 4778]. A frequently used measure of reliability of mining equipment is the mean time between failures (MTBF), calculated by considering scheduled working hours only. Equipment reliability is influenced by not only the quality of parts and manufacture of a machine, but also by the planning, design and methods of preventative maintenance implemented at a mine. Preventative maintenance is a proactive policy which aims to predict, prevent and plan for machine failures in advance of unplanned failures which detrimentally effect production.

Maintainability is defined as "the ability of an item under stated conditions of use to be retained in or restored to a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources" [British Standard 4778]. A commonly used measure of maintainability is the mean time to repair (MTTR) a machine, calculated by considering scheduled repair hours only. Maintainability is influenced by the degree of modularization used in the design of the machine, the accessibility of components, the quality of available documentation and the ease of troubleshooting the machine [Nilsson and Ouellette, 1992]. Equipment maintainability becomes of increased importance when maintenance practices become reactive rather than proactive. "Breakdown maintenance" policies disrupt production schedules and generally result in higher maintenance costs through the necessities to schedule overtime maintenance work, to obtain parts at short notice and to repair secondary damage that could have been prevented if the onset of the failure had been detected at an earlier stage. Caterpillar Inc. estimates that repair costs before a major component fails can be one third of an after-failure repair with only moderate sacrifice in component life [Caterpillar, 1994].

1.2 Preventative Maintenance

Preventative maintenance is defined as the practice of performing inspections and/or servicing tasks that have been pre-planned for accomplishment at specific times to retain the functional capabilities of operating equipment [Smith, 1993]. Preventative maintenance practices include time-based maintenance (TBM) aimed directly at failure prevention (also called scheduled maintenance), and condition-based maintenance (CBM) aimed at detecting the onset of failures. Condition-based maintenance can be divided into periodic condition monitoring by testing or inspection and on-line electronic monitoring practices. Oil debris analysis [Hunt, 92] and tyre tread thickness assessment are good examples of periodic test and inspection-based condition monitoring.

1.2.1 On-Line Monitoring Systems

As the need to reduce costs for competitive reasons has grown and as equipment has become more complex [Chatham, 1995], on-line condition monitoring systems have become more prevalent in mobile mining equipment. Their application has been facilitated by the introduction of electronic controls which have replaced mechanical control systems, and the general evolution of monitoring system hardware and software. The primary objective of an on-line condition monitoring system is to detect the onset of failures before they significantly impair a machine's functionality. On-line monitoring systems can also assist equipment troubleshooting.

Another factor which is driving the introduction of on-line monitoring systems is the growth in development of autonomous and semi-autonomous mobile mining equipment. This growth is motivated by the desire to minimise operator exposure in hazardous areas [see Moyano and Vienne, 1993; Chadwick, 1994a], and the desire to increase labour productivity through single operator - multiple machine operation [see Baiden and Henderson, 1994]. Operators of conventional mobile equipment are adept at detecting degradational changes in machine performance through the five human senses of sight, sound, smell, touch and taste. The removal of operators from the proximity of mobile mining machines requires the installation of on-line condition monitoring systems to detect and warn of incipient failures.

A shortcoming of on-line condition monitoring systems is that they generally produce excessive amounts of data which require significant interpretation skills to turn into useful information. For example, Caterpillar's latest onboard performance and condition monitoring system, the Vital Information Monitoring System (VIMS), monitors and records 52 haul truck parameters directly and calculates an additional 17 values from these parameters [Chatham, 1995]. In addition to alerting an operator to take failure avoidance action, VIMS stores data on-board for later off-board analysis. Off-board failure diagnosis generally proceeds by extracting significant features from the time-series data, deciding which of these features represent abnormal behaviour and which are relevant to the diagnostic reasoning process, and concludes by reasoning with this set of extracted features to arrive at a diagnosis. This process demands a level of signal processing and interpretation skills which most mine mechanics or electricians do not possess.

Whilst the provision of appropriate training programs would be one way of tackling this problem, recognising that user acceptance of VIMS lies ultimately in providing a product which is both reliable and easy to use, Caterpillar are presently working on a concept called "Advanced Product Services" (APS) [Scholl, 1995]. This product is essentially a decision support system which will include on-board analysis of sensor signals, communication, off-board analysis, interpretation and recommendation of action. The goal is to computerise the process as much as possible, thereby requiring an expert to get involved only when new or special interpretation is needed [Ferguson, 1994]. Caterpillar is not alone in this type of product development. Shovel manufacturers such as Harnischfeger and Marion have developed decision support systems linked to on-board monitoring systems [White, 1995] and underground equipment manufacturers such as Tamrock are in the process of developing decision support software for failure diagnosis of load-haul-dump vehicles from on-line condition monitoring information [Tamrock Loaders, 1994].

1.3 Breakdown Maintenance

Mines that utilise some form of condition monitoring will in most cases realise some cost savings, but generally on-line condition monitoring systems are viewed as highly expensive to implement and maintain [Peck and Burrows, 1994]. In addition, some OEM monitoring systems are not easily retrofitted to older equipment models, as sensors and communication buses can be built into new equipment during construction. Many mines operate older equipment which are not equipped with on-line condition monitoring systems. In addition, mine preventative maintenance practices are frequently less than ideal. Maintenance of mobile production equipment is often performed on a reactive basis as equipment fails ("breakdown maintenance") rather than on a proactive basis.

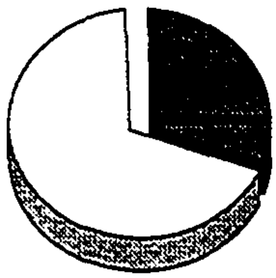

Figure 1.2 Repair Time Distribution for One Year's Operation of Three ST-8B LHD Vehicles at a Canadian Hardrock Underground Mine.

Figure 1.2 illustrates the extent of breakdown maintenance at one underground Canadian metalliferous mine. The diagram shows the allocation of down time resulting from one year's operation of three Atlas-Copco Wagner ST-8B load-haul-dump vehicles. Repair data was recorded from the maintenance log books for the three machines [Knights, 1993a]. Classification of the maintenance time was performed by a maintenance foreman. The graph shows that a little over 68 % of the total recorded down time was due to unplanned repairs. A further 6.5 % was due to idle time (waiting for available space in the workshop or waiting upon parts or labour). Only one quarter of the total down time was spent on preventative maintenance. Looking at these figures, a mine manager has two options to address the disproportionately high level of breakdown repairs. Firstly, the frequency of breakdowns can be reduced by changing operator practices or reassessing preventative maintenance practices (for example, on-line condition monitoring systems could be introduced). Secondly, the average duration of breakdown repairs can be addressed.

Outokumpu Mining Services estimates that less than 20 percent of the time to repair a breakdown is actively spent repairing the failure [Harjunpää, 1993]. Up to 80 percent of down-time is consumed by waiting for a supervisor's instructions, accessing the failed component or subsystem, diagnosing the cause of the failure, seeking relevant manuals or drawings, waiting on resources such as spare parts, consumables and specialist labour. Diagnosis is a task which demands considerable expertise and is complicated by the fact that there frequently exists a multiple-to-one relationship between failure causes and symptom sets. As figure 1.1 illustrates, three means are available to assist equipment troubleshooting; failure indicators, specialised diagnostic tools and decision support systems.

Failure indicators, as distinct from condition monitoring systems, exist solely for the purpose of isolating the cause of a failure once it has occurred. Indicator panels are well suited to electrical equipment, where GO/NOGO lamps can be inexpensively wired into the electrical system. Diagnostic tools, such as Noranda's "Mechanic's Stethascope" [Johnson et al, 1994] which measures the instantaneous rotational velocity (IRV) of diesel engine flywheels and predicts cylinder combustion problems, can provide cost savings for specific equipment diagnostic applications. Decision support systems, capable of assisting the diagnosis of a range of equipment problems and capable of retrieving and displaying operator manuals, drawings and parts lists, are well suited to reducing the repair times for breakdown failures. Dependent on the reduction in repair times, maintenance labour savings may also be realisable. The productivity benefits of decision support systems as applied to breakdown repairs are discussed in more detail in Chapter 7.

In addition to reducing breakdown repair times and assisting in the interpretation of on-line condition monitoring data, diagnostic decision support systems can reduce the number of incorrect diagnoses made, saving money on unnecessary parts. Decision support systems can also be valuable aids to train junior maintenance personnel in equipment troubleshooting. By prompting personnel to adopt approved repair procedures, they can enhance the level of occupational health and safety within a mine. The promotion of "understanding" of a machine can also lead to more responsible operation.

1.4 Decision Support Systems

The definition of a decision support system (DSS) is "a computer program designed to assist humans in decision making" [McDaniel, 1994]. Since this definition encompasses a broad class of programs including many conventional business applications, in the context of this thesis decision support systems will be taken to include knowledge-based and hypertext systems. The previous discussion established that decision support systems can be employed to facilitate the diagnosis of;

- incipient failures through interpreting data collected from on-line condition monitoring systems, and
- breakdown failures, thus reducing the mean time to repair breakdown failures.

The next section will focus on issues associated with developing both knowledge-based and hypertext decision support systems.

1.4.1 Knowledge-Based Systems

Knowledge-based systems (KBS) are defined as "software systems capable of supporting the explicit representation of knowledge in some specific competence domain and exploiting it through an appropriate reasoning mechanism in order to provide high-level problem solving performance" [Guida and Tasso, 1994]. A large class of knowledge-based systems are better known as expert systems, because they attempt to emulate the cognitive processes of human experts. Knowledge-based systems derive their name principally because they represent and use knowledge and are oriented towards symbolic processing. Conventional programs represent and store data and are oriented towards numerical processing [Arockiasamy, 1993].

Intelligence $A \rightarrow B \;\&\; B \rightarrow C \Rightarrow A \rightarrow C$

↑

Knowledge $A \rightarrow B$

↑

Information A is true

↑

Data $\frac{A \quad 000}{\neg A\, 0000}$ *time*

Figure 1.3 Intelligence Hierarchy [After Rao, 1994]

The distinction between data and knowledge is well illustrated in Figure 1.3. Data is defined as "any representation such as characters or analogue quantities to which meaning is or might be assigned" [McDaniel, 1993]. In this thesis the latter definition will be adopted (that of the potential for meaning) so that information is derived when meaning is assigned to data. In the example above, from interpretation of a trend in the process data set, information can be deduced in the form of fact A being true. This fact is not useful until a conclusion can be drawn regarding its consequence. To do this, the user must know the rule that IF (A is true) THEN (B is true) applies to the process. This can be written as a production rule $A \rightarrow B$, meaning A implies B. Knowledge, therefore, consists of facts (declarative knowledge about objects, events or situations) and rules (procedural knowledge about courses of action). These rules may be derived from well defined or logically derived processes, or from experience or intuition (heuristic knowledge) [Rolston, 1988]. Although the definition of intelligence is somewhat contentious, intelligence invariably implies an ability to reason based on a knowledge of facts and rules. In the example shown, if the additional rule $B \rightarrow C$ is known, then through the *modus poenus* reasoning process it can be inferred that action C should be taken to effect control of the process.

Figure 1.4 illustrates the general components of a knowledge-based system. The knowledge-base stores available knowledge concerning the problem domain in an appropriate form able to be manipulated by the computer. This form is dictated by the type of knowledge representation supported by the KBS. Two commonly used forms of knowledge representation are production rules and frames (or schema). Frame-based systems use templates to describe certain relationships (such as a parent and child memberships), and thus provide a means of structuring knowledge within a knowledge-base. A key feature of a KBS is that the knowledge-base is separated from the reasoning mechanism [Buchanan, 1988]. This feature has enabled many expert system development tools or "shells" to be developed which provide an inference engine (reasoning mechanism) and user interface. Facts deduced during intermediate solution steps and derived from questioning the user during the reasoning process are stored in the system's working memory.

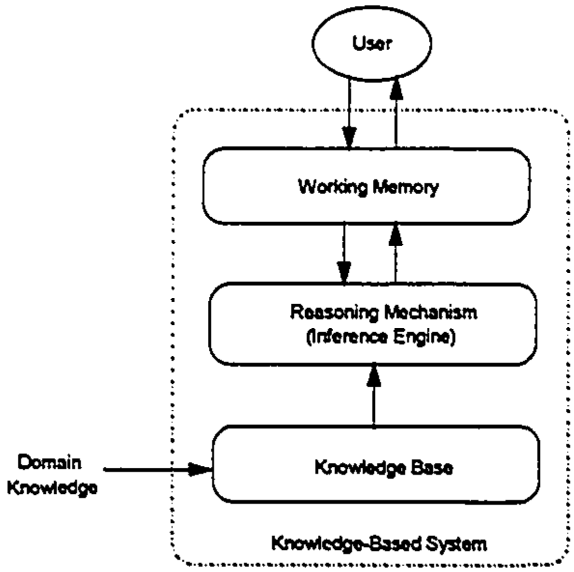

Figure 1.4 General Features of a Knowledge-Based System [Guida and Tasso, 1994]

During the last two decades, much interest has been directed towards developing knowledge-based systems for diagnostic applications. One of the earliest, and perhaps the most famous expert system, is MYCIN, a system for diagnosing bacterial infections in blood samples [Shortcliffe, 1976]. Although much interest exists within the mining industry in applying knowledge-based systems (a recent market analysis of automation opportunities in the mining sector conducted for the National Research Council of Canada (NRC), Industry Canada (IC) and the Canada Centre for Mineral and Energy Technology (CANMET) identified the use of knowledge-based systems for troubleshooting equipment as a key area for potential development [Hatch Associates Ltd. 1994]), only a small number of knowledge-based systems have been developed to assist in troubleshooting mobile mining equipment (see Chapter 2). As will become evident, developing a KBS to solve equipment diagnostic problems is not as straightforward as "just adding knowledge" to an appropriate shell.

1.4.2 Hypertext Systems

Hypertext systems enable a user to browse in a non-linear or non-sequential fashion through a network of nodes. Each node is a collection of knowledge organised around a specific topic. Knowledge in a node can be represented in many forms, including text, images, video and sound clips. Nodes may be designed within a single hypertext document, or as independent documents, external files or programs. When activated, embedded links within a hypertext document launch the user to other nodes. Strictly speaking, hypertext is a subgroup of hypermedia, but following common practice, the term will be used to describe text-only and multi-media applications [Seyer, 1991].

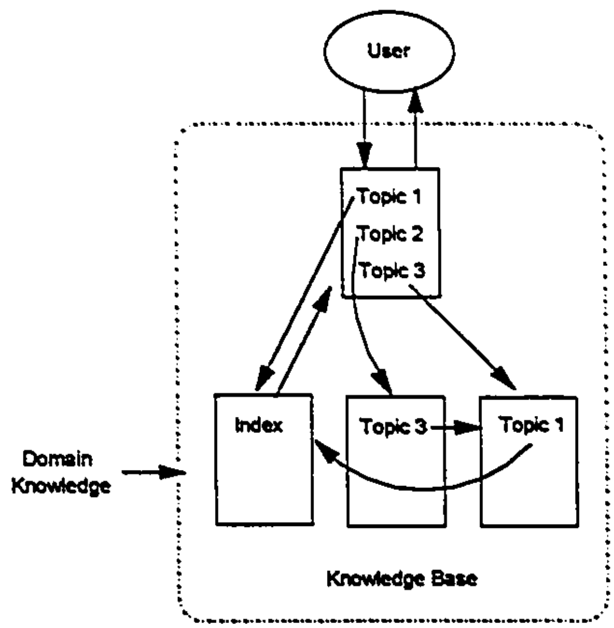

Figure 1.5 Hypertext System Illustrating Distributed Knowledge Base

Figure 1.5 illustrates the non-linear browsing ability of hypertext systems. Unlike a knowledge-based system, knowledge in a hypertext system is distributed amongst the network of nodes which comprise the system. Simple inferences can be represented by hypertext links (e.g. $A \rightarrow B$), but more complex inference statements involving conjunctions or disjunctions (e.g. $A \wedge B \vee C \rightarrow D$) cannot be represented by hypertext links. Conventional hypertext systems provide no reasoning mechanism to manipulate inferences, rather reasoning is left up to the user (well designed network structure and nodes can assist the user in drawing conclusions). However, substantially less knowledge representation effort is involved to develop a hypertext system than is necessary to develop an equivalent knowledge-based system. This is because knowledge can exist in near-original form in a hypertext system (scanned diagrams, for example), but must be formalised by decomposition into rules and/or frames for a knowledge-based system. Thus, whilst hypertext systems require less knowledge representation effort, they lack the reasoning power of knowledge-based systems. As Chapter 6 will show, for diagnostic applications, this drawback can be circumvented be employing appropriate hypertext node and network design strategies.

1.4.3 Knowledge Acquisition

A common feature of both knowledge-based and hypertext decision support systems is that their diagnostic performance is highly dependent on the quality and completeness of knowledge upon which they draw. The process by which knowledge is elicited, formalised, implemented and tested in decision support systems is called knowledge acquisition. Knowledge acquisition has long been considered the major constraint in developing expert systems [Cullen and Bryman, 1988]. The task is often cited as a difficult one, as one necessitating much patient work and is usually termed a bottleneck [Dubas, 1990]. McGraw and Harbison-Briggs [1989] state that "although it may be possible for one or two people to develop a small expert system in a few months, the development of a sophisticated system may require a team of several people working together for more than a year. Much of the time required for development can be attributed to knowledge acquisition".

For example, to effectively diagnose and repair mobile mining equipment, a maintenance technician requires knowledge of the following;

- equipment structure: the physical layout of components and the connections and flow of information between components,
- equipment function: how components operate (how inputs are converted to outputs),

- equipment behaviour; acceptable and unacceptable ranges of output performance taking into account machine duty cycle and operating environment,
- equipment history: when and what repairs have previously been effected on a machine
- equipment test procedures: how to discriminate between competing failure hypotheses, what instruments and labour are required and associated costs and suppliers, and
- equipment repair procedures: how to effect repairs, what materials and labours are required, associated costs and appropriate suppliers [after Vagenas, 1991].

This knowledge is not available from a single source. Some is documented in the form of troubleshooting manuals, maintenance logs, company policies, journals or books, whilst much resides as heuristic knowledge in the mind of the maintenance technician. The challenge facing a knowledge engineer charged with developing a decision support system is to identify and work with the available knowledge sources (documents and domain experts) to elicit and represent all facts and procedures necessary to solve specific equipment diagnostic problems.

The knowledge engineer would probably begin by examining existing equipment troubleshooting and service guides. However, troubleshooting guides would most likely quickly be found to be inadequate [Vagenas, 1991]. There are three reasons for this;

- Equipment maintenance has traditionally been the responsibility of equipment owners, usually mines. Whilst equipment manufacturers are involved in supporting maintenance programs, they do not have access to the day-to-day experience of mine maintenance personnel. Troubleshooting guides compiled by OEMs, therefore, do not generally include the heuristic knowledge of mine maintenance personnel. These heuristics include knowledge as to the likely frequency of types and classes of failures; heuristics which are of vital importance in ranking competing failure hypotheses.
- Troubleshooting guides and maintenance manuals are usually prepared to coincide with the release of new equipment models. Since little direct experience in maintaining the new model equipment exists, manufacturers turn to the experience gained in supporting older

model machines. The resulting troubleshooting guide is of limited applicability to the newer model machine.

- Both OEMs and mines can introduce equipment design changes which are not reflected in the troubleshooting documentation.

Having examined the available troubleshooting guides, the knowledge engineer would begin the process of acquiring knowledge from domain experts (equipment designers and maintenance technicians). Here the first task is the selection of a suitable knowledge acquisition technique or method. Knowledge acquisition techniques and tools are either manual or computer-based. The latter class includes automated and interactive knowledge acquisition tools. Automated tools for knowledge acquisition focus on learning from data rather than the direct acquisition of knowledge from a human expert [Lehto et al, 1992]. Interactive tools are generally associated with a particular knowledge acquisition methodology, and aim either to assist the knowledge engineer in capturing and organising knowledge or to empower a domain expert to explicate and formalise knowledge independently of a knowledge engineer. For the interested reader, Lehto, Boose, Sharit and Salvendy [1992] provide a good review of both interactive and automated knowledge acquisition tools. Despite the variety of tools available, the prevailing attitude amongst expert system developers is that manual knowledge acquisition is the most effective way to start building an industrially useful expert system. Bult [1991] of MacDonald, Dettwiler and Associates, states that "in our experience, getting a non-AI, non-software expert to interact with an expert system building tool does not work yet, except when the tool has been already tailored for the problem domain and for a given solution approach. Such an approach should not be hard-wired into a tool until the essential approach of experts in the field is understood!".

Assuming therefore that the knowledge engineer selects manual knowledge acquisition, there are a variety of techniques at his/her disposal with which to elicit knowledge. These are [Lehto et al, 1992];

- Brainstorming: the rapid generation of a large number of ideas,

- Unstructured interviewing: asking general questions and hoping for the best, recording as much a possible,
- Semi-structured interviewing: interviewing with open questions and a general list of topics to cover,
- Structured interviewing: interviewing with a strict agenda and a list of questions relating to features of the system,
- Teachback interviewing: the knowledge engineer demonstrates understanding by paraphrasing or solving a problem,
- Neurolinguistic Programming: observing physical cues (eyes, movement, body language) to enhance communication with the expert,
- Tutorial interviewing: the expert delivers a lecture,
- Protocol analysis: recording and analysing transcripts from experts thinking aloud whilst solving actual or simulated problems (sometimes called process-tracing),
- Participant observation: the knowledge engineer becomes an apprentice and participates in the expert's problem solving process.

A variety of techniques can be employed to organise knowledge elicited from these processes prior to formalization, including goal hierarchies, decision trees, flow diagrams and attribute/value matrices.

In practice, many problems are associated with manual acquisition techniques. Gaining access to experts can be difficult [Dubas, 1990]. Mines are reluctant to assign good mechanics away from their duties, since production might suffer. Multiple experts may have to be interviewed, which can result in conflicting knowledge relating to diagnostic approaches. The knowledge engineer may not understand the terminology used by the mechanics. Sometimes important pieces of information may be omitted from a knowledge base because the wrong questions were asked during an interview, or because the expert deemed something to be too trivial to explicitly state. In addition, knowledge acquisition problems can arise due to representation mismatch [Gruber and Cohen, 1988], where knowledge is lost during formalization due to the inability of current representation schemes to adequately express all types of knowledge.

1.4.4 Rapid Prototyping

Because of the difficulty in fully specifying the behaviour of the knowledge-based system at the beginning of a project, and because of the difficulties associated with acquiring knowledge, development of knowledge-based systems has been found not to fit the "waterfall" model of conventional software. In the waterfall model, software development follows clearly definable steps of analysis, design, coding, testing and maintenance with feedback loops occurring between stages [Pressman, 1992]. Development of knowledge-based systems has been found to fit an evolutionary process based on rapid prototyping [Hull and Kay, 1991]. In rapid prototyping, knowledge is obtained from experts via a series of interviews followed by the rapid development of a prototype working system before the knowledge-base is complete. The prototype is then used to prompt the experts to refine the existing knowledge base and supply additional expertise [Cullen and Bryman, 1988]. In 1991 a survey conducted of 23 US industry and government knowledge-based system developers found that all but one organisation made extensive use of rapid prototyping [Fenn and Veren, 1991].

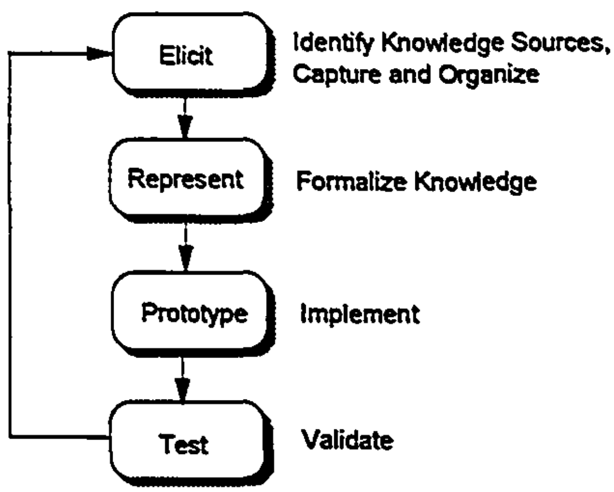

Figure 1.6 Rapid Prototyping Development of a Knowledge-Base

Figure 1.6 illustrates the development of a knowledge-base using rapid prototyping. Four development steps are iteratively repeated. The first step is to determine what knowledge is used by an expert to perform a cognitive task and to acquire and organise this knowledge [Hull and

Kay, 1991]. The second step is to formalise this knowledge, followed by step 3, the construction of a prototype of the expert system using existing knowledge. In step 4, the prototype is evaluated by expert users in order to identify missing knowledge or erroneous solutions. A variation of the prototype-and-test methodology is not to construct and test an actual prototype, but to represent the captured knowledge by means of semantic networks, flow diagrams or tables for evaluation. This type of knowledge-base refinement was used by Placer Dome to develop and implement an expert system for on-line process control of the rod mill at Dome Mine [Bowen, 1995].

The number of prototypes that need be developed prior to implementing an operational KBS depends on the availability of suitable experts, the skill of the knowledge engineer, the knowledge acquisition methods employed, the size of the domain and the selection of expert system development shell. Hull and Kay [1991] of NASA recommend that a minimum of five prototypes be constructed. In order of development, these are; demonstration, research, field, production and operational prototypes.

The prototype-and-test nature of acquiring knowledge and developing decision support systems is both people and time intensive. This has lead equipment manufacturers such as Atlas Copco to conclude that "expert systems .... are very costly and few users are willing to make the investment" [Nilsson and Ouellette, 1992]. Although the development costs of knowledge-based systems are not generally published, to illustrate this latter point, one large expert system which was successfully implemented in the pulp and paper industry is PITCH EXPERT which cost $2.8 million and required some 21 person years to complete [Kowalski et al, 1993]. PITCH EXPERT diagnoses pitch deposition quality defects in kraft pulp mills, and consists of approximately 1200 rules and 3000 schemata.

1.4.5 Model-Based Approaches

The discussion so far has focused on acquiring declarative, procedural and heuristic knowledge from domain experts in order to construct diagnostic decision support systems. Where knowledge is available regarding causes and symptoms but failure mechanisms are poorly understood, it is referred to as "compiled knowledge". In recognition of the problems posed by knowledge acquisition, in recent years much research in mechanism diagnosis has been directed towards model-based approaches. Milne [1987] distinguishes two classes of models used in KBS development. These are (i) computational models where an underlying mathematical description is used to numerically or qualitatively simulate the behaviour of a machine, and (ii) causal models which represent the causal sequences by which failure mechanisms occur. To this a third class of model should be added, namely (iii) structural models (schematics), which are non-computational in nature and used to represent the connections between components and system inputs and outputs.

The construction of numerical or qualitative models to simulate the behaviour of mobile mining equipment is a task which is complicated not only by the complexity and dynamic nature of a machine's subsystems, but also by the difficulty in modelling the interaction of a machine within a constantly changing environment. For this reason, the majority of decision support systems developed for mobile mining equipment have employed compiled knowledge or causal modelling approaches (see Chapter 2). Structural models do not attempt to explain the function or behaviour of mechanisms. They can be used to guide the acquisition of causal knowledge, or embedded as rules in the knowledge-based of a KBS to describe the connectivity of a device.

Maintenance technicians commonly use structural models as diagnostic aids in isolating failures. Reasoning generally follows the "trace-back" principle [Benjamins and Jansweijer, 1994], whereby the components upstream from a output observed to be faulty are sequentially examined for signs of malfunction [see Payne and McArthur, 1990]. Milne [1987] describes a variation of this process, trace-back and set intersection, whereby "one first identifies the path of information flow from the input of the portion of the device of interest to it's output. The path contains all the sub-components involved in that information flow .....all elements of the path are possible candidates.... One normally uses this approach by collecting a set of known good paths and a set of known bad paths. By intersecting paths known to be good and bad, faults in some portion of the system can be ruled out. That is, the sub-paths of a bad path that also occur in a good path can be assumed to be correct. The candidate set is then reduced to only those elements which occur in bad paths. This decision is solely based on GO/NOGO information and can be very efficient".

1.5 Research Objectives

From the previous discussion, the objectives of the thesis can be established. These are;

1. to adapt AI model-based diagnosis techniques to fault diagnosis of mobile mining equipment without developing computational simulation models, and
2. to demonstrate that, by reducing dependency on compiled knowledge sources and by reducing the number of prototyping stages necessary to develop a knowledge-base, the resulting methodology can be applied to accelerate the development of diagnostic decision support systems, and
3. to provide guidelines for estimating the benefits and costs of developing, implementing and maintaining a decision support system for mobile mining equipment troubleshooting.

1.6 Scope and Limitations

In the context of the thesis, two qualifications are necessary. The first is that this thesis is primarily concerned with the processes of hypothesis generation and hypothesis discrimination. These are the processes of generating possible explanations for faulty behaviour and of adding additional observations to discriminate between competing candidates. Symptom detection, the process of detecting behavioural discrepancies, is not covered in great detail other than to define normal and anomalous behaviour. The original proposal for doctoral work focused on the development of both a fault detection and a fault diagnosis system for an Atlas Copco Wagner ST-8B Load-Haul-Dump vehicle [Knights, 1993c]. This included the establishment of a set of sensor specifications for on-line condition monitoring of a semi-automated ST-8B vehicle (see Appendix 3), but did not extend to installing these sensors. Since a scaled-down sensor system was not implemented until August 1995, research effort in this thesis was directed towards fault diagnosis. As related to mobile mining equipment, the challenge of fault detection is to provide a measure of context-sensitivity by isolating factors such as working environment, ground interaction and machine duty cycle from recorded observations. Many techniques are associated with context-sensitive discrepancy detection, some of which have been the subjects of entire doctoral theses [see Lever, 1991]. Time and space requirements preclude a detailed review of these techniques.

The second qualification is that, although a method of diagnosing simultaneous multiple failures is presented in chapter 4, this thesis is mainly focused on the diagnosis of single failures. In practice, single failures account for the majority of mechanical and electrical failures [Knights, 1993a]. Simultaneous multiple failures are possible, and may occur dependently as the failure of one component triggers the failure of a neighbouring or downstream component, or independently. In addition common cause failures such as a fires or collisions can also result in multiple failures.

1.7 Contribution

The thesis is original and makes a number of contributions to the body of knowledge in the mining and related equipment industry. The first three points are of generic significance. It;

1. is the first work to apply set theoretical concepts to structural models of mobile mining equipment in order to diagnose faults,
2. provides significant modifications to the trace-back process used to generate contributor and normality sets (see chapter 4),
3. illustrates how the resulting analytical technique can be used to reduce the time, cost and number of prototyping stages necessary to develop a decision support system,
4. is the first mining-related work to implement a diagnostic decision support system in HTML (the standard language of the world-wide-web), and to demonstrate how HTML and web browsers can be used to implement low-cost, maintainable decision support systems for mobile mining equipment,
5. is the first work to suggest disseminating equipment diagnostic and maintenance knowledge over company wide internets ("intranets"), and
6. provides heuristic guidelines for estimating the costs and benefits of implementing diagnostic decision support systems for mobile mining equipment.

1.8 Thesis Organisation

Including the introduction and references, the thesis is organised into nine chapters as follows;

- Chapter two reviews work undertaken in the mining industry associated with decision support systems for mobile mining equipment troubleshooting.
- Chapter three provides a brief review of work undertaken in the AI community in regard to logic-based diagnosis. In particular, it focuses on model-based diagnostic approaches and introduces a generic model of diagnosis. Key concepts such as hierarchical diagnosis, contributor sets, normality sets and hypothesis testing techniques are introduced in this chapter.
- Chapter four presents the theoretical body of the thesis. This chapter introduces a hypothetical hydraulic circuit to demonstrate hypothesis set construction for single and multiple simultaneous independent fault diagnosis. In addition, the trace-back procedure for generating contributor sets is critically assessed.
- Chapter five applies the techniques developed in chapter four to the hydraulic circuit and the diesel engine of an Atlas-Copco Wagner ST-8B LHD vehicle.
- Chapter six discusses how manual knowledge acquisition techniques were used both to refine the knowledge base developed in the previous chapter and to add knowledge to discriminate between hypothesis candidates. The chapter also discusses how the completed knowledge base was implemented as a hypertext-based decision support system using the HTML language.
- Chapter seven presents a procedure for estimating the costs and benefits of developing both knowledge-based and hypertext decision support systems for equipment troubleshooting.
- Chapter eight concludes the thesis and discusses future work.

2. Decision Support System Applications

This chapter presents a review of decision support systems which have been or are in the process of being developed by OEMs, mining companies and research institutes to assist in troubleshooting mobile mining equipment. No attempt is made to review those companies and research institutes developing on-line monitoring systems or failure indicator systems. Such systems are mentioned only in the context of being associated with decision support systems to provide high-level interpretation of data. Throughout this chapter, emphasis is placed on the sources and techniques employed during knowledge elicitation, the type of knowledge representation employed and the life-cycle management of the decision support system.

2.1 Research Institutes

2.1.1 United States Bureau of Mines

Since the late 1980's the US Bureau of Mines has been active in conducting research on the application of knowledge-based system technology to mining equipment diagnostics and predictive maintenance. The USBM's approach has been to implement knowledge-based reasoning capabilities to the interpretation of on-line monitoring systems for continuous mining machines. Research has focused on three critical sub-systems of these machines; the hydraulic system, the electrical motors and the electrical control circuits [Cawley, 1991].

In 1990 a prototype expert system was developed for off-line diagnosis of electrical system faults in a Joy 16CM continuous miner [Berzonsky, 1990]. The system is a production rule system and was developed using the Level 5[1] development tool. Berzonsky states that "rule-based systems which contain a large number of rules can be difficult to develop and maintain". It was found advantageous to divide the electrical system of the Joy 16CM into four separate functional

[1] TM Information Builders, Indialantic, FL, USA.

circuits, the pump circuit, the conveyor circuit, the tramming circuit and the cutter circuit, and to separately develop and test the knowledge-base for each system. The user interacted with the system by answering a series of true/false and multiple choice questions.

In 1991, an on-line knowledge-based diagnostic system for the hydraulic system of a Joy 16CM continuous mining machine was developed [Mitchell, 1991b]. This system was initially implemented using the Rulemaster production-rule development tool, but later moved to the Goldworks[2] frame-based expert system platform as inadequacies became evident. The project was divided into two phases; the first phase addressed the development of the knowledge base containing the hydraulic diagnostic information and the second phase addressed sensor selection and data interpretation. Mitchell [1991a] describes the process of knowledge acquisition as "creating the biggest bottleneck in expert system development because of the difficulty in accessing every piece of knowledge an expert uses in solving problems". Two experts were used during the knowledge acquisition process; a designer who had had considerable experience in designing hydraulic systems for the mining industry and a maintenance technician with 14 years experience in maintaining the Joy 16CM continuous miner. Interviews were largely conducted by using protocol analysis. The designer reviewed the hydraulic schematics (structural models), broke the system into circuits and followed the propagation of faults from a component level. From this information, the structure of the knowledge base was laid out. The second expert reviewed the knowledge gained during the first phase, and both experts played an important role in validating the formalised coded knowledge base. Mitchell [1991a] states that "rules were misinterpreted during the transfer of knowledge from the domain expert to the knowledge engineer", and also that the "cycle of gathering knowledge, formalising and coding knowledge and validating the resulting knowledge repeats itself continuously as part of maintaining the system".

Recent diagnostic work sponsored by the USBM has moved away from consultation-based diagnostic decision support systems to diagnostic approaches that require no user input. In 1994, a sensor-based diagnostic system for the electrical control circuit of Joy 14CM machine was developed and tested [Kohler et al, 1994]. The developers examined the use of knowledge-based

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2 ™ Gold Hill Inc., Cambridge, MA, USA.

systems to assist in troubleshooting the control circuit, but rejected consultation-based systems because "they require the user to make a series of manual electrical measurements during a consultation" [Kohler and Sottile, 1993]. The system implemented by Kohler and Sottile employs 59 sensors which measure voltage into and out of critical circuit components, and is capable of identifying 35 different component failures. An Intel 44/10a micro-controller is used to evaluate a series of logic equations using the sensed voltages, and the user is notified of the presence of a fault via a two digit error code [Kohler et al, 1994]. In effect, the resulting troubleshooting system is a sophisticated failure indicator panel which uses software logic in place of hard-wired logic (HWL). Whilst the failure indicator approach can be appropriate for electrical circuits because of the relative ease of implementing voltage measurements, this type of approach is not suited to hydro-mechanical systems because of the expense and effort required to installing large numbers of sensors and because of the reliability problems associated with a large number of sensors.

2.1.2 University of Alabama

In 1989, a rule-based expert system to troubleshoot electrical faults in a Joy 21C shuttle car was developed by researchers working in the Department of Mineral Engineering at the University of Alabama [Novak et al, 1989]. The system, called SCAR, was initially developed using the Insight 2+[3] expert system development tool. The SCAR knowledge base, which consists of approximately 600 production rules, was developed using a model-based approach employing qualitative reasoning. Knowledge of the structure and behaviour of the pump, conveyor and traction circuits were used to construct a logical simulation of the circuits from first principles. Causal equations were derived by considering qualitative finite output states for components such as "high", "low" and "normal" [see Whitehead & Roach, 1987].

The SCAR knowledge-based system exhibited a number of deficiencies in that potential faults were considered in the order that components occurred in a circuit (no priority was given to faults on the basis of probability), and crude graphic capabilities prevented the presentation of

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3 ™ Level Five Research Inc.

schematics to the user [Patton et al, 1989]. To address the latter deficiency, a second generation system called SCAR.2 was constructed using the M1[4] expert system development tool. The original knowledge base of SCAR contained little or no structure which made changing rules extremely difficult. In SCAR.2, the knowledge base was restructured along hierarchical lines by considering major components as a collection of minor parts. This allowed the knowledge base to be structured into 10 distinct modules. In addition, a graphics module written in Microsoft C and HALO[5] was added to M1 to display circuit schematics to the user. As the system prompts the user to perform voltage measurement tests, a wiring diagram indicating the appropriate test point is presented to the user. In addition, a tutorial and explanation module was added to the system using the TURBO BASIC language [Novak et al, 1989].

2.1.3 University of Alberta

In August 1992 the Intelligence Engineering Laboratory of the University of Alberta, Syncrude Canada Limited and NSERC (National Science and Engineering Research Council of Canada) initiated a collaborative research project to develop an Intelligent Maintenance Support System (IMSS) for condition monitoring and troubleshooting the 190 ton Marathon LeTourneau T2000 diesel-electric trucks used by Syncrude [Intelligence Engineering Laboratory, 1993]. On-line condition monitoring was implemented using 21 analogue and 25 digital signals collected via the Marathon LeTourneau VSM™ (Vital Signs Monitoring) unit installed on each truck. The prototype IMSS was based on an in-house intelligent hypermedia system called INTEMOR, which has an integrated real-time event handling module and a knowledge-based reasoning module and supports SGML (Standard General Markup Language) hypertext documents. A hybrid approach to failure diagnosis was proposed for the system, whereby diagnosis would first proceed using case-based reasoning, and if the failure database could not find a match for the symptom set, the fault would be deemed novel and diagnosis would proceed via production rules based on compiled knowledge. It is not known what procedures were used to construct the

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[4] ™ Teknowledge Inc., Palo Alto, CA, USA.

[5] ™ Media Cybernetics Inc.

diagnostic knowledge-base, however the project was later cancelled when Syncrude Canada withdrew financial support.

2.1.4 University of Alaska, Fairbanks

Two prototype decision support systems produced by the Department of Mining and geological Engineering at the University of Alaska, Fairbanks, are DES (Dragline Expert System) and an expert system to diagnose faults in longwall shearers [Bandopadhyay and Venkatasubramanian, 1990; ibid, 1991]. Both systems were production rule systems written in PROLOG. Augmented fault trees were used for deriving production rules. Bandopadhyay and Venkatasubramanian [1991] acknowledge the difficulties inherent in acquiring knowledge, and state that a key contribution of their work is the establishment of a framework for failure diagnosis which uses failure information to back track along fault propagation paths within the system to locate sources of failure, and then identifies causes at these sources.

2.1.5 Luleå University of Technology

PROGNOS and DIAGNOS are two prototype expert system applications which were developed by Vagenas [1991] at the Division of Mining Equipment Engineering at Luleå University, Sweden. PROGNOS is a production rule system for diagnosing faults in the transmission of Toro 500 LHD models at LKAB's Kiruna Mine, Sweden. It was developed using a development tool called 1st Class[6], and is capable of identify 96 faults and 102 different repair actions [Vagenas, 1991a]. The knowledge-base for PROGNOS was elicited mostly from mine fault reports and from discussions with repair personnel. As knowledge was gathered, rule formalisation became possible and these rules were separated into modules representing the key transmission components or parts. Vagenas [1991] states that "the vehicle's manual provided limited information".

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6 TM Programs in Motion Inc., MA, USA.

DIAGNOS is another production rule system which diagnoses faults in the electrical system of Kiruna 1050 electric trucks. Vagenas [1993] describes knowledge acquisition as the "critical step in the design process of an expert system, and lists the major source of knowledge for DIAGNOS as design documentation provided by Asea Brown Boveri (ABB) Drives AB., supplemented by knowledge elicited from interviews with ABB design specialists and Kiruna maintenance personnel and knowledge derived from relevant textbooks. DIAGNOS was implemented using the 1st Class development tool, and is distributed by ABB Drives AB. It is interesting to note that in an earlier report, Vagenas [1991b] examined the application of computational model-based diagnosis systems and concluded that the development work required for such systems "demands long term commitment from equipment manufacturers" and is "a time consuming and costly task".

2.1.6 Colorado School of Mines

A mine management intelligent decision support system (MMIDSS) has been developed by researchers at the Colorado School of Mines [Lever, 1993; ibid, 1992; Lever et al, 1991; Lever 1991; Schricker et al, 1988]. The system classifies patterns in electrical consumption of a shuttle car, and detects and diagnoses discrepancies. The system was first implemented at Western Fuel Utah Inc.'s Deserado Mine using an electric shuttle car as a test vehicle [Schricker et al, 1988]. Initial work concentrated on development of a parsing algorithm to fit a linear piece-wise regression model to the monitored data [Schricker et al, 1988]. Pattern recognition techniques were applied to identify the stages of the shuttle car duty cycle to enable context sensitive detection of irregularities [Lever et al, 1991]. Machine learning algorithms were developed to detect significant changes in electrical demand patterns for electrical equipment as compared to previously recorded patterns [Lever, 1992]. A difference detection algorithm was developed to quantify the resulting performance differences, and a production rule system implemented using Knowledge Craft Tools to assist in diagnosing the resulting production problems. The production rules were developed from interviews conducted with mine managers [Lever, 1993].

2.2 Mining Companies

2.2.1 INCO Limited

A prototype expert system was developed by INCO Limited in the late 1980's to assist maintenance personnel in troubleshooting faults in a Wagner ST-8A Load-Haul-Dump vehicle [Baiden, 1988]. The M1 rule-based expert system shell was selected as the development tool and an initial estimate of 5000 rules was made as to the size of a complete diagnostic system. That the development of such a knowledge-base would require many prototype and test stages was acknowledged by Baiden who stated that "the knowledge base will evolve over the next five years being constantly updated and enhanced". A development team consisting of a project manager, maintenance expert and a knowledge engineer was formed to undertake the project, with each team member having a clearly defined role. To facilitate development, the project was broken down according to major vehicle subsystems with initial development concentrating on the brake system of the ST-8A. A test system consisting of 80 rules was constructed, however when Wagner introduced the ST-8B vehicle which has hydraulic wet-disk brakes as opposed to the older calliper disk brake system on the ST-8A, the project was shelved.

A second expert system application was developed by INCO Limited to assist operators of an automated haulage truck [see Baiden, 1992] in determining the cause of PLC-based error codes. This system was developed using the Comdale/X[7] development tool, and made extensive use of Comdale's hypertext interface since it was acknowledged that; "the user interface is a very important aspect of the expert system. It determines to a large extent whether or not the application will be accepted by the user" [Zakaria, 1994]. Knowledge acquisition for the system was acknowledged to be difficult, and ultimately limited the scope of the system to serving as a tool for equipment operators rather than equipment maintenance personnel.

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7 TM Comdale Technologies Inc., Toronto, Canada.

2.2.2 Noranda Inc.

A somewhat different approach to diesel engine diagnosis has been taken by Noranda Inc. The Mechanic's Stethoscope is a computer-based test instrument developed at the Noranda Technology Centre which is intended for use during regular vehicle service periods [Johnson et al, 1994]. The instrument plugs into an on-board sensor which measures the instantaneous rotational velocity (IRV) of the engine crankshaft. Data acquisition and processing is performed by a computer and software external to the machine. Processed data is graphically presented to the user, allowing the user to interpret combustion irregularities in individual engine cylinders. The suite of software includes a hypertext maintenance manual to assist the mechanic and a hypertext system called CatBase[5] which enables electronic representation of parts books [Noranda Technology Centre, 1994].

2.2.3 Ruhrkohle AG.

At RuhrKohle AG. an expert system called INTEX has been developed for the failure diagnosis of longwall shearers. This rule-based system was developed using heuristic compiled knowledge [Danielczyk, 1993]. INTEX also provides a hypertext facility capable of supplying the user with text, images, audio and video clips concerning repair procedures.

2.3 Original Equipment Manufacturers

2.3.1 Caterpillar Inc.

As touched upon in Chapter 1, Caterpillar have developed a comprehensive on-board monitoring unit called VIMS (Vital Information Management System) which is already in production on Caterpillar's larger mining shovels and trucks. VIMS is a modular system that contains a main

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5 TM Novalog Informatique Inc., Montréal, Canada.

control module, one or more interface modules, an operator display, key pad and application software to download and display monitored data [Chatham 1995]. The main module communicates over a high speed data link to data acquisition and control modules, for example the ECM (engine control module) on a diesel/electric truck. The main module performs alarm handling based upon critical parameter thresholds and stores data. VIMS alarm handling provides three levels of alarm severity; "be aware", "modify operation" and "shut the machine down" [White, 1995]. Three categories of data can be stored;

- exception-based data; stores data when an "event" is detected by either a monitored parameter exceeding a defined limit or a failure code is directly received from an electronic module.
- recorder data; can be initiated by an event or at the command of the operator to record all monitored parameters for a period of time, and
- prognostic data; displays trends, histograms, averages and cumulative values recorded in a specific time frame.

The data collected by VIMS can be telemetered to just about any location. As of September 1994, Caterpillar Preoria were receiving on-line data via satellite and fibre optics from two dozen mining shovels in the field, and in one case, were able to predict and prevent a major pump failure one hour before the operator knew there was a problem [Ferguson, 1994].

However, as mentioned in Chapter 1, VIMS can generate an enormous amount of data, which requires interpretative skills to convert into useful information. In recognition of this problem, Caterpillar is working on a concept called Advanced Product Services (APS) which will provide off-board software to trend, and detect anomalies in machine performance. Discrepancy detection will employ a performance model of a machine capable of taking into account the machine's working environment and application [Ferguson, 1994]. At this stage, APS will perform symptom detection only. When a potential or existing problem is detected, the mechanic can refer to the Caterpillar Service Information System (SIS) which is a set of computer compact discs containing the latest service and technical information in multimedia form. SIS includes a set of fault charts which a mechanic can use to troubleshoot faults [Scholl, 1995].

2.3.2 Shovel Manufacturers

In addition to Caterpillar, other manufacturers of cable and hydraulic mining shovels have also implemented on-board monitoring systems with microprocessor-based diagnostics. Harnischfeger has introduced an system which continuously monitors for the presence of electrical faults. If faults are detected, they are displayed to the operator in everyday language so that the operator need not consult a list of error codes. Appropriate procedures to correct the fault are also displayed to the operator. The system provides a large data storage capacity, and can be used to record performance information such as swing angles and times [White, 1995].

Marion Indresco Inc. [1995] has redesigned the electrical control and diagnostic systems of its new series III 301M and 351M shovels. The new SCEPTER™ electrics system incorporates fully digital drive regulators and controls. Microprocessor-based controls enable enhanced diagnostics capability to be built into each drive motor. Each drive is capable of reporting 170 different error types to a master computer. Fault causes and recommended actions are displayed to the operator in common language.

Mannesmann-Demag offer an electronic monitoring system for their shovels called the Electronic Check System, or ECS system. The system is capable of monitoring vital parameters, logging data and providing decision support for equipment troubleshooting via an integrated HELP function. If an error is detected by the monitoring system, possible causes are displayed to the operator. For example, if HELP is invoked for the message "Oil Temperature too high", the following will be displayed; "Check cooler for contamination - Check oil level". The most recent version of ECS is called ECS/T, which is capable of taking over real-time control functions, can be programmed on site via a laptop PC and has a larger non-volatile memory to facilitate storage of service instructions [Wulfert, 1994].

In addition to the three systems mentioned above, Bucyrus-Erie, Liebherr, Hitachi and O&K offer diagnostics built around microprocessor-based electronic control systems [White, 1995]. For each manufacturer, the design rational appears to have been to develop a comprehensive onboard monitoring system (linked with a microprocessor control system) and to add limited decision support facilities for fault explanations and recommended action. The percentage of machine faults able to be detected and diagnosed therefore depends mainly on the diagnostic coverage provided by these onboard monitoring systems.

2.3.3 Tamrock Loaders (ARA) Oy.

The State Technical Research Centre (VTT) Laboratory of Computer Technology at Oulu, Finland, are currently in the process of developing a computer-based fault diagnostic system for LHD vehicles manufactured by Tamrock Loaders (ARA) Oy. [TEKES, 1994]. When complete, the system will utilise sensor-based information from Tamrock Loaders modular condition and production monitoring system to analyse machine condition and prompt for tests to be performed during regular service periods. Fully developed, the system will provide assistance in locating faults in loaders. The initial project was of two man-years duration, with knowledge acquisition being undertaken in conjunction with personnel from Outokumpu Oy. Current project status is unclear, however it was acknowledged upon conclusion of the initial project in October 1994 that a continuation was necessary in order to implement solutions into practice [TEKES, 1994].

2.4 Discussion

Three observations can be made in relation to the surveyed decision support system applications. The first of these is that diagnostic decision support systems are well suited to equipment subsystems where failure indicator approaches are too costly or intrusive to implement. For example, electrical systems are well suited to failure indicator diagnostic approaches because of the ease of establishing voltage measurements, but retrofitting sensors to a hydraulic system is a costly alternative. Troubleshooting decision support systems are therefore well suited to hydraulic or mechanical subsystems which do not have built-in microprocessor sensing or control capabilities.

The second observation is that all of the decision support systems surveyed employed a multistage prototype and test approach to development, and in almost all cases manual knowledge acquisition techniques were used in which a knowledge engineer elicited knowledge from one or more domain expert. The exception to this is the University of Alabama's SCAR system, which used a model-based approach to knowledge acquisition. In this approach, structural diagrams were used to establish qualitative equations regarding subsystem functions. Constraint suspension was then used to simulate faulty behaviour, and components grouped according to system behaviour to generate sets of fault hypotheses. This work is perhaps the closest related to the work presented in this thesis. In common with the SCAR system, a model-based approach to knowledge acquisition is presented. The major difference in the approach of this thesis, however, is that structural models, rather than computational models are used for hypothesis generation. The development of numerical or qualitative models to simulate equipment behaviour is not required, however a non-relational form of qualitative reasoning is used to discriminate between hypotheses in the form of fault likelihoods.

The third observation is that, for each diagnostic decision support system reviewed in this chapter, little information is published regarding operational experience. Most published articles deal exclusively with DSS development, and the reader is left wondering about the relative success in implementing and maintaining the systems. The need to refine and upgrade the knowledge base of a DSS is an important consideration in the life cycle of a DSS, and one that should be budgeted prior to commencing a project (see chapter7).

3. Model-Based Diagnosis

In 1983 a seminal expert systems textbook stated that; "uncovering the underlying model of the process used to generate solutions in the domain can be an important step in formalising knowledge. The types one can look for include both behavioural and mathematical models. If the expert uses a simplistic behavioural model when reasoning or justifying reasoning, analysing it may yield numerous important concepts and relations. If there is a mathematical (numerical or statistical) model underlying part of the conceptual structure, it may provide enough additional problem solving information to be included directly into the expert system. Or it may serve merely to justify the consistency of causal relationships in the expert system's knowledge base" [Hayes-Roth, Waterman, Lenat, 1983].

The term "model-based diagnosis" is one which is widespread in knowledge-based system literature, but one which also gives rise to considerable confusion due to its lack of specificity. Confusion arises because there are many different types of models. Models can be used at different stages of the diagnosis process, and may be embedded within or used externally from a DSS. This chapter distinguishes how different model types, especially structural models, effect diagnosis. A generic model of diagnosis is introduced and shown to be applicable to the diagnosis of systems modelled at successively finer hierarchical levels of abstraction.

3.1 Logic-Based Diagnosis

Diagnosis can be divided into two dominant paradigms; logic-based and probabilistic-based approaches. In the logic-based paradigm, diagnostic knowledge is typically represented as a first-order theory of operation for the system being diagnosed, and the diagnosis task is to find the set of diagnoses which are logically possible given the symptoms. In the probabilistic approach, knowledge is typically represented as a set of associations between disorders and their symptoms, with the task being to find the set of disorders which is most likely given the symptoms

[Hamscher, 1991]. Probabilistic approaches are more prevalent in medical diagnosis, since ill people can have multiple interacting disorders, symptoms are not definitively associated with a particular disorder and there is often considerable uncertainty about whether a symptom is present or not [Bobrow, 1994]. Logic-based approaches are more common in mechanism diagnosis, since first-order models are more readily derived for mechanical devices.

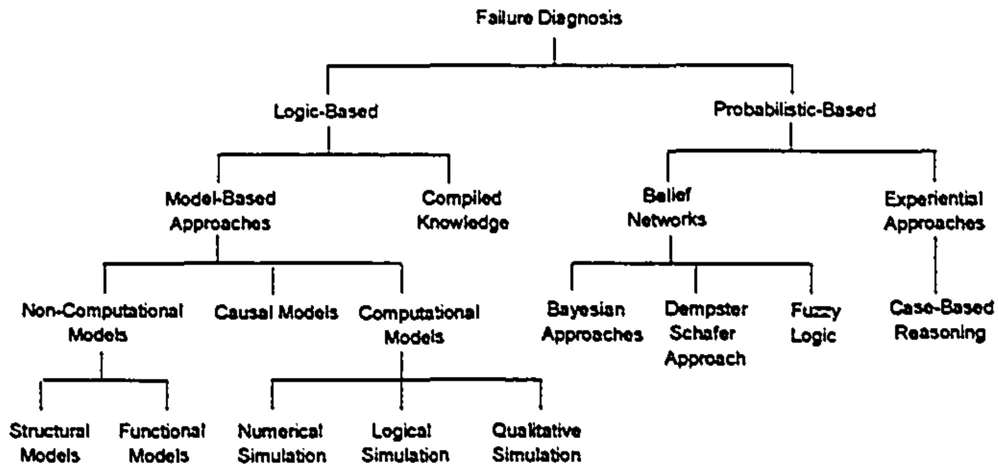

Figure 3.1 Knowledge-Based Approches to Diagnosis

Figure 3.1 illustrates the major knowledge-based diagnostic approaches and shows how they relate to the two dominant paradigms. Logic-based diagnosis includes model-based approaches and production rule approaches based on compiled knowledge (direct symptom-fault association). As mentioned in Chapter 1, model-based diagnosis can be subdivided into computational models and causal models (cause-effect chains). In turn, the computational modelling approach can be split into structural reasoning, numerical simulation [see for example Patton et al, 1989] and qualitative simulation [see for example Forbus, 1984; Kuipers, 1984]. On the right hand side of the figure, probabilistic reasoning can be partitioned into two distinct approaches; belief networks [see for example Pearl, 1986] and experiential or learning approaches. Belief networks primarily provide a mechanism for focusing searches in fault hierarchies in the presence of uncertainty. Three navigation techniques which are commonly employed are; Bayesian approaches, Dempster-Shafer belief functions and, more recently, fuzzy logic approaches. Experiential approaches embrace the domain of machine learning. An area of growing importance in commercial diagnostic decision support systems is case-based reasoning, which is the ability to reason based on past experience [Kolodner, 1993; Pauley, 1994; Abu-Hakima, 1994].

3.2 Task Decomposition

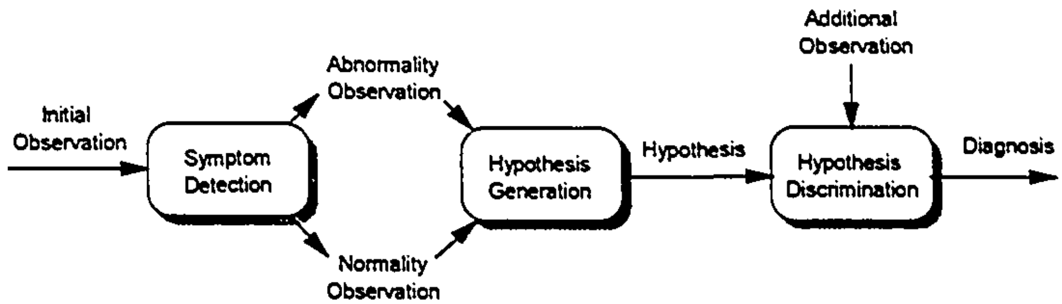

Figure 3.2; Generic Task Decomposition of Diagnosis [Benjamins and Jansweijer, 1994]

Diagnosis is the problem of trying to find out what is wrong with a system based on knowledge about the design/structure of the system, possible malfunctions that can occur in the system and observations made of the behaviour of the system [Poole, 1989]. Figure 3.2 illustrates a generic decomposition of diagnosis as postulated by Benjamins and Jansweijer [1994]. Diagnosis is viewed as three distinct processes;

- Symptom detection; finding out whether a complaint is in fact a symptom (an observation that deviates from its expectation)
- Hypothesis generation; generating possible causes based on the symptoms and the initial observations, and
- Hypothesis discrimination; using additional observations to discriminate among generated hypotheses.

Additional observations are treated separately from initial observations, since these observations are often the cost determining factor in practical diagnosis.

3.2.1 Hierarchical Abstractions

Two factors are frequently cited as being important performance indicators for diagnostic decision support systems; coverage and resolution. A decision support system has coverage if it detects all the faults that could occur in a device. Resolution is the specificity with which the system can identify the parts that could be responsible when a fault is detected [Hamscher, 1983]. Models can be chosen which represent systems at different levels of abstraction, and resolution is affected by the resulting grain size of each model. It has long been recognised that hierarchical system abstractions can be employed to speed up knowledge-based diagnosis by effectively pruning diagnostic decision trees [Brown, 1976]. In 1984, IBM demonstrated that hierarchical diagnosis is more efficient by providing a comparison of computation costs for hierarchical and non-hierarchical diagnosis [Genesereth, 1984].

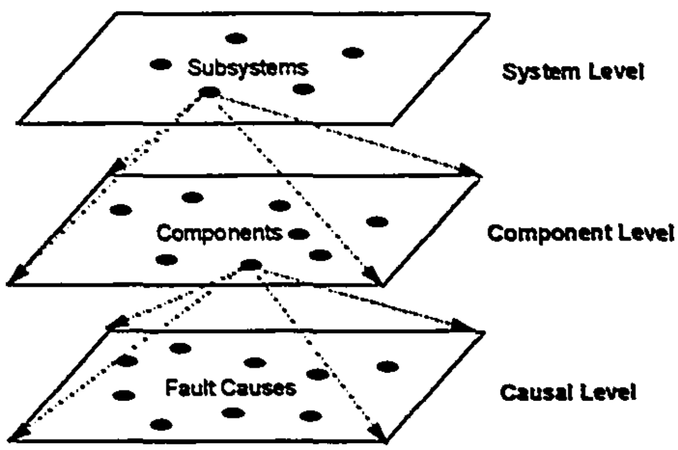

Figure 3.3 Hierarchical Failure Diagnosis

Figure 3.3 illustrates how hierarchical diagnosis works. The diagram illustrates a three-level diagnosis process, but, in practice, diagnosis of complex machines may require more levels of abstraction. When a malfunction is observed in a device, the failure is first isolated to a suspect sub-system. Diagnosis then moves down to the component level, where components of that subsystem are considered. Having isolated the failure to a specific component, the causes of the component failure are considered at the lowest level of abstraction, the causal level.

The generic task model outlined in Figure 3.2 is an important one because it can be iteratively applied at the different levels of system abstraction. For instance, in newer model long-hole drills, electrical control systems have replaced hydraulic pilot control systems. If, for example, a fault was observed in the drill feed mechanism of a newer model drill having electric-over-hydraulic controls, diagnosis would proceed by first isolating the failure to either the electrical or hydraulic system. Applying the diagnosis task model, a mechanic would, for example, formulate a hypothesis that one or other of the sub-systems was at fault and then additional observations would be added to confirm or eliminate the hypothesis. If the hypothesis was confirmed, the mechanic would begin the diagnosis process over again at a lower level of the sub-system in question, probably the component level. If the hypothesis proved false, diagnosis would switch to the component level of the alternative sub-system.

3.3 Symptom Detection

The first task in diagnosis is to classify the behaviour of a machine as either normal or abnormal. Symptom detection consists of making actual observations of machine behaviour during operation and comparing these with expected behaviour in order to detect discrepancies representative of faults.

3.3.1 System Observations

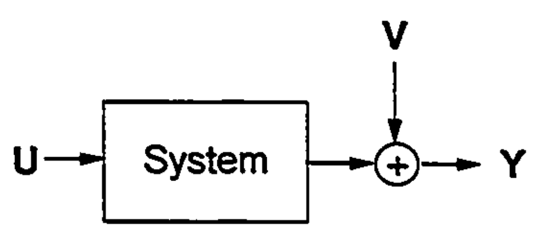

Figure 3.4 System Inputs and Outputs

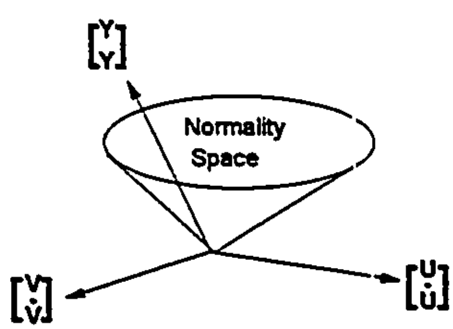

Figure 3.5 Normality Space in N Dimensions

Knights and Daneshmend [1995] define observations as follows. Figure 3.4 illustrates a simple block representation of a system without feedback [see Isermann, 1989]. The vector **U** represents inputs to the system and **Y** represents measurable outputs (mechanical and electrical systems are commonly designed to fulfil more than one function, and consequently more than one output must be monitored for behavioural discrepancy). **V** represents disturbances introduced to the system from the machine's working environment. These disturbance influences result from a multitude of factors, including changes in geological properties, rock hardness, and blast design. Some of these factors are unmeasurable in practice, but may be qualitatively observable. If adequate information is available regarding the environment **V**, context sensitive comparison between actual and expected behaviour becomes possible. An observation vector can be defined which incorporates observations of **U**, **V** and **Y** together with their respective time derivatives. A region of normal expected behaviour can be represented in N-dimensional space as in Figure 3.5. The boundaries of this region of normal behaviour will change according to the duty cycle of the machine. If an observation vector should fall outside of this normality space, the system's behaviour is considered faulty. These abnormality observations can be classified as failure modes according to the magnitude and direction of the deviation of the observation vector from the normality space envelope. An observation therefor consists of a set of;

{ {input actions or conditions}, {output measurements} }.

Output behaviour may either be measured quantitatively by sensors (as in the case of on-line monitoring systems) or qualitatively by humans.

3.3.2 Generating Expected Values

Generating expected values for machine performance can be achieved by a number of means. The first is the qualitative assessment of machine behaviour based on operator experience (compiled knowledge). Whilst this form of expectation generation provides a measure of context sensitivity, some disturbance influences may not be directly quantifiable by an operator. The second form of expectation generation is via a look-up table. This is used, for example, during maintenance servicing procedures such as stall testing diesel engines.

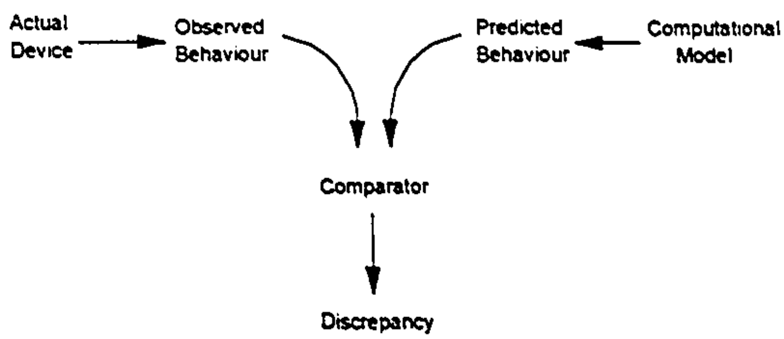

Figure 3.6 Model-based Symptom Detection [Davis and Hamscher, 1990]

The third means of generating expected behaviour is via computational models capable of simulating machine behaviour (see Figure 3.6). Simulation using functional computational models are perhaps the most classical use of models in diagnosis. However, these models are difficult to develop for mobile mining equipment, since machine environmental parameters are constantly changing and machine-ground interaction is not fully understood and difficult to model.

3.3.3 Comparing Actual and Expected Values

Comparing the expected value of a behavioural parameter with an observed value can be performed by a number of methods. These are [Benjamins and Jansweijer, 1994];

- Exact comparison; where the observation and expectation are directly compared,
- Threshold comparison; where the observation is compared to an alarm threshold. The severity of an alarm can be measured by how much the threshold has been traversed. Trending techniques, such as curve fitting and moving averages and rate-of-change can be used to predict when alarm thresholds will be crossed.

- Order-of-magnitude comparison; where the expectations and observations which differ but are in the same order of magnitude are considered equal,
- Historical comparison; where the observation is compared to historical data. Doyle [1995] provides a variation of this called the deviation measure which compares current discrepancy values to previously recorded discrepancy values to provide a measure of alarm severity.
- Teleological comparison; provides context sensitive alarm handling by taking into account the duty cycle of a machine when an observation is made.
- Statistical comparison; where the expectation is expressed in the form of statistical information (such as a normal distribution) before comparing it with the observation

3.4 Hypothesis Generation

The hypothesis generation task produces a set of suspect entities (sub-systems, components or component failure modes), each of which, if faulty, would explain all initial observations. This resulting set is known as the hypothesis set. There are two basic methods for generating hypothesis sets; compiled and model-based methods [Benjamins and Jansweijer, 1994].

3.4.1 Compiled Methods

The compiled method exploits direct relationships between symptoms and causes. Compiled methods are often used in domains such as medical diagnosis where failure mechanisms are not fully understood. Probabilistic filtering techniques are frequently used with compiled knowledge systems to generate and rank entities within hypothesis sets.

3.4.2 Model-Based Methods

Model-based hypothesis generation methods exploit structural, computational or causal models of the system under diagnosis. Hypothesis sets are generated by;

- finding sets of model entities which *contribute* to an abnormality observation,
- transforming these contributor sets into a hypothesis set, and
- using prediction-based filtering to discard entities from the hypothesis set if they are inconsistent with the initial observations [Benjamins and Jansweijer, 1994].

3.4.3 Contributor Sets

A contributor set is a set of entities at least one of which, if faulty, would explain an abnormality observation made *a single* system output independent of the behaviour of other system outputs. Contributor sets have also been called "conflicts" [de Kleer and Williams, 1987] and "conflict sets" [Reiter, 1987]. Finding these contributor sets can be achieved by a number of methods; trace-back, causal cover or prediction-based simulation [Benjamins and Jansweijer, 1994].

Trace-back finds the contributors by tracing back from the affected output to the system inputs along paths of information flow between entities. In a structural model, these paths are the connections (electrical wiring or hydraulic pipes) between components. However, trace-back commonly relies on the assumption that faults propagate in the direction of information flow between entities [Hamscher 1983; Milne, 1987; Payne and MacArthur 1990]. As Chapter 4 will show, this is not always the case.

The causal cover method of generating contributor sets operates on causal models. It is based on including within the hypothesis set all of those entities represented by branches in the cause-effect diagram associated with an observed symptom.

Prediction-based simulation systematically uses numerical, qualitative or logical models to simulate and suggest possible faulty entities. A good example of logic-based simulation is the General Diagnostic Engine (GDE), introduced by de Kleer and Williams [1987]. GDE provides a systematic means of generating contributor sets by considering mathematical combinations of the components making up a device, assuming that these components are healthy (the assumption set), simulating device output behaviour and comparing it with actual observed behaviour. Where a discrepancy results, the set of components in the assumption set are concluded to be a contributor set. In order to generate minimal contributor sets (sets in which no subset is itself a contributor set), GDE begins by considering only the minimum number of components necessary to generate an output response. GDE exploits an assumption-based truth maintenance (ATMS) reasoning process [de Kleer, 1986] to keep track of the assumptions as well as truth values. However, ATMS uses a breadth first manner of incrementing its search [Stanojevic et al, 1994] which makes it computationally expensive and difficult to scale up to diagnostic problems involving large numbers of components.

3.4.4 Normality Sets

A normality set is a set of entities *all* of which must be functioning normally in order to explain normal, or expected behaviour observed at *a single* system output considered independently of other system outputs. Normality sets have also been called corroborative sets, first introduced in the expert systems LOCAL [de Kleer, 1976] and SOPHIE [Brown et al, 1976]. Normality sets are sub-sets of the contributor sets associated with system outputs. Normality sets can be used in the hypothesis generation process to yield extra discriminatory power. This was observed by Milne [1987] who stated that sets of entities in "good" paths (normality sets) can be used to eliminate entities in "bad" paths (contributor sets). Work by Poole [1989] and Console and Torasso [1990] also examines the use of normality observations to augment hypothesis generation.

3.4.5 Hypothesis Sets

Hypothesis sets can be established from the contributor and normality sets developed for each system output. A hypothesis set contains component sub-sets, each of which, if faulty, would explain overall system behaviour. Overall system behaviour consists of a combination of normality and fault observations as observed at all system outputs. Dependent on whether single or multiple faults are suspected within a mechanism, two hypothesis generation methods can be employed; set intersection and set covering [Benjamins and Jansweijer, 1994]. In the set intersection method, contributor sets associated with faulty outputs are intersected to obtain an intersection set. A hypothesis set is obtained from the intersection set by eliminating those components common to the normality sets associated with the healthy outputs.

In the set-covering method, first introduced by Reggia, Nau and Wang [1983], the hypothesis set consists of a set of component sub-sets, called cover sets. Each cover set has a non-zero intersection with each of the contributor sets associated with the system's faulty outputs. Each cover set therefor "covers", or explains all of the system fault observations. Cover sets are important in the diagnosis of systems in which multiple simultaneous faults are suspected. The set covering method was formalised by Reiter [1987] who introduced a logic-based algorithm to generate cover sets, or "hitting" sets, by considering contributor sets only. A set-covering method which incorporates normality observations is presented in Chapter 4

3.4.6 Hypothesis Filtering

Prediction-based filtering is employed by some knowledge-based diagnostic systems and omitted from others. Prediction-based filtering is not a means of discriminating between hypotheses, but rather a means of filtering inconsistent hypotheses out of the hypothesis set. Three techniques which can be employed to filter hypothesis are; constraint suspension, corroboration, and fault simulation [Benjamins and Jansweijer, 1994]. Constraint suspension was first introduced by Davis [1984], and involves relaxing the inference and simulation constraints imposed on the functional simulation of a hypothesis set entity in order to confirm that the simulated model behaves according to the initial fault observations. Corroboration applies the idea that if a measured value matches a predicted value at a particular point in a network, then the component responsible for the measured behaviour must be innocent and can be discarded from the hypothesis set [Davis and Hamscher, 1990]. Fault simulation models the hypothesised fault in a device and simulates device behaviour to checks for discrepancies between observed faulty behaviour and predicted faulty behaviour.

3.5 Hypothesis Discrimination

The hypothesis discrimination task involves adding additional observations to the diagnostic process in order to eliminate candidates from the hypothesis set and isolate the cause (or causes) of a failure. The discrimination task consists of three sub-tasks; hypothesis selection, testing and updating the hypothesis set.

3.5.1 Hypothesis Selection

Additional observations are added to the diagnosis process via physically testing a system. The order in which hypothesis set entities are selected and tested can guided either by random selection techniques or by consideration of the cost of testing each hypothesis. Costs can be established using a number of criteria, including *a priori* probabilities or the expected number of tests necessary to isolate the fault with sufficient resolution.

3.5.2 Testing Techniques

Testing hypotheses can be achieved by one of four methods; compiled tests, probes, manipulation or replacement of components [Benjamins and Jansweijer, 1994]. Compiled tests utilise knowledge which is laid down as test procedures. Probes involve the use of test instrumentation to taking additional measurements of the behaviour of a device. In mobile mining machinery this can expensive, since certain components can be difficult to access and inspect (for example, the rollers in a dragline swing assembly). The additional observations resulting from probing must again be compared with expected results for discrepancies. Again, computational models can be used to simulate these expected results. Recently, the attention of researchers has turned towards devising optimal probing strategies with the realisation that probing costs limit the practical application of knowledge-based systems [see de Kleer and Raiman, 1995].

Manipulation methods force the inputs of a system to known values and determine system outputs. The vector combination of inputs necessary to test a particular sub-system or component must be known in advance for manipulation methods to be effective. Such techniques are commonly employed in, for example, computer self-diagnostics. Replacement testing methods work by replacing suspect components (or sometimes subsystems) in order to test hypotheses. In such a way, replacement tests not only isolate failures, but also effect repairs. However, replacement testing should be used with caution since considerable expense can arise if faulty components are not corrected first time around.

3.5.3 Updating the Hypothesis Set

As the results of additional testing become known, the hypothesis set must be updated by eliminating entities proved to be functioning normally and retaining those entities still considered suspect. Dependent on the type of the test employed, updating the hypothesis set can be achieved either by eliminating single, isolated entities or by using a divide-and-conquer approach to split the hypothesis set into sets of entities known to be normal and entities still considered suspect. Dependent on the nature of the diagnostic domain and the *a priori* probability of failure of each of the hypothesis set entities, tests designed to divide-and-conquer can be the more efficient alternative. The selection of divide-and-conquer tests can be significantly guided by the use of a structural model of the system under diagnosis. If a suitable computational model of the system exists, an alternative means of updating the hypothesis set is to use the model-based hypothesis generation process again, but this time incorporating the additional as well as the initial observations.

3.6 Summary

This chapter has introduced a generic model of diagnosis which can be iteratively applied on hierarchical models representing a system at successively finer levels of abstraction. Diagnosis is viewed as a three stage process, comprising symptom detection, hypothesis generation and hypothesis discrimination. Structural models can be usefully employed both during the hypothesis generation and hypothesis discrimination processes. Contributor sets contain at least one entity which if faulty would explain an anomaly observation made at a *single* system output. Hypothesis sets contain at least one entity which, if faulty would explain behavioural observations made at *all* system outputs. Trace-back is a commonly employed technique to generate contributor sets, but relies on the assumption that faults always propagate in the direction of information flow. Many open research questions existed surrounded the modelling process, including problems related to scaling up model-based techniques to cope with real world problems, problems with choosing an appropriate level of model abstraction, and problems which occur when a fault effects the underlying structure of a mechanism [Davis and Hamscher, 1990].

4. Hypothesis Generation Theory

This chapter presents an approach to deterministically generating hypothesis sets from structural models of equipment sub-systems. Hypothesis generation is considered for the cases where both single faults and multiple simultaneous faults are assumed present in a system. Following from the previous chapter, the methodology can be summarised as follows;

1. construct a structural model of the system under investigation,
2. identify the contributor sets and normality sets associated with each system output,
3. use either set-intersection (single fault diagnosis) or set-covering (multiple fault diagnosis) to operate on these contributor and normality sets.

This chapter makes a number of novel contributions, including significant modifications to the conventional trace-back method of generating contributor and normality sets [Milne, 1987; Hamscher and Davis, 1990] and the introduction of normality sets to the set-covering approach for generating multiple fault diagnoses. A structural model of a hypothetical hydraulic circuit is introduced in order to explain and demonstrate the principles developed. Real-world examples of the application of the theory are presented in the chapter 5.

4.1 Constructing Structural Models

The sub-systems of mobile mining equipment are typically electro-mechanical in nature. In constructing a structural model of an electro-mechanical system, the following points must be identified;

- location of the system's boundaries
- system inputs and outputs
- an appropriate level of system abstraction

- major system components (including function, type and attributes) and
- relationships between components (physical structure plus interconnections)

Engineering systems can be thought of as a series of processes which successively operate on inputs of resources which include material, energy, labour, capital and information. Each process transforms its inputs to useful output products. A sequence of such transformations can be thought of as a process flow. In electro-mechanical systems, process flows are either fluids (hydraulic oil, cooling water, fuel or combustion air) or energy (thermal, electrical, chemical, potential or kinetic energy).

4.1.1 System Boundaries

Boundaries are necessary in order to confine the analysis of a system. In general, system boundaries are determined by one of two means; by function type or by common process flow. An example of the first is a vehicle fire suppression system which is designed to perform a single function, namely extinguish fires. An example of the second is the hydraulic system of a mining shovel which is designed to perform multiple functions such as boom-up, bucket-dump, propel and brake, all of which are powered by flow of hydraulic oil.

4.1.2 System Inputs and Outputs

Once the boundaries of a system have been established, the inputs and outputs of the system can be determined. External system inputs and outputs cross the system boundary. External system inputs can be categorised as either command signals or consumables (such as power supply or combustion air). External system outputs include the main functional outputs, and sensor-based outputs for control, alarm and status indicating purposes. Internal system inputs and outputs do not cross the system boundary and usually represent feedback loops which have been "broken" in order to simplify the block representation of a system's structure.

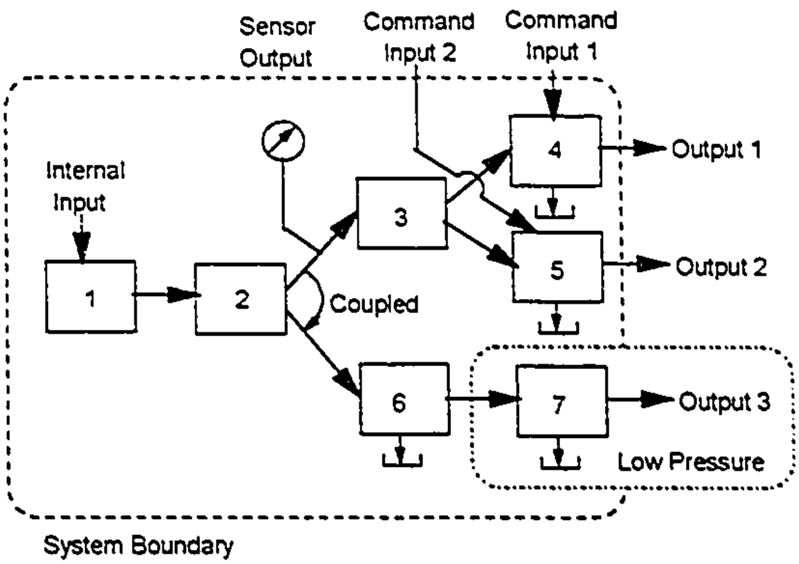

Figure 4.1 Sample Hydraulic System Structural Model

For example, consider the hypothetical hydraulic system illustrated in Figure 4.1. The system is made up of seven LRU's (least repairable units), each represented by a block. Unit 1 is a hydraulic power-pack which represents the supply source of the process medium, namely hydraulic fluid. Unit 2 is a charge valve which charges unit 3 in preference to unit 6. Unit 3 is a flow divider which divides supply flow equally between units 4 and 5, which are integral valve and actuator units. Unit 6 is a pressure reducing valve which provides low pressure flow to unit 7, a low pressure circuit. The system has two external inputs and three external outputs. Return lines to the hydraulic power pack are represented by internal outputs at units 4, 5, 6 and 7 and an internal input at unit 1.

4.1.3 Level of Abstraction

In developing a structural model, it is important to select an appropriate level of representational abstraction. For example, the pipe and hose connections between units are not represented as physical components in Figure 4.1. Hypothesis generation based on the model would not include those faults due to hose or pipe failures. Extra blocks could be included between functional units to represent hose and pipe connections, but the model would become more complex. In effect, the choice has been made here to consider connection failures at a lower level of hierarchical abstraction (see Chapter 3). Choosing the right level of abstraction is a compromise between the need to bound the analytical complexity of the model and the diagnostic coverage provided by the resulting hypothesis sets.

This trade-off between complexity and coverage is a key issue in model-based diagnosis. In fact, Davis and Hamscher [1990] comment that "model-based reasoning is only as good as the model". As in any form of analysis, the model developer needs to make simplifying assumptions about a system. Davis and Hamscher suggest that every model is itself defined by a unique set of assumptions, and that simply changing the order in which we apply assumptions can result in different models. The most appropriate model for a task could then be selected from a family of possible models. However this would be a rather exhaustive process. For practical purposes the level of abstraction of a model should not exceed that of the least repairable unit.

4.2 Modified Trace-Back Analysis

Once the structural model for a system has been established, contributor sets can be generated by trace-back analysis. Conventional trace-back diagnosis operates by considering the process flow paths leading to a faulty output and, commencing at that output, sequentially examining upstream neighbouring components for failures. However, as this section will show, there are a number of practical problems with using the conventional trace-back approach to generate contributor and normality sets.

4.2.1 Paths of Causal Interaction

The first problem with trace-back is that it assumes that faults propagate along the same paths as the process medium. In other words, it assumes that flow paths in a structural model determine the pathways of causal interaction. Whilst this can be a useful first level approach to diagnosis, in physical system there are often other pathways of interaction at work. For example, consider problems caused by excessive heat transfer between components or systems. Electromagnetic radiation is another possible pathway. It has been suggested that different pathways of interaction could be used to define different kinds of models which can then be layered to provide a sequence of successively more complex views [Davis, 1984]. Other than acknowledging this shortcoming, this thesis does not provide a deterministic solution to this problem. One approach (as used in chapter 6) is to follow structural model evaluation by a period of manual knowledge acquisition to elicit heuristic knowledge regarding other possible pathways of causal interaction.

4.2.2 Principal Flow Paths

Prior to outlining other inadequacies of the conventional trace-back procedure, it is necessary to define some terms relating to flow paths. The first of these is the principal flow path. Each functional output in a system has a principal flow path. This is the path of primary power transmission to the output. For example, in Figure 4.1, the principal flow path to output 1 is the path connecting units 1, 2, 3 and 4. The principal flow path to output 3 is that connecting 1, 2, 6 and 7.

4.2.3 Flow Convergence

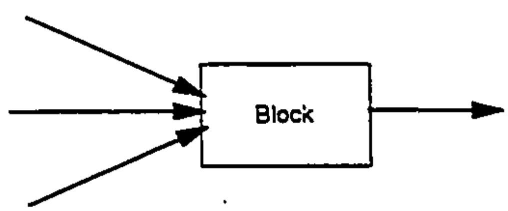

Figure 4.2 Converging Flow Lines

Figure 4.2 shows a condition where two or more a process flow paths merge. Two types of flow convergence are possible; fan-in [Hamscher, 1983], where flow from each input is permitted to merge, and selector-in, where process flow is switched between input paths. If a flow convergence is of a selector-in type and the system failure was observed to occur when a particular flow path was selected, trace-back should proceed along that path only. Where the selector position is unknown or the convergence is of fan-in type, trace-back should proceed down all merging flow lines.

4.2.4 Flow Divergence

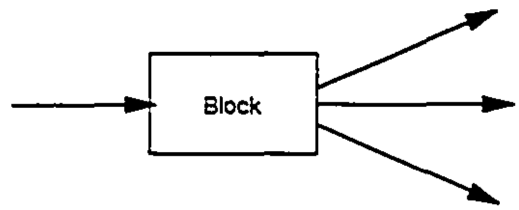

Figure 4.3 Diverging Flow Lines

Figure 4.3 shows a condition where a flow path divides to follow two or more output branches. Two type of flow divergence are possible; fan-out [Hamscher, 1983], where flow is continuously distributed amongst all of the output paths, and selector-out, where flow is switched between one or more of the output paths. According to the conventional trace-back process as described by Milne [1987] and Hamscher [1983], when a diverging flow path is encountered during trace-back analysis, components on non-principal diverging flows line are excluded from the resulting contributor set; only components on the principal flow path are included within the contributor set. However, there exist two conditions when this does not hold true; in the presence of coupled flow paths and for sensors installed at intermediate locations along a flow path.

4.2.5 Coupled Flow Paths

Diverging flow paths can be considered "coupled" when a component failure on a diverging branch would cause the functional failure of a component on an opposite branch before causing the malfunction of a component in the common root supply path. In other words, the path of causal interaction is from branch-to-branch, rather than from branch-to-root.

For example, consider the hydraulic circuit of Figure 4.1. Diverging flow lines occur at units 2 and 3. The branching flow lines at unit 2 will be considered first. Unit 2 is a charge valve which, if pressure falls below a certain threshold in the circuit comprising units 3, 4 and 5, will deliver oil to unit 3 in preference to unit 6. In determining the path of causal action of a failure in a flow line, it is useful to consider two extremes; flow line breakage or blockage. If a blockage occurred in the upper branch circuit comprising 3, 4 and 5, oil would continue to flow to the lower branch units 6 and 7. If a break (or leak) occurred in the same upper branch circuit, the charge valve at unit 2 may be "stuck" servicing unit 3. Thus a failure observed at output 3 can be caused by a failure of units 3, 4 or 5 in the upper branch circuit. In this case, the upper branch is coupled to the lower branch. This is denoted in Figure 4.1 by the small semi-circular arrow in the junction of the two branches. Note that the arrow is unidirectional. This is because the flow lines are not coupled for the inverse analysis case. A blockage or break in the lower branch will not directly effect the functional performance of components in the upper branch circuit. It will directly effect the functional performance of components in the root path (units 1 and 2).

Directing attention to the other example of branched flow lines in Figure 4.1, unit 3 is a flow divider which divides supply flow equally between units 4 and 5. If a leak occurs in unit 4, it will not affect flow to unit 5 (and vice-versa). Similarly, a blockage in unit 4 will not affect the performance of the unit 5 (and vice-versa) since excess oil would simply be vented through a relief valve to unit 1 (the hydraulic tank). Therefore, the branched lines stemming from unit 3 are not coupled.

In effect, identifying coupled flow lines makes use of functional knowledge in the context of a structural model. Knowledge about the causal paths of interaction following a failure must be used to determine coupled flow lines. Conventional trace-back cannot be used with coupled flow lines, as components on the coupled flow path must be included within the resulting contributor set by the use of "trace-forward" analysis.

4.2.6 Intermediate Sensors

There is yet another case where trace-forward must be employed. This is in the case where a sensor output is placed on an intermediate section of a flow line. For example, in Figure 4.4 there is one sensor output which measures a flow variable, in this case, pressure. If the gauge read low pressure, it would be indicative of leakage somewhere along the principal flow lines to outputs 1 and 2. Thus components {1, 2, 3, 4, 5} would make up the contributor set. If, on the other hand, high pressure was recorded at the gauge, it would indicate a blockage in the flow lines connecting components {3, 4, 5}. Trace-forward analysis has been used to generate contributor sets for both of the above scenarios. However, each scenario represents a failure mode for the sensor output. In the theory that follows, a binary health variable is considered for each output; normal (expected observation) or faulty (anomaly observation). The contributor set for the case of a fault reading at the pressure gauge is the union of the two contributor sets generated for each fault mode, namely {1, 2, 3, 4, 5}. In principle, an analyst may choose to preserve information by establishing contributor sets for each fault mode. This would necessitate the generation of separate hypothesis sets for each failure mode. However, greater diagnostic resolution might be attained through reducing the cardinality of at least one of the resulting hypothesis sets. The same reasoning holds true for measurements of variables such as flow rate or temperature.

4.2.7 Low Power Subsystems

In the diagnosis procedure described by Milne [1987], trace-back is used to generate both contributor sets and normality sets. The set-intersection method is then applied to produce hypothesis sets. However, using trace-back to establish normality sets can be erroneous due to the possible presence of components which significantly reduce power within a system. Dependent upon the process flow medium, power may be measured as (pressure $\times$ flow rate), or (torque $\times$ speed). For example, in Figure 4.1 unit 6 is a pressure reducing valve which vents high pressure flow to the hydraulic tank. Unit 7 therefore makes up a low power subsystem of the circuit. If we were to observe output 3 to be behaving according to expectation, it is possible to conclude that unit 7 is healthy, but we can conclude nothing regarding the health of components on the high power side of the principal flow path (units 1, 2 and 6). This is because units 1, 2 or 3 may fail due to a partial blockage or leak, yet still deliver sufficient low pressure flow to unit 7 for output 3 to function normally. Regions of low power need to be identified in structural models, and when generating normality sets, trace-back should terminate at components that significantly reduce power.

4.3 Hypothesis Sets

The above discussion has addressed several inadequacies of the traditional trace-back analysis procedure. It is now instructive to illustrate how to practically apply the principles developed to generate hypothesis sets from the hypothetical circuit of Figure 4.1.

4.3.1 Contributor Sets

Output #	Contributor Set
Output 1	{1, 2, 3, 4}
Output 2	{1, 2, 3, 5}
Output 3	{1, 2, 3, 4, 5, 6, 7}

Table 4.1 Contributor Sets for the Sample Hydraulic Circuit

Contributor sets are generated by considering observed faulty behaviour at each output in turn independently of the behaviour of the remaining outputs. The contributor sets associated with outputs 1 and 2 are generated by considering those components on the principal flow path of each output. The contributor set for output 3 must include units 3, 4 and 5 because of the unidirectional coupling of flow lines at the branch following unit 2.

4.3.2 Normality Sets

Output #	Normality Set
Output 1	{1, 2, 3, 4}
Output 2	{1, 2, 3, 5}
Output 3	{7}

Table 4.2 Normality Sets for the Sample Hydraulic Circuit

Likewise, normality sets are generated by considering normal behaviour observed at each output independently of the behaviour of the remaining outputs. The normality sets associated with outputs 1 and 2 consist of the entities on each of the principal flow paths to the outputs. Because element 6 is a power reducing valve, the normality set for output 3 consists of unit 7 only.

4.3.3 Single Fault Diagnosis: Set Intersection

Hypothesis set generation proceeds by considering combinations of observed output behaviour. Since the observed behaviour of each output is classified according to a binary health status (healthy or faulty), the number of possible fault combinations, NPFC, is given by;

$$NPFC = 2^n - 1 \qquad \text{equation (4.1)}$$

where n = no. of system outputs.

In practice not all of these fault combinations may be realisable because of interdependencies between outputs (under the assumption of a single fault occurring in the system, it may be impossible for a certain combination of outputs to be faulty without entailing that all outputs be faulty). For single fault diagnosis, the procedure for generating hypothesis sets is as follows;

1. Take the set intersection of all those contributor sets associated with faulty outputs to obtain an intersection set. Each element of the intersection set, if faulty, would explain the observed output anomalies.
2. Eliminate from the intersection set those elements which are common to the normality sets associated with the healthy outputs.

Mathematically, this procedure is as follows;

$$A = \bigcap_{i=1}^{n} (1-\theta_i)C_i \qquad \text{equation (4.2)}$$

and

$$H = A - \bigcup_{i=1}^{n} A \cap (\theta_i N_i) \qquad \text{equation (4.3)}$$

Where C_i is the contributor set associated with output i,

N_i is the normality set associated with output i,

θ_i is the binary health variable associated with each output such that $\theta_i = 0$ represents faulty behaviour and $\theta_i = 1$ represents normal behaviour,

n is the number of system outputs,

A is the intersection set, and

H is the hypothesis set.

Faulty Output(s)	Hypothesis Set
Output 1	{4}
Output 2	{5}
Output 3	{6,7}
Output 1 and Ouput 2	{1,2,3}
Output 1 and Output 3	{4}
Output 2 and Output 3	{5}
Output 1 and Output 2 and Output 3	{1,2,3}

Table 4.3 Hypothesis Sets for the Sample Hydraulic Circuit

By applying equations (4.2) and (4.3) to the contributor and normality sets developed in Tables 4.1 and 4.2, hypothesis sets can be generated for combinations of observed faulty behaviour in the model hydraulic circuit.

4.3.4 Multiple Fault Diagnosis: Set Covering

The possibility of the presence of multiple faults in a system complicates the process of generating hypothesis sets. An approach is presented here which is based on the cover set model of Reggia, Nau and Wang [1983], the hitting set model of Reiter [1987], and the assumption-based truth maintenance system of de Kleer and Williams [1987]. In contrast to these approaches the procedure outlined in this chapter has been augmented to accommodate reasoning with normality sets. It is also the first hypothesis generation procedure to explicitly suggest the use of power sets to generate alternatives. The procedure is as follows;

1. Take the union of all those contributor sets associated with faulty outputs.
2. Eliminate from the resulting union set all those elements which are common to the normality sets associated with healthy outputs.
3. Form a power set from the resulting set. A power set is defined as the set of all possible subsets belonging to a set. For example if A = {1, 2, 3} then the power set is denoted by $2^A = \{\emptyset,\{1\},\{2\},\{3\},\{1,2\},\{1,3\},\{2,3\},\{1,2,3\}\}$ [Lipschutz, 1964]. Subtract the null set from the resulting set.
4. Filter the resulting set by eliminating those subsets which have a null intersection with any of the contributor sets associated with faulty outputs. The resulting sets are known as cover sets (or "hitting sets" [Reiter, 1987]), because each hypothesis "covers" or explains all fault observations present in a system.
5. Use the principle of parsimony (Occam's razor) to filter the resulting cover sets by selecting only minimal cover sets. A cover set is minimal if no proper subset of it is a cover set. The resulting set is the required hypothesis set.

Mathematically, the procedure can be represented as follows;

Let $A = \bigcup_{i=1}^{n} (1-\theta_i)C_i$ equation (4.4)

$B = A - \bigcup_{i=1}^{n} A \cap (\theta_i N_i)$ equation (4.5)

$C = 2^B - \varnothing$ equation (4.6)

Define $f : C \rightarrow D$ for all $S_k \in C$

where $f(S_k) = \begin{cases} \varnothing \text{ if } \prod_{i=1}^{n} (1-\theta_i)C_i \cap S_k = \varnothing \\ S_k \text{ otherwise} \end{cases}$ equation (4.7)

$E = D - \varnothing$ equation (4.8)

Define $g : E \rightarrow F$ for all $S_j \in E$ and $S_l \in E$

where $g(S_j) = \begin{cases} \varnothing \text{ if } S_l \subset S_j \text{ for all } l \neq j \\ S_j \text{ otherwise} \end{cases}$ equation (4.9)

Finally $H = F - \varnothing$ equation (4.10)

Where C_i is the contributor set associated with output i,

N_i is the normality set associated with output i,

θ_i is the binary health variable associated with each output such that $\theta_i = 0$ represents faulty behaviour and $\theta_i = 1$ represents normal behaviour,

n is the number of system outputs,

A, B, C, D, E, F are intermediate sets, and

H is the hypothesis set.

A={1,2,3,4,5}
B={1,2,3,4,5}
C={.1,2,3,4,5,(1,2),(1,3),(1,4),(1,5),(2,3),(2,4),(2,5),(3,4),(3,5),(4,5), etc.}
D={O,1,2,3,(1,2),(1,3),(1,4),(1,5),(2,3),(2,4),(2,5),(3,4),(3,5),(4,5), etc}
E={1,2,3,(1,2),(1,3),(1,4),(1,5),(2,3),(2,4),(2,5),(3,4),(3,5),(4,5), etc}
F={O,1,2,3,(4,5)}
H={1,2,3,(4,5)}

Table 4.4 Multiple Fault Diagnosis for Faults Observed at Outputs 1 and 2

As an example of the application of equations (4.4) to (4.10), consider the case of faults observed at outputs 1 and 2 of the sample hydraulic circuit in Figure 4.4. The hypothesis set and intermediate sets are as illustrated in Table 4.4. Note that the power set expansion process has the potential to lead to combinatorial explosion for large sets. One way to overcome this is to proceed with a layered diagnostic approach; generate and test for the presence of double failures first. If a diagnosis does not result, expand the power set to the next layer (three simultaneous failures) and repeat the hypothesis testing process. This procedure was adopted for the power set C in Table 4.4. In fact, expanding the power set to the level of double failures is sufficient to establish all possible minimal cover sets.

4.4 Hypothesis Discrimination

The above discussion has focused on using analytical techniques to generate hypothesis sets. However, if a system is observed to be faulty and the corresponding hypothesis set contains a number of candidates, we require a probing strategy to discriminate between competing hypotheses. Without a knowledge of the costs associated with probing and without *a priori* failure probabilities, it is difficult to analytically determine optimal probing strategies. Heuristic knowledge regarding component failure likelihoods can be used to determine appropriate probing strategies. If detailed maintenance records are available for a machine, historical data can be used to determine *a priori* failure probabilities (see Appendix 2). However maintenance log books and work order records frequently only record part replacements, and do not accurately record work involving minor equipment adjustments such as re-setting a relief valve. For this reason, it may be more appropriate to acquire heuristic knowledge of component failure rates through manual knowledge acquisition techniques. This, in fact, is the approach utilised in the construction of the decision support system described in chapter 6.

4.5 Summary

This chapter has addressed the issue of generating hypothesis sets from structural models. The trace-back method of generating contributor and normality sets has been shown to have a number of inadequacies, which can be addressed by considering flow path coupling, low power sub-systems and intermediate sensor placement. Set theory algorithms were provided for generating both single fault and multiple-fault hypothesis sets. Single fault hypothesis sets are generated via a set intersection approach, whilst multiple fault hypotheses are generated by using a set covering approach.

5. Hypothesis Generation Case Studies

This chapter demonstrates how the theoretical principles developed in the previous chapter can be applied to isolating faults in both the hydraulic system and the diesel engine of an Atlas Copco Wagner ST-8B Load-Haul Dump vehicle (see Appendix 1). Load-Haul-Dump (LHD) vehicles are commonly used for loading and transporting ore and waste in underground hardrock mines. The vehicles function like front-end loaders, but are specially adapted for underground mining applications. They are commonly diesel driven and have low profile and small turning radius for mobility in tunnels and drifts. Other significant differences from their surface cousins include a transmission with four speeds available for forward and reverse movement, a side mounted operator cab to enable clear visibility both forward and aft, and emission control devices to minimise the concentration of diesel particulate matter (DPM) in the atmosphere underground. Recent studies of LHD failures have identified the hydraulic system and the diesel engine as the two most significant sources of unplanned downtime [Knights, 1993; Paraszczak and Perreault, 1994].

5.1 ST-8B Power Converting Subsystems

Prior to analysing the more complex hydraulic and engine subsystems of the ST-8B, it is instructive to begin at a high level of system abstraction and to demonstrate how faults can be isolated to the subsystem level. Although such first-level diagnoses are routinely performed by maintenance personnel, applying the disciplined diagnostic approach outlined in the previous chapter yields several valuable insights.

5.1.1 Structural Model

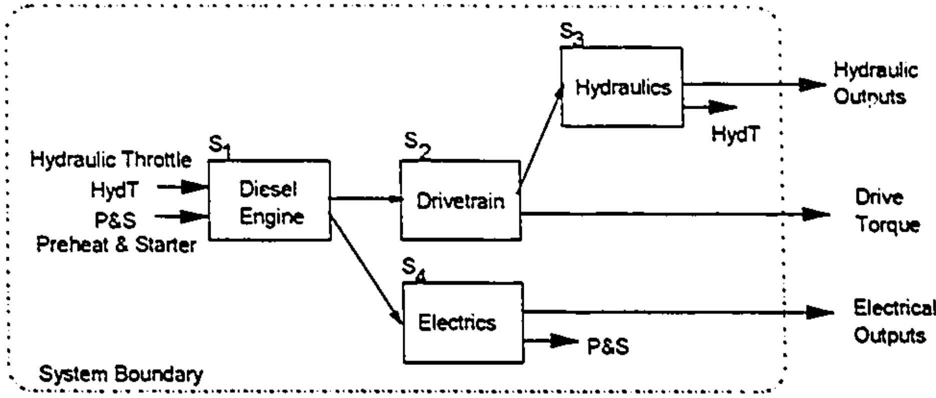

Figure 5.1 Structural Model of ST-8B Power Converting Subsystems

The major power converting subsystems of the ST-8B are as illustrated in Figure 5.1. The vehicle's diesel engine (set S_1) provides power to the drivetrain (S_2) and to the electrical system (S_4) through the alternator. The hydraulic system (S_3) derives its power from rotary gear pumps driven via the torque converter (a member of S_2). The outputs of the hydraulic, drivetrain and electrical system have been grouped together to represent single sets of outputs. Command inputs to the system have been omitted for clarity in the analysis. Fuel delivery to the diesel engine is regulated via a hydraulic throttle system. Internal inputs to the diesel engine therefore consist of the hydraulic throttle (HydT) and the preheat and starter (P&S) inputs from the electrical system.

5.1.2 Contributor and Normality Sets

Output	*Contributor Set*	*Normality Set*
Hydraulic	$\{S_1, S_2, S_3, P\&S\}$	$\{(S_3 - HydT), P\&S\}$
Drivetrain	$\{S_1, S_2, HydT, P\&S\}$	$\{S_1, S_2, HydT, P\&S\}$
Electrics	$\{S_1, S_4, HydT\}$	$\{S_4\}$

Table 5.1 Contributor and Normality Sets for ST-8B Power Converting Subsystems

A binary health status can be assigned to each output set where "normal" implies that all outputs in a set are normal and "faulty" implies that or at least one output in the set is malfunctioning. Since there exist no coupled flow lines within the system, contributor sets can be generated for each output set by using conventional trace-back analysis (see Table 5.1). Note that the hydraulic throttle (HydT) need not be included within the contributor set for the hydraulic system, since HydT is a subset of S_3 which is already present in the contributor set.

Normality set generation requires a knowledge of the function of each block. The electrical system is a low power system in comparison to the engine, drivetrain and hydraulic systems. It's normality set therefore consists of just S_4. The normality set for the drivetrain outputs can be generated by direct application of trace-back analysis. However, in establishing the normality set for the hydraulic system outputs, the health of drivetrain components such as the transmission, differentials and planetary axles is indeterminate. S_2 must therefore be excluded from the resulting normality set. Similarly, minor faults may be present in the engine which do not propagate to the hydraulic system outputs. S_1 must be excluded from the normality set. The hydraulic throttle (HydT) behaviour is not directly observable and hence the hydraulic throttle must also be excluded from the normality set. Since the engine must have started in order for the hydraulic system to function, the preheat and starter (P&S) circuits can be concluded to be functioning normally and included within the normality set.

5.1.3 Hypothesis Sets

Output Faults	*Hypothesis Set*
Hydraulic	$\{(S_3 - HydT)\}$
Drivetrain	$\{S_1, S_2, HydT\}$
Electrics	$\{(S_4 - P\&S)\}$
Hydraulics & Drivetrain	$\{S_1, S_2, HydT\}$
Hydraulics & Drivetrain & Electrics	$\{S_1, HydT, P\&S\}$

Table 5.2 Hypothesis Sets for ST-8B Power Converting Subsystem Faults

Hypothesis sets can be generated by the set intersection method described in Chapter 4. This assumes that multiple subsystem failures will not occur. For the model in Figure 5.1 which has a high level of representational abstraction, this assumption is justified (two subsystems are unlikely to be simultaneously faulty). There are $2^3 - 1$ possible faulty combinations of output behaviour (equation (4.1)), but in practice the electrical system cannot be faulty in combination with the other two systems unless the engine is faulty which implies that all three systems are faulty. The results of the analysis allow us to isolate failures at the subsystem level and some useful observations can be made. The first is that the systematic approach towards generating hypotheses enables a user to consider possible causes that might otherwise be overlooked. An example of this is if the vehicle was observed to be lacking tractive power (a drivetrain fault). An operator or maintenance technician might begin by testing the engine first, without considering the possibility of a leak in the hydraulic throttle system. The potential exists to waste considerable time and resources before locating the fault. The hypothesis sets developed above could be used to establish diagnostic test routines (probing strategies) to follow in the event of particular failure observations.

5.2 ST-8B Hydraulic Circuit

The hydraulic system of the ST-8B provides power to actuate the boom lift, bucket dump, steering and braking functions of the machine. In addition, the pilot circuit provides pressure to the hydraulic throttle system which regulates engine speed. On several occasions during the manual knowledge acquisition exercises described in chapter 6, maintenance personnel cited the hydraulic system as being the most difficult system to troubleshoot on the ST-8B vehicle. Combined with the fact that the hydraulic system is responsible for approximately 30 percent of ST-8B maintenance downtime [Knights, 1993a; see also Appendix 2], this makes it an ideal candidate to again demonstrate the diagnostic principles developed in chapter 4.

5.2.1 Structural Model

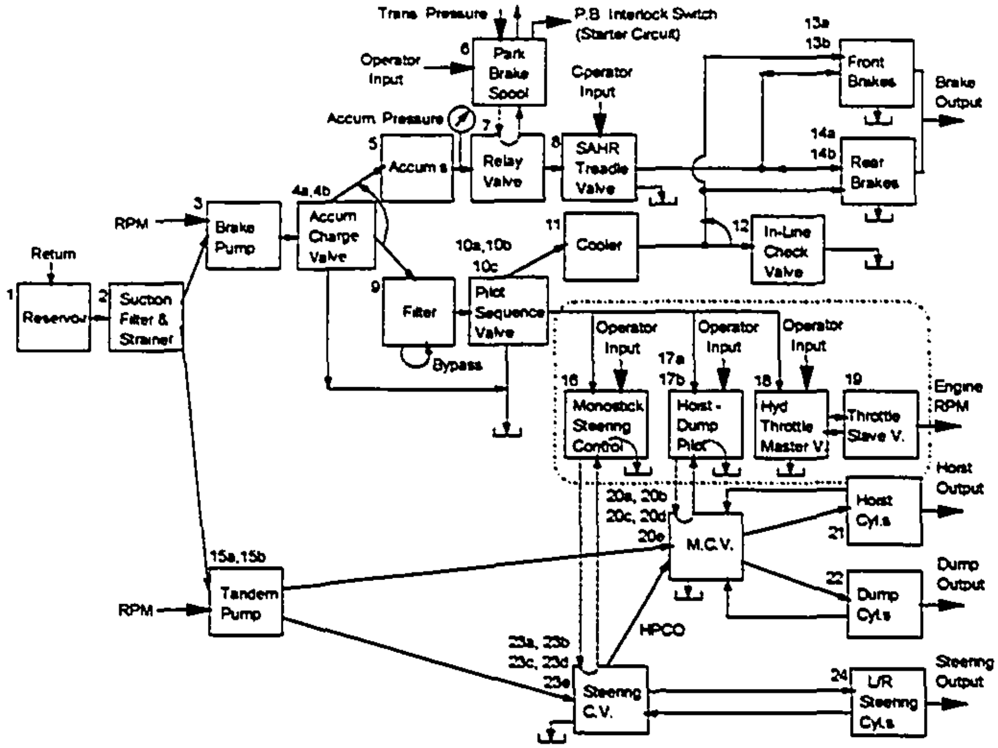

Figure 5.2 Structural Model of ST-8B Hydraulic System

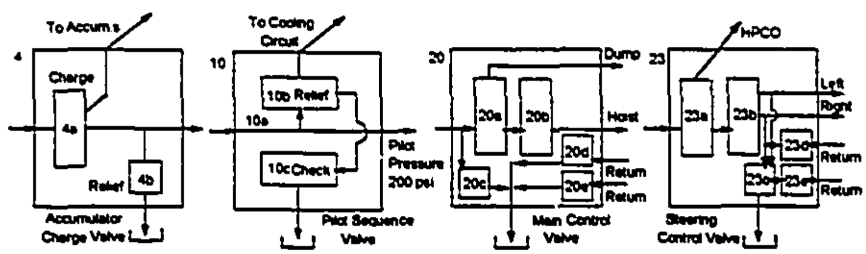

Figure 5.3 Details of Selected ST-8B Hydraulic System Valves

Figure 5.2 is a structural model of the hydraulic system of a Wagner ST-8B Load-Haul-Dump vehicle. The level of abstraction of the model bridges both the component level and the sub-component (parts) level. The convention has been adopted to include the hydraulic hoses and pipes connecting each component with its downstream neighbours within the block representing each component. Components such as pressure and flow valves have been expanded to the parts level in Figure 5.3, since some of these parts (or smaller components) are repairable or replaceable. Parts are denoted by alphabetic subscripts. The Main Control Valve, (20), and Steering Control Valve, (23), have been simplified by omission of minor directional flow valves within the valve spools. The circuit has been "broken" at the return lines to the hydraulic tank in order to display the main functional outputs at the right of the diagram. A brief description of the major sub-circuits which make up the hydraulic system is as follows;

Brake circuit; The brake pump, (3), is a rotary gear pump which draws hydraulic oil from the reservoir, (1), via a suction filter and strainer, (2), and delivers it to the accumulator charge valve, (4), at 2000 PSI and 19 GPM. The accumulator charge valve controls the charging flow to the accumulators, (5). If pressure in the accumulators drops below 1600 PSI the charge valve permits a portion of flow to divert to the accumulators, (4a), until 2000 PSI is attained, whereupon all flow is transferred through to the brake cooling circuit. Relay valve, (7), is a safety valve which prevents oil flow to the brakes if either the park brake button, (6), is activated or loss of transmission pressure (torque converter delivery pressure) occurs. The SAHR (spring applied, hydraulic release) brake system is a proprietary "wet disk" system developed by Wagner Mining and Construction Equipment Inc. The brakes are of fail-safe design, in that positive oil pressure is necessary to maintain the brakes in a released state. A foot operated treadle valve, (8), controls the flow of oil to the brake disks, (13a and 14a).

Brake Cooling Circuit; Oil not diverted to the accumulators passes through a bank of oil filters, (9), and onto the pilot sequence valve, (10). The pilot pressure valve is a full relief valve that maintains the pilot circuit, {16, 17, 18, 19}, at 200 PSI and vents excess pressure through to the hydraulic cooler, (11). An in-line check valve, (12), prevents pressure spikes from damaging the brake cooling lines and maintains low pressure oil to the brake disk cooling circuits, (13b & 14b).

Pilot circuit; The hoist, dump, and steering systems of the ST-8B vehicle are controlled by pilot-operated flow control valves. The operator steers via a toggle linked to the pilot steering control valve, (16), which directs pilot flow to the valve spool in the steering control valve, (23).

Similarly, a toggle with two degrees of freedom linked to the hoist-dump pilot control, (17), directs flow to two spool valves in the main control valve (MCV), (20). The pilot circuit also charges the hydraulic throttle system which consists of a foot operated master treadle valve, (18), and a slave actuator valve, (19) which regulates fuel flow to the engine.

Hoist, Dump and Steering Circuits: A tandem rotary gear pump directs oil flow through two independent chambers, (15a & 15b), to the Main Control Valve, (20), and steering control valve (23). At the MCV priority is given to the dump action, (20a). When the dump circuit is inactive, full pressure (2300 PSI) is available for hoisting, (20b). As soon as the dump toggle is activated, pressure is diverted to the dump cylinder. The steering control valve contains two spool valves, a compensator spool, (23a), and the main spool, (23b). When flow is not required for steering purposes, the compensator spool directs flow via the high pressure carry-over (HPCO) port to the MCV for full power during breakout and hoisting.

5.2.2 Contributor and Normality Sets

Output	*Contributor Set*	*Normality Set*
SAHR Brake	{1,2,3,RPM,4a,4b,5,6,7,Trans P,8,10a,10b,11,12, 13a,13b,14a,14b}	{1,2,3,RPM,4a,4b,5,6,7,Trans P,8,13a,14a}
Accum. Pressure	{1,2,3,RPM,4a,4b,5,7,8,10a,10b,11,12,13b,14b}	{1,2,3,RPM,4a,4b,5}
RPM	{1,2,3,RPM,4a,4b,10a,10b,18,19}	{RPM,10a,10b,18,19}
Hoist	{1,2,3,RPM,4a,10a,10b,15a,15b,17a,17b,20a,20b, 20c,20d,20e,21,23a}	{1,2,RPM,10a,10b,15a,15b,17b,20a,20b,20c,20e,21,23a}
Dump	{1,2,3,RPM,4a,10a,10b,15a,15b,17a,20a,20c,20d, 22,23a}	{1,2,RPM,10a,10b,15a,15b,17a,20a,20c,20d,22,23a}
Steering	{1,2,3,RPM,4a,10a,10b,15b,16,23a,23b,23c,23d,23e,24}	{1,2,RPM,10a,10b,15b,16,23a,23b,23c,23d,23e,24}

Table 5.3 Contributor and Normality Sets for ST-8B Hydraulic Circuit Outputs

Returning now to the hydraulic circuit of Figure 5.1, the outputs which can be observed in order to classify the circuit's behaviour must first be identified. These are the five functional outputs (brake, engine RPM, hoist, dump and steering) and one instrument output (accumulator pressure).

As Table 5.3 illustrates, each output has an associated contributor and normality set. Since an output's normality set is a subset of it's contributor set, the generation of contributor sets for these six system outputs will be discussed first.

There are a number of diverging flow branches in the hydraulic system. These occur at the suction filter, (2), the accumulator charge valve, (4), the pilot sequence valve, (10), before the in-line check valve, (12), at the tandem pump, (15), and the main control valve, (20). The branch following the accumulator charge valve, (4), is coupled, since a leak in the cooling circuit could result in slow charging of the accumulators which, in the event of rapid cycling of the brakes, would result in loss of pressure to the SAHR brakes and subsequent unintentional brake application. Components which make up the brake cooling circuit must therefore be added to the brake contributor set. The branched flow line prior to the in-line check valve (12) is coupled, since a leaking check valve may prevent oil from reaching the brake cooling circuits. The diverging flow lines at the tandem pump, (15), are not coupled, since two independent pump chambers supply each path. Likewise, the branched flow paths at the suction filter, (2), and main control valve (20) are uncoupled.

Next, consider the accumulator pressure sensor output. Two possible fault modes must be considered for the sensor; low pressure and high pressure alarms. Low pressure implicates all those components on the principal flow line to the brakes plus those components on the coupled cooling circuit. All components on these flow lines must be included within the contributor set for the accumulator gauge. Contributor sets for the hydraulic throttle (engine RPM), hoist, dump and steering functional outputs can be generated by conventional trace-back procedures. Note that trace-back must also follow the converging pilot circuit flow paths at the MCV, (20), and the steering control valve (23). Note also that the hydraulic filters, (9), have been excluded from the contributor sets because each filter is fitted with a relief valve which enables flow to bypass in the event of a filter blockage. Trace-back ceases when the reservoir, (1), is reached, since this acts as a significant "buffer" to propagating faults.

Normality sets can now be generated for each of the hydraulic circuit's six outputs. Generally speaking, an output's normality set includes only those components on the output's principal flow path and associated converging flow paths. Components on diverging flow paths cannot be included within the normality set, since they may be subject to minor faults which do not significantly impair the behaviour of the principal output. Returning to Figure 5.1, the normality set for the brake output includes all components on the principal flow line plus the park brake spool, (6) (since this lies on a converging flow line). The normality set for the accumulator pressure gauge includes only those components directly upstream. The pilot sequence valve (10) acts to reduce flow potential (i.e. pressure) to the pilot circuit, hence trace-back for the normality set for the throttle output (engine RPM) cannot proceed past the sequence valve (10). Normality set generation for the hoist, dump and steering proceeds in straightforward fashion by directly employing conventional trace-back analysis.

5.2.3 Hypothesis Sets

Faulty Output(s)	*Hypothesis Sets*
Brakes	{Trans P,6,7,8,11,12,13a,13b,14a,14b}
RPM	{18,19}
Hoist	{17b,20b,20c,21}
Dump	{17a,20d,22}
Steering	{16,23b,23c,23d,23e,24}
Accum. P	{11,12,13b,14b}
Accum. P & Brakes	{3,4a,4b,5,7,8,11,12,13b,14b}
Hoist & Dump	{15a,17a,20a,20c,23a}
Hoist, Dump & Steering	{15b,23a}
Hoist, Dump, Steering & RPM	{10a,10b}
Hoist, Dump, Steering, RPM, Accum. P & Brakes	{1,2,3,RPM,4a,10a,10b}

Table 5.4 Hypothesis Sets for ST-8B Hydraulic Circuit Faults

Having established contributor and normality sets for each output independently, hypothesis sets can be derived which contain suspect components for combinations of observed output behaviour.

Since the behaviour of each output is considered as a binary function (normal or faulty), from equation (4.1) there are $2^6 - 1$ possible faulty behavioural combinations. In practice, this reduces to 11 possible combinations because of interdependencies between outputs. Under the single fault diagnosis assumption, set intersection techniques (equations (4.2) and (4.3)) can be applied to generate the hypothesis sets listed in Table 5.4.

The hypothesis sets reveal many insights which may not be immediately obvious to a mechanic charged with isolating hydraulic system faults. For example, if both the hoist and dump cylinders were observed to be lacking power (hoist and dump faults), in addition to examining the obvious possibilities of a faulty main control valve, {20a, 20c}, or faulty pilot circuit, (15a, 17a}, Table 5.4 indicates that the high pressure carry over spool in the main steering valve, (23a) should also be held suspect. Clearly, the hypothesis sets generated in Table 5.4 can be usefully applied to troubleshooting the ST-8B hydraulic system.

5.3 Deutz FL-413-FW Diesel Engine

The Atlas-Copco/Wagner ST-8B is commonly powered by a Detroit Diesel or KHD Deutz diesel engine dependent upon customer specifications. In the past decade, the Deutz 12 cylinder FL-413-FW engine has been favoured by several large Canadian mining companies since, its two-stage combustion system leads to reduced diesel particulate matter (DPM) emissions in underground mines and its forced air cooling system was believed more reliable than a water cooling system. However, the introduction of microprocessor-based engine monitoring and control systems by Deutz's competitors currently threatens its favoured status. Microprocessor-based control systems such as Detroit Diesel's DDEC-III system [Detroit Diesel Corp., 1994], Cummins's CENTRY system [Chadwick, 1994b], and Caterpillar's electronic control module (ECM), lead to reduced DPM emissions, reduced fuel consumption, greater engine efficiencies and enhanced diagnostics. Deutz does not currently offer an electronic monitoring system for the FL-413-FW engine, hence the set theory techniques developed in the previous chapter can again be usefully applied to assist in diagnosing failures.

5.3.1 Structural Models

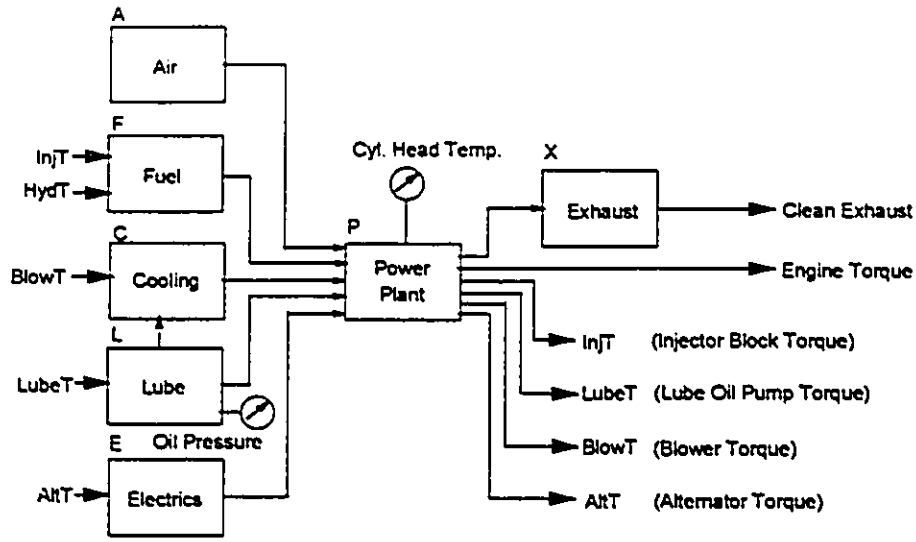

Figure 5.4 Structural Model of Deutz FL-413-FW Diesel Engine

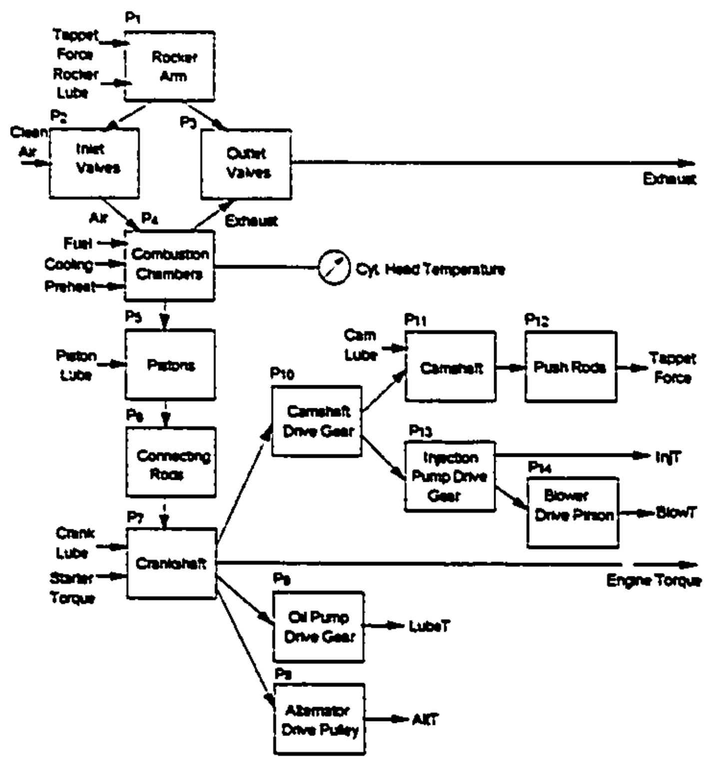

Figure 5.5 Power Plant Structural Diagram

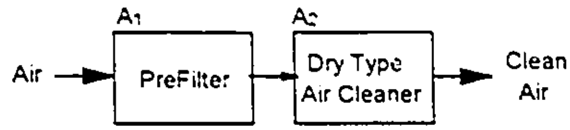

Figure 5.6 Air System Structural Diagram

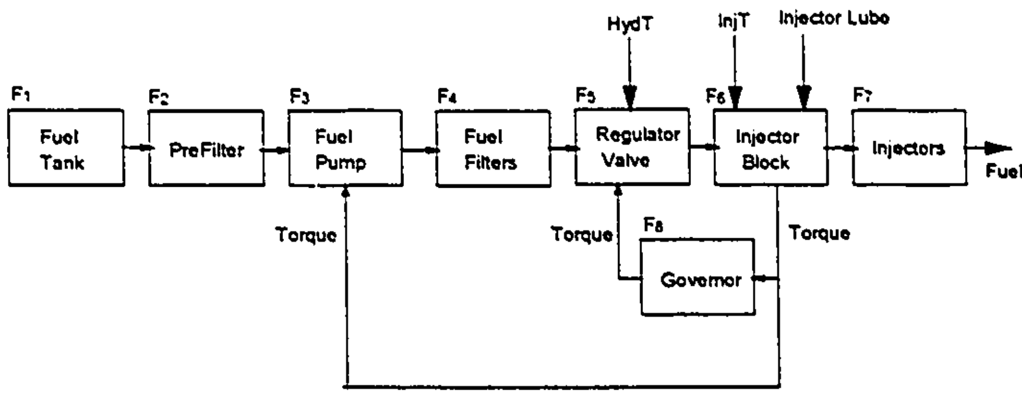

Figure 5.7 Fuel System Structural Diagram

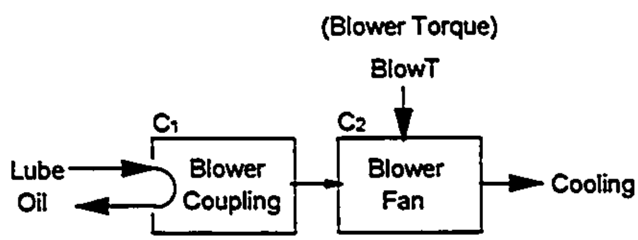

Figure 5.8 Cooling System Structural Diagram

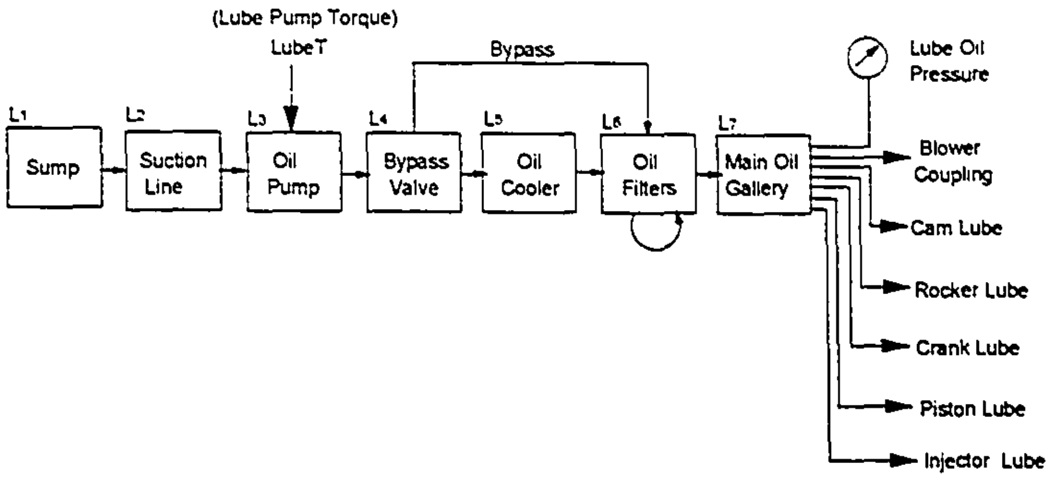

Figure 5.9 Lube Oil System Structural Diagram

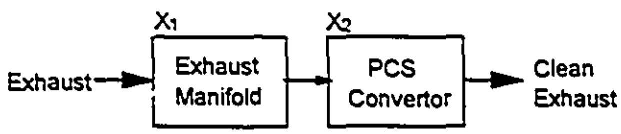

Figure 5.10 Exhaust System Structural Diagram

The Deutz FL-413-FW diesel engine consists of seven major subsystems as illustrated in Figure 5.4. Note that the flow lines in this figure represent different process flow media. The inputs to the power plant are clean combustion air from the air system (set A, Figure 5.6), diesel fuel from the fuel system (set F, Figure 5.7), cooling air from the cooling system (set C, Figure 5.8), lubricating oil from the lube oil system (set L, Figure 5.9) and electrical current to power the preheat and starter systems from the electrical system (set E). The outputs of the power plant are engine torque and exhaust gases (set X, Figure 5.10). Gear trains powered from the engine crank shaft provide torque the injector pumps (InjT; injector block torque), lube oil pump (LubeT), blower (BlowT) and a pulley powers the alternator (AltT). Note that the structural model in Figure 5.4 represents the second level of hierarchical abstraction for the engine which follows the first level abstraction in Figure 5.1. Figures 5.5 to 5.10 are third-level abstractions for the diesel engine.

5.3.2 Contributor and Normality Sets

Output	*Contributor Set*	*Normality Set*
Engine Torque	{A,F,L,E,P,X,HydT}	{A,F,(P-BlowT-LubeT),E,HydT}
Cylinder Head Temperature	{A,F,C,L,E,P,X}	{C,BlowT,E}
Lube Oil Pressure	{C,L,BlowT,LubeT}	{L,LubeT,E}

Table 5.5 Contributor and Normality Sets for Deutz FL-413-FW Engine Outputs

In the Figure 5.4 there are four observable outputs; engine torque, exhaust, cylinder head temperature and lube oil pressure. However, as Chapter 7 outlines, the analysis of the Deutz FL-413-FW diesel engine was motivated by the need to establish a troubleshooting decision support system for an operator teleoperating the vehicle from a remote operator console. For this scenario, it was concluded that the operator would not easily be able to categorise the health of the vehicle's exhaust, and so hypothesis set were generated assuming only three observable outputs, engine torque, cylinder head temperature and lube oil pressure.

Two flow couplings can identified within the structural model presented in Figure 5.4. The first of these is between the power plant output to the exhaust and the engine drive torque. We have used the functional knowledge that, if a blockage occurs in the exhaust system, exhaust gases lingering in the engine cylinder chambers may dilute air charges drawn during subsequent breathing cycles and result in loss of engine power. The second flow coupling is between the engine cooling system and the lube oil system. The flow line between the lube oil system and the cooling system represents lube oil flow to the blower fan oil coupling, which also functions as a centrifugal filter for the lube oil. The coupled flow lines are used here to represent heat flow between the two systems, an alternative path of causal interaction. Excess engine heat can lead to diminished lube oil viscosity which in turn can result in low oil pressure. With the two flow couplings in mind, contributor and normality sets can be generated as listed in Table 5.5.

5.3.3 Hypothesis Sets

Output(s)	*Hypothesis Set*
Engine Torque	{A, F, (P-BlowT-LubeT), X, HydT}
Cylinder Head Temperature	{C, BlowT, X}
Lube Oil Pressure	{L, LubeT}
Eng. Torque & Cyl. Head Temp.	{A, F, (P-LubeT), X}
Eng. Torque & Lube Pressure	{L, LubeT}
Cyl. Head Temp. & Lube Pressure	{C, L, BlowT, LubeT}
Eng. Torque & Cyl. Temp. & Lube Pressure	{L, BlowT, LubeT}

Table 5.6 Hypothesis Sets for Deutz FL-413-FW Diesel Engine Faults

Hypothesis sets for the Deutz engine were generated using the set intersection method and are as presented in Table 5.6. Without increasing the number of non-redundant system observations, it is impossible to achieve greater diagnostic resolution than has been calculated in Table 5.6. In order to add observations, additional sensors must be installed within the engine. The set-theoretical approach outlined in this thesis and Figures 5.5 to 5.10 could be applied to help determine additional monitoring parameters and sensor locations. Naturally, compromise would have to be reached regarding the diagnostic resolution enabled by additional sensors and the cost and reliability of the sensors and their associated signal processing requirements.

5.4 Discussion

The hypothesis sets generated in this chapter provide differing levels of diagnostic resolution. The resolution achieved for the ST-8B hydraulic system is of real benefit in establishing a knowledge-base to troubleshoot the system. On the other hand, the resolution achieved for the Deutz FL-413-FW engine is poor. Maintenance technicians would have to resort to heuristic knowledge or OEM troubleshooting guides to isolate engine failures at the component level.

From these examples it can be concluded that diagnostic resolution depends firstly on the size of the system, and secondly on a ratio combining the number of observable system outputs and the number of input sub-systems. System size can be measured by the number of field repairable units (FRUs) represented by the structural model. For the hydraulic circuit there are 24 FRUs. For the Deutz FL-413-FW engine, we desire to be able to troubleshoot the system down to the level of hierarchical abstraction illustrated in Figures 5.5 to 5.10 inclusively. The engine therefor has 36 FRUs.

To explain the ratio combining the number of observable system outputs and input sub-systems, it is useful to refer to Figure 5.4. The Deutz engine has 5 input sub-systems (combustion air, fuel, cooling air, lube oil and electrical sub-systems) and 3 observable outputs (torque, exhaust and cylinder head temperature). The structure of the diesel engine can be approximated as a star, having the power plant as centre with 5 input branches and 3 output branches. Because the input branches are fan-in converging flow lines (i.e. each contributor set must include all components on these lines), hypothesis sets that differentiate between faulty components on each of the input paths cannot be established. If it is assumed that field repairable units which make up the engine are uniformly distributed amongst each branch of the star arrangement, then the largest hypothesis set (the hypothesis set with highest cardinality) will have at least $\frac{5}{5+3} \times 36 \approx 23$ members. Applying the same technique to the hydraulic circuit in Figure 5.2, the hydraulic system has five observable outputs and one input sub-system (the hydraulic powerpack). The largest hypothesis set will therefore have approximately $\frac{1}{1+6} \times 24 \approx 4$ members. (In fact, as Table 5.4 shows, the largest hypothesis set generated for the hydraulic circuit contains 9 FRU members).

The above discussion suggests the formation of a useful heuristic test to determine the effectiveness of applying the set theoretical approaches outlined in this thesis to different systems. A resolution index (RI) is suggested where;

$$RI = \left(\frac{\text{no. input subsystems}}{\text{no. input subsystems} - \text{no. observable outputs}} \right) \times \text{no. system FRUs} \qquad \text{equation (5.1)}$$

In order to effectively apply the set theoretical methods outlined in chapter 4, it is suggested that the resolution ratio be calculated for a structural model prior to commencing detailed system evaluation.

6. Decision Support System Case Study

The preceding chapters have described and demonstrated an analytical means of acquiring causal failure knowledge for mobile mining equipment subsystems. However, to successfully diagnose mobile mining equipment failures, a DSS knowledge-base must also contain test (or probing) knowledge to discriminate between hypotheses, and, dependent upon user requirements, knowledge concerning equipment repairs and spare parts. This chapter focuses on how to refine the hypothesis set knowledge acquired in the previous chapter, how to acquire probing knowledge in order to isolate faulty components from hypothesis sets, and how to implement the knowledge-base as a decision support system. A manual knowledge acquisition process is described in relation to a case study involving the development of a decision support system for a semi-automated ST-8B LHD vehicle.

6.1 Background

Faced with declining accessible reserves of high grade minerals, labour costs that are high by world standards and a regulatory environment that is perceived to be restrictive in comparison to competitor nations, Canadian mines are increasing looking towards automation to compete in the global marketplace [Hatch, 1994]. One such company is INCO Limited, a major Canadian producer of nickel, copper and cobalt. INCO's Ontario Division operates eleven underground hardrock mines located in and around Sudbury. Led by INCO Mines Research, a comprehensive automation program has been underway in Sudbury since the mid 1980's. In addition to the development of a 70 ton automated haul truck [Baiden, 1992], an automated guidance system has been developed for Load-Haul-Dump vehicles and a non line-of-sight teleoperation console has been developed to enable an LHD operator to remotely muck and dump [Baiden and Henderson, 1995].

Figure 6.1 INCO LHD Teleoperation Console [CIM Reporter, 1994]

During the plenary session of the 1994 CIM annual meeting, INCO demonstrated the simultaneous operation of two LHD vehicles on 2600 and 3000 level of Copper Cliff North Mine from Toronto, a distance of some 450 km away. The operator alternately mucked or dumped one vehicle whilst the other trammed between the draw point and ore pass under automatic guidance. Figure 6.1 shows the operator console developed by INCO Limited. The operator controls mucking and dumping via a video monitor that displays images received from a closed circuit television camera mounted on each vehicle. A second monitor provides a real-time analogue display of machine condition monitoring data via a supervisory control and data acquisition (SCADA) system. This "virtual dashboard" [Knights et al, 1993], visible on the left-hand side of the operator console, was created by INCO Limited using FIXDMACS[1] industrial SCADA software.

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1 TM Intellution Inc., Norwood, Ma, USA.

In December 1994 INCO took delivery of a new Atlas Copco Wagner ST-8B and fitted it with a fuel tank large enough to keep the vehicle operating for two continuous eight hour shifts in place of an operator cabin [Casteel, 1995]. The vehicle, nicknamed "RoboScoop 1", was installed at Stobie Mine and operated under conventional line-of-sight teleoperation whilst the full tele-remote system was prepared. The vehicle has been operating under non line-of-sight remote control since August 1995.

6.2 Requirements Analysis

Removing an operator from the proximity of a machine requires that condition monitoring sensors be installed to detect incipient faults (see Appendix 3). To this end, a report was prepared specifying appropriate monitoring parameters and sensor locations [Knights, 1993b]. The report based its conclusions on an analysis of repair statistics collected for a years operation of three ST-8B vehicles and for Deutz FL-413-FW repairs undertaken by Inco's Divisional Workshops over a five year period. Of the 34 sensors recommended by the report, on-line data is currently available from seven sensors installed on RoboScoop. These sensors are as listed in Table 6.1.

Sensor	*Signal Range*	*Operating Range*	*Normal Operating Range*
Engine Oil Pressure	1-5 Volts	0-300 PSI	25-80 PSI
Right Cylinder Head Temperature	0-10 Volts	0-185 C	120-150 C
Left Cylinder Head Temperature	0-10 Volts	0-185 C	120-150 C
Converter Pressure	1-5 Volts	0-300 PSI	210-230 PSI
Converter Temperature	0-10 Volts	0-300 F	180-200 F
Brake Accumulator Pressure	1-5 Volts	0-3000 PSI	1900-2400 PSI
Main Hydraulic Pressure	1-5 Volts	0-3000 PSI	2300 PSI

Table 6.1 Condition Monitoring Sensors Installed on RoboScoop 1

Under non line-of-sight teleoperation, a fault may be observed either as an irregularity in a monitored variable displayed on the operator's virtual dashboard (an "instrument alarm"), or as an anomaly in the vehicle behaviour perceptible to the operator (a "performance fault"). Alarm handling (symptom detection) is effectively left to the SCADA system and the operator respectively. Once detected, it was desired that the operator be informed of the severity of the fault, and be able to perform an initial diagnosis of the cause. Because of the ready availability of a computer monitor and processing power, a decision support system was identified as being a solution to these demands. Once invoked, the decision support system would prompt the operator to perform specific test routines in order to isolate specific faults. It was recognised that there would be other faults which test routines would not be able to isolate, and. in these cases, the most likely cause of a fault would be suggested to the operator.

Inco Mines Research also desired that the resulting DSS be upgradeable to be able to communicate bi-directionally with a maintenance management system (MMS) containing details of work orders and part replacements for RoboScoop. This posed a problem, since the current MMS in use at Stobie Mine was MAXIMO[2], a Microsoft Windows™ based application, and senior management desired to implement MINCOM[3], a Unix based system throughout all mines. Additional user requirements of the system were for;

- ease of maintenance; the DSS knowledge-base should be able to be upgraded by INCO personnel to reflect refinements to the knowledge base or design changes made to the machine,
- mouse-driven menu interfaces; the operator should not require a keyboard to interface with the DSS,
- user friendly graphics; a DSS having a limited number of well designed window interfaces has more chance of being accepted by a user.

6.3 Knowledge Sources

Maintenance log books were examined with a view to establishing failure probabilities for specific repair actions (see Appendix 2). Whilst major vehicle repairs were listed in these records, it became obvious that minor repair tasks frequently went undocumented. In the absence of complete probabilistic failure data, heuristic methods represented the most effective means of hypothesis discrimination.

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2 ™ Project Software and Development Inc., Cambridge, Ma, USA.

3 ™ Mincom Ltd., Greeenslopes, Queensland, Australia

To this end, from the 18th to 30th April 1995, a series of interviews were conducted with leading hand mechanics at INCO's Stobie Mine aimed at collecting heuristic failure information for the engine, hydraulic, drive train and electrical systems of the ST-8B LHD vehicle (see Appendix 4). Since removal of the domain experts from work responsibilities was of concern to the mine, dedicated access to the mechanics was not possible and interviews were conducted underground during the course of normal work shifts.

6.4 Selection of Domain Expert

Initially, one shift was spent on 2400 level attempting to elicit knowledge from a domain expert who had been nominated by mine management. However, this individual was uncertain in his responses to certain questions relating to the function of ST-8B components. Subsequent interviews were conducted with a leading hand mechanic on 1800 level who was selected by the author for having 25 years underground experience as a diesel mechanic and for having a conscientious approach to his work. A good working relationship ensued which highlights the importance of compatible personal interaction between the knowledge engineer and domain expert.

6.5 Knowledge Acquisition Methodology

A variety of knowledge elicitation techniques were employed during the interviews, including semi-structured interviewing, protocol analysis, participant observation and teach-back (see Chapter 1). The structural models and hypothesis sets developed in Chapter 5 were used to accelerate knowledge elicitation for both the hydraulic system and the Deutz FL-413-FW diesel engine. In addition to structural models, troubleshooting information provided by both the Atlas Copco Wagner ST-8B service manual [Wagner Mining Equipment Co., 1991] and the Deutz FL-413 service manual [KHD Deutz, 1990] was used to focus knowledge acquisition for the engine, drivetrain and electrical systems (the ST-8B drivetrain consists of a Clarke 8000 series torque converter, a Clarke 5000 series powershift transmission, and two Clarke 21D3960 planetary drive axles).

The domain expert was asked to corroborate the hypothesis sets developed in Chapter 5 and to identify common failure modes for each component. Once hypothesis sets had been verified, the expert was asked to rank the competing hypotheses according to the observed frequency of each fault. Components were grouped into three categories according to high, medium and low failure likelihoods. "What if" questions were used to observe the expert's reasoning processes (protocol analysis). A cassette recorder was used to record the interviews, and, following the conclusion of each interview session, the recording was played back in order to extract salient facts and rules. These knowledge components were arranged into causal diagrams whereby, during subsequent interview sessions, the author could explain what he had learnt in the previous session and gaps or inaccuracies in the knowledge-base could be rectified (teach-back).

A sample of the completed knowledge base is presented below. Supposing a vehicle is observed to be lacking hoist power then from Table 5.4 the hypothesis set is {17b, 20b, 20e, 21}. Diagnosis proceeds as follows;

DIAGNOSIS;

20e, [High] Port relief valve damaged or leaking
21, [Med.] Leaking cylinder seals
21, [Med.] Cylinder bypass
20b, [Low] Leaking spool in MCV
17b, [Low] Leaking pilot valve

ADDITIONAL CHECKS;

Check engine stall speed
Check hydraulic oil level
Check muck density (heavy loads)
Check main relief valve setting (20c).

Fault likelihoods are denoted in square brackets. The additional checks are intended as a safeguard against an operator inaccurately reporting the true nature of a fault (for example, neglecting to state that the dump and steering system are perhaps also lacking power.)

Following the site visit, transcripts were prepared for each of the interviews. These transcripts are included in their entirety in Appendix 4. Transcripts enable a more detailed analysis of knowledge elicited from interviews to be undertaken. A classical means of distilling knowledge from transcripts is to read through and underline relevant statements. This process was applied to the transcripts in Appendix 4 in order to verify and refine the completed knowledge base.

6.6 Completed Knowledge Base

Tables 6.1 and 6.2 list the completed knowledge-base. The resulting knowledge-base is distinct from that provided by the troubleshooting guides in the vehicle service manuals in that it;

- provides a more complete list of failure causes than do the service manuals,
- reflects mine experience through specifying the most likely causes of failures,
- includes a severity class ranking of high, medium or low for each failure dependent upon the economic or safety consequences of the failure. These severity rankings can be used by a mine to set procedures for operators to follow in the event of failures occurring.

Table 6.2 ST-8B Instrument Alarms

Fault	*Severity Class*	*Cause*	*Tests*
Powertrain			
Engine Oil Pressure Low	High	[High] Low engine oil level caused by; A. External oil leakage due to; 1. leaking oil cooler 2. leaking filters 3. Excessive crankcase pressure B. Internal oil leakage due to 1. Restricted air cleaners 2. Worn crankshaft bearings 3. Worn piston rings [Med] Clogged oil filters [Low] Damaged oil pump or blocked intake screen [Low] Fuel leakage from injector pump or charge pump	Check oil level Check oil filters and air cleaners Verify gauge reading with external pressure gauge.
Engine Oil Pressure High	High	[Med] Engine oil cooler blockage; [Low] Blocked oil gallery	Check oil cooler Verify gauge reading with external pressure gauge
Cylinder Head Temp. High	Medium	[High] Dirt build up on 1. Transmission or hydraulic coolers 2. Cylinder cooling fins [Med] Dirt build up on engine cooler [Med] Low engine oil level caused by; A. External oil leakage due to 1. leaking oil cooler 2. leaking filters 3. Excessive crankshaft pressure (cylinder blow by) B. Internal oil leakage due to 1. Restricted air cleaners 2. Worn crankshaft bearings 3. Worn piston rings [Low] Blower failure	Check oil level Check oil filters If necessary, wash down coolers
Converter Pressure Low	High	[High] Low transmission oil level caused by; 1. Damaged or restricted gravity drain line 2. Leakage at cooler [Med] Air leak at charge pump (check o-rings, loose connections) [Low] Excessive clutch leakage (Fwd, 1st & 2nd more common) [Low] Damaged converter charge pump	Check coolers Check downstream valve on convertor
Converter Temp. High	High	[High] Dirt build up on transmission cooler [High] Low oil level caused by; 1. Damaged or restricted gravity drain line 2. Leakage at transcmission cooler [Med] Air leak at convertor charge pump [Med] Hot oil in the hydraulic system due to; 1.Dirt build up on hydraulic cooler 2.Low hydraulic oil level 3.Air leaks and cavitation 4.Cylinder or relief valve bypass [Low] Excessive clutch leakage (Fwd, 1st & 2nd more common) [Low] Damaged converter charge pump	Check transmission & hydraulic oil coolers. Feel hydraulic tank for excessive heat Check for noisy pump indicating cavitation

Table 6.2 (cont.)

Fault	*Severity Class*	*Cause*	*Tests*
Hydraulic System & SAHR Brakes			
Dump/Hoist Pressure Low	Medium	[High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Med] Dirt jamming main relief [Low] Leaking damaged compenastor spool in main steering valve [Low] Damaged dump/hoist pump	Check hydraulic oil level Run engine at high and boom up to maximum. Continue to hold the boom lever control open and read the dump/hoist pressure. If this is below 2000 PSI, the main relief needs adjusting Check for noise in the tandem pump
Accumulator Pressure Low	Medium	[High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [High] Dirt jamming accumulator charge valve [Low] Loss of accumulator gas charge [Low] Damaged brake pump	Check hydraulic oil level Check for noise in the brake pump Check for vibration in brake pump
Accumulator Slow to Charge	Medium	[High] Dirt blocking accumulator charge valve [High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Low] Damaged Brake Pump	Check hydraulic oil level Check hydraulic hoses
Accumulator Cycling Rapidly	Medium	[High] Internal leakage at the foot pedal control valve	Check for hot hydraulic oil
Electrical System			
Charging Volts Low	Low	[High] Slipping or worn alternator belt [Med] Wiring problems at the alternator [Med] Defective master switch [Low] Defective alternator	Check alternator belt condition and tension Check for burnt-out master switch
Charging Volts High	High	[High] Defective regulator in alternator	Replace alternator

Table 6.3 ST-8B Performance Faults

Fault	*Severity Class*	*Cause*	*Tests*
Powertrain			
Engine difficult to start	Low	[High] Electrical problem (see Electrical System Faults) [Med] Insufficient fuel to engine caused by: 1. Empty fuel tank 2. Restricted fuel lines (check filters & line from tank to charge pump) 3. Air leaks in fuel suction line 4. Defective fuel shut-off solenoid 5. Restricted injector pump plunger or nozzle [Low] low compression due to: 1. sticking or burnt valves 2. worn piston rings 3. Cylinder head gasket leaking.	Check electrical system first Check fuel system
Lack of engine power	Medium	[High] Insufficient fuel to engine caused by: 1. Empty fuel tank 2. Restricted fuel lines (check filters & line from tank to charge pump) 3. Air leaks in fuel suction line 5. Defective fuel shut-off solenoid 6. Restricted injector pump plunger or nozzle [Med] Restricted air cleaners [Med] Hydraulic throttle problem caused by: 1. A leak at throttle treadle valve 2. A leak at throttle slave valve 3. No pilot pressure [Low] Non engine related problem 1. Torque convetor slipping 2. Transmission clutch pack slipping	Check air cleaners Check relief setting on throttle treadle valve
Transmission slipping at gear change	Medium	[Low] Clutch pack leaking (Fwd, 1st and 2nd more common)	When forward is engaged, if the transmission slips at both first and second gear changes, the problem is the forward clutch pack. Otherwise the problem can be isolated to the approriate clutch pack (1st or 2nd)
Engine smoking	High. Fire Hazard	[High] Leaking transmission or hydraulic oil cooler [Low] Smoking from dip stick or filters 1. Cylinder blow by 2.Blocked crankcase breather valve	Check for cooler leaks
Exhaust smoking	Medium	[High] Restricted air cleaners [Med] Too much oil in the sump [Low] Injection nozzle restricted [Low] Cylinder head gasket leaking [Low] Worn piston rings	Check air cleaners Check oil level in the engine sump
Excess engine noise/vibration	Medium	[High] External sources 1. Broken cooler brackets 2. Broken engine mounts [Med] Internal sources 1. Restricted air supply 2. Restricted fuel supply 3. [Low] Worn blower bearing 4. [Low] Worn timing gear train 5. [Low] Worn piston rings	Check transmission and hydraulic oil cooler brackets. Check engine mounts Check air filters

Table 6.3 (cont.)

Fault	*Severity Class*	*Cause*	*Tests*
Excess driveline noise/vibration	Medium	[Low] Damaged driveline or universal joint [Low] Damaged differential	
Excess engine oil consumption	Medium	[Med] External oil leakage due to; 1. leaking oil cooler 2. leaking filters 3. Excessive crankcase pressure (cylinder blow by) [Low] Internal oil leakage due to; 1. Worn crankshaft bearings 2. Worn piston rings [Low] Extended operation with restricted air cleaners	Check oil filters Check oil cooler Check for breather restriction on the cranckcase
Hoist, Dump & Steering			
Lack of hoist power (slow boom-up)	Low	[High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Med] Hoist cylinder bypass [Med] Dirt jamming main relief valve [Low] Broken cap on pilot to MCV [Low] Worn hydraulic pump [Low] Broken hoist cylinder eye [Stobie lower levels] High density muck	Carry out a stall test on the engine. Put the brakes on, engage 2nd gear in forward and rev the engine. Dump/Hoist pressure should be greater than 2150 PSI. If the pressure is lower, either the main relief valve is venting or the engine has a power delivery problem. Check for low hydraulic oil level. Work the machine for several cycles Feel the temp of the hoist cylinders If one is hotter, it indicates cylinder bypass.
Hoist not holding load (boom dropping)	Low	[High] Port relief valve leaking [Med] Hoist cylinder bypass	Check for low oil level Work the machine for several cycles Feel the temp of the hoist cylinders If one is notter, it indicates cylinder bypass.
Lack of dump power (slow roll-back)	Low	[High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Med] Dump cylinder bypass [Med] Dirt jamming main relief valve [Low] Broken cap on pilot to MCV [Low] Worn hydraulic pump [Low] Broken dump cylinder eye	Check for low oil level Work the machine for several cycles Feel the temp of the dump cylinders If the cylinder is excessively hot, it indicates cylinder bypass.

Table 6.3 (cont.)

Fault	*Severity Class*	*Cause*	*Tests*
Dump not holding load (bucket rolls back by itself)	Medium	[High] Port relief valve leaking (spring broken) [Med] Cylinder bypass	Place the bucket flat on the ground and extend the stabilizer cylinder so thet the front wheels of the LHD are raised off the graound. If the dump cylinder cannot hold the weight of the machine, this indicates a leaking dump port relief valve. Check cylinder temperature for cylinder bypass.
Lack of steering power	Medium	[High] Low hydraulic oil level [High] Blown Steering hoses [Med] Steering Cylinder bypass [Low] Pilot valve leaking [Low] Damaged Steering control valve [Low] Damaged steering pump	Carry out a stall test on the engine. Put the brakes on, engage 2nd gear in forward and rev the engine. Dump/Hoist pressure should be greater than 2150 PSI. If the pressure is lower, either the main relief valve is venting or the engine has a power delivery problem. Check steering cylinder hoses. Check for low hydraulic oil level. Work the machine for several cycles Feel the temp of the steering cylinders If one is hotter, it indicates cylinder bypass.
Lack of hoist & dump power	Medium	[High] Pilot pressure problem caused by; 1. Dirt jamming accumulatot charge valve [High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Med] Clogged hydraulic filters [Low] Scored/damaged spool in MCV [Low] defective tandem pump [Low] Packing/Dirt jamming main relief valve	Carry out a stall test on the engine. Put the brakes on, engage 2nd gear in forward and rev the engine. Dump/Hoist pressure should be greater than 2150 PSI. If the pressure is lower, either the main relief valve is venting or the engine has a power delivery problem. Check for low hydraulic oil level.
Lack of hoist, dump & steering power	Medium	[High] No pilot pressure due to; 1. Dirt jamming accumulator charge valve [High] Low hydraulic oil level due to; 1. A broken hose 2. Leaking cylinder seals 3. Leaking brake seals [Med] Clogged hydraulic filters	Carry out a stall test on the engine. Put the brakes on, engage 2nd gear in forward and rev the engine. Dump/Hoist pressure should be greater than 2150 PSI. If the pressure is lower, either the main relief valve is venting or the engine has a power delivry problem. Check for low hydraulic oil level.
Hydraulic pump noisy	Medium	[High] Low oil level [High] Air leak to suction side [Med] Breather valve on tank plugged [Med] Blocked suction filters [Low] Incorrect hydraulic fluid [Low] Damaged pump [Cond] Cold hydraulic oil (-20 to -30 ambient temperature)	Check for low hydraulic oil level Cold hydraulic oil will casue the pump to be noisy for 10 to 15 minutes until the oil warms sufficiently

Table 6.3 (cont.)

Fault	*Severity Class*	*Cause*	*Tests*
SAHR Brakes			
Brakes applying during operation	Medium	[High] Brake hoses ruptured or leaking [High] Brake foot pedal control valve jamming [Med] Dirt jamming accumulator charge valve [Low] Low transmission pressure [Low] Electrical fault in starter circuit	Check hose connections to brakes Check converter oil pressure
Brakes slow to apply	High	[Med] Foot pedal control valve jamming (flow restricted from brakes)	Check foot pedal control valve
Brakes slow to release	Medium	[Med] Foot pedal control valve jamming (flow restricted to brakes)	Check foot pedal control valve
Brake face seals leaking	Medium	[Med] Check valve jammed causing overpressure in brake cooling circuit [Low] Seal failure	Check 5 PSI check valve
Electrical System			
Engine not starting	Low	[High] Electrical problems due to: 1. Battery charge low 2.Starter motor stuck/rusted 3. Master switches faulty 4. Cross-over solenoid defective 5. Defective starter motor [Med] Fuel Supply problem (see Powertrain faults)	Check electrical problems first, then fuel problems
No power to lights	Medium	[High] Damaged lights or wiring [High] Harness plug disconnected (muck) [Med] Circuit breaker tripped (load too high)	

6.7 Expert System Demonstration Prototype

Inco Mines Research initially expressed interest in developing an expert system as a solution to the problem of troubleshooting ST-8B faults. Prior to completing the knowledge acquisition process, an expert system demonstration prototype was constructed for evaluation. The demonstration prototype was written using the Comdale/X[4] (Release 5.12) development shell, and consisted of approximately twenty five production rules (see Appendix 5). Because Comdale/X has an integrated hypertext facility, rules were used for high level processing (for example, to ask the user which subsystems are malfunctioning), and hypertext modules were used to display faults and associated likelihoods. Hypertext interfaces enable a list of failure hypotheses to be displayed to the user, as distinct from providing the user with only the most likely hypothesis. This approach was deemed beneficial, since a user might possess heuristic knowledge not available to the expert system which could be applied to the hypothesis discrimination process.

Although initial reaction to the expert system prototype was positive, several factors weighed against the implementation of a full scale system. The first of these was that Comdale/X is limited to the OS/2™ or Windows™ operating systems. Future integration with a UNIX-based maintenance management system would be difficult. Secondly, although it was possible to design a mouse-activated system (ignoring keyboard specification of certainty factors), it was not possible to program a large number of mouse-driven alternatives per window for the rule-handling component of Comdale/X. This resulted in the user having to traverse an unacceptably high number of windows before a conclusion could be reached. It was felt that this would be a time consuming attribute that would not lead to user acceptance in a mine.

However, the dominant factor negating the use of a full-scale expert system concerned system maintenance. During the life of a decision support system, a knowledge-base will almost certainly require modification as either inaccuracies require correction or machine modifications are made. The process of representing knowledge as production rules and implementing the rules in Comdale/X requires familiarity with the development environment and knowledge as to the effect

[4] ™ Comdale Technologies Inc., Toronto, Canada.

of a modified rule on inference chaining. Since it was estimated that over 330 production rules[5] would be necessary in order to implement the knowledge-base established in Chapter 6, the only person who could reasonably be expected to modify the expert system would be the developer. The mine would therefore be dependent on the developer to implement changes, and, in the event of unavailability of the developer, the expert system would most likely lapse into disuse. With these criticisms in mind, an alternative knowledge-delivery platform was sought.

6.8 Hypertext Mark-up Language

The world wide web (WWW) is a global, cross-platform, distributed hypertext information system that runs over the Internet [Lemay, 1995]. The world wide web is based upon a client-server architecture using web browsers (clients) and web servers. The web browser's job is twofold. Firstly, it requests information by sending instructions to a web server to retrieve information from a specific site, or uniform resource locator (URL). The web retrieves the requested information (which may reside on another computer on the Internet), and sends it back to the browser. The browser then formats and displays this information (consisting of text, graphics, sound bits or video clips) to the user. What web browsers do most of is to handle web documents. These documents are written in Hypertext Mark-up Language (HTML), a language that has become the standard of the web. Since it's introduction in 1990, HTML has undergone two major revisions; HTML 2.0 and HTML+. A third revision, HTML 3.0, was scheduled for release at the end of Summer 1995 [Udell, 1995].

Aware of the relative strengths and weaknesses of expert system technology for the ST-8B decision support system application, HTML was examined as a means of implementing the diagnostic knowledge-base. Several benefits immediately became apparent. These are;

5 The knowledge base in Table 6.2 and 6.3 is in the form of a look-up table. The number of equivalent rules (see chapter 7) can be estimated by indexing the look-up table and counting the number of indices.

- hypertext documents written in HTML are operating system independent. Web documents can be implemented on computers running UNIX, Windows, VMS, OS/2 or Mac operating systems as long as a web browser exists for that operating system.
- Many web browsers are available free-of-charge at sites on the Internet (see Table 6.4).
- A decision support system written in HTML can be organised as an interconnected series of pages. Each page occupies one ASCII file. Just as in a folder, new pages may be added and old pages edited, removed or replaced.
- HTML files can be authored using just a text editor or a word processor. Documents can be structured so that a user need only know a few HTML commands in order to add or modify pages (see Tables 6.5 and 6.6).
- A web document can be implemented on either a local environment (which does not require the use of a web server) or over a networked environment.
- A DSS implemented in HTML can be interfaced with a maintenance management system with the aid of a web server and customised CGI (Common Gateway Interface) scripts.

Operating System	*Web Browser*	*Company*
OS/2 Warp	IBM WebExplorer included with Extended Services	IBM
OS/2 Release 2.1	IBM WebExplorer. Require TCP/IP Installation	IBM
Windows 95	Proprietary Browser	Microsoft Corp.
Windows 3.1	Netscape WinMosaic WinWeb Air Mosaic	Netscape Communications NCSA MCC Corp. Spry Corp.
Unix	NCSA Mosaic Lynx	NCSA

Table 6.4 Popular Web Browsers

HTML Tag	*Use*
<HTML>....</HTML>	Denotes the start and end of an HTML document
<HEAD>....</HEAD>	Denotes the head of an HTML document
<TITLE>....</TITLE>	Indicates the title of the document
<BODY>....</BODY>	Encloses the body (text and tags) of the HTML document
<H1>....</H1>	Denotes a type 1 heading
<H2>....</H2>	Denotes a type 2 heading
<H3>....</H3>	Denotes a type 3 heading
<P>....</P>	Denotes the start and end of a text paragraph
<HR>	Denotes a horizontal line
<UL>....</UL>	Denotes the beginning and end of an unordered list
<OL>....</OL>	Denotes the beginning and end of an ordered list
<LI>	List item for ordered or unordered lists
<IMG SRC="filename" ALIGN=BOTTOM ALT="description">	Inserts an image into the document. ALIGN is used to align text following the image. ALT provides an alternative description of the image for use with browsers that do not support graphics
<A>....</A>	Denotes the "anchor" of a hypertext link
<ADDRESS>....</ADDRESS>	Denotes the author and last revision of a document

Table 6.5 Basic HTML Tag Statements

A decision support system implemented in HTML would thus be a maintainable and expandable. In addition, by installing a single web server and a private network, a Inco Ontario Division would be able to disseminate maintenance information to workshops in each of its eleven mines in the Sudbury area. Under this scenario, experience acquired from maintenance shops in each mine could be disseminated amongst other mines from a single, maintainable knowledge-base. (Corporate wide internets have already been installed by a number of companies to disseminate information, including US West, Morgan Stanley and Turner Broadcasting. Such corporate wide internets have been dubbed "intranets" [Sprout, 1995]). However, an HTML decision support system does not have the inference abilities of an expert system (see Chapter 1). Hypertext links can be used to represent simple inferences, but conjunctions and disjunctions cannot be represented.

As an example of this inferencing limitation, in the expert system demonstration prototype, the user was asked to select which one or more of the dump, hoist, steering, SAHR brakes and hydraulic throttle subsystems were faulty. Based on user replies, AND/OR statements were used to invoke the correct hypertext module containing suggested causes. In HTML, this is not possible, and combinations of faulty behaviour must be exhaustively listed. Fortunately, for the ST-8B few such combinations are practically possible (there are eleven such combinations for the hydraulic system), so that DSS users are not inundated with an excessive number of fault options. For a system having a large number of non-redundant observable outputs where many behavioural combinations are possible, this approach may be of limited applicability.

6.9 System Architecture

This section describes the development of the HTML decision support system designed to assist personnel in diagnosing faults in semi-automated Atlas Copco Wagner ST-8B Load-Haul-Dump vehicles. The system, called "First Level ST-8B Diagnostics" was written with two user groups in mind;

- Operators of non line-of-sight teleoperated ST-8Bs ("RoboScoops"), and
- Diesel mechanics, fitters and electricians training to maintain ST-8B machines.

Recapping on the requirements analysis of section 6.2, under non line-of-sight teleoperation, a fault may be observed either as an irregularity in a monitored variable displayed on the operator's virtual dashboard (an "instrument alarm") or as an anomaly in the vehicle's behaviour perceptible to the operator (a "performance fault"). Symptom detection (alarm handling) is left to the SCADA system and LHD operator respectively.

6.9.1 Instrument Alarms

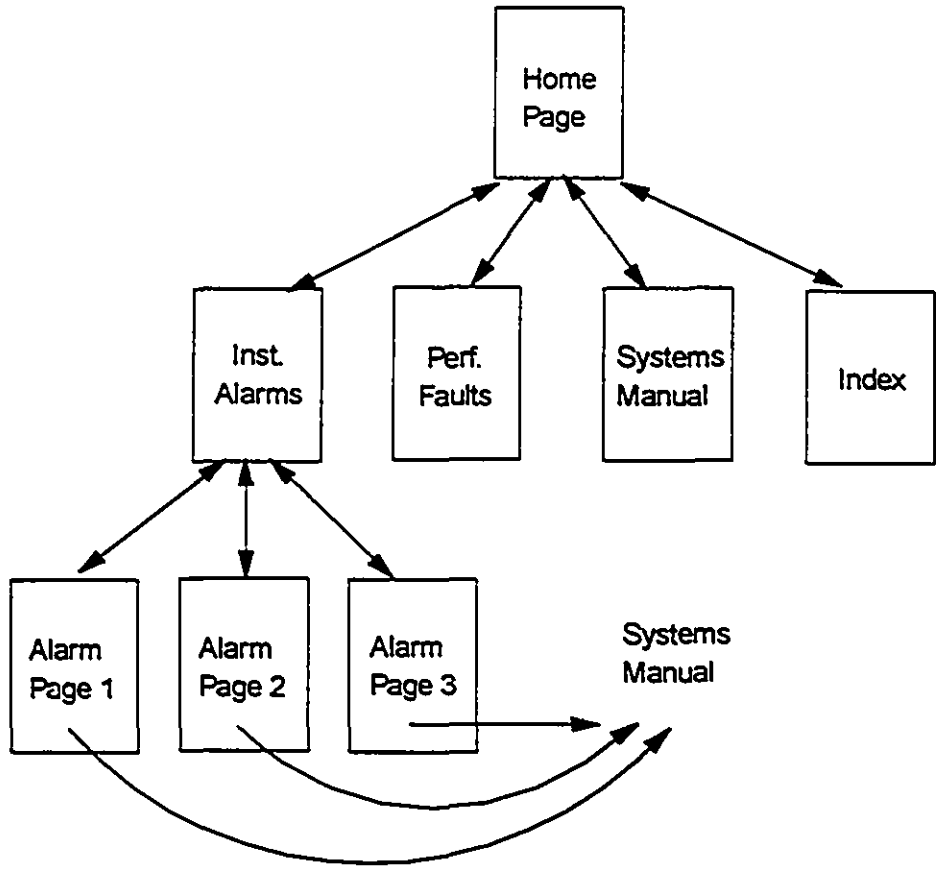

Figure 6.2 Instrument Alarm Pages

"First Level" is a web document which is composed of 141 independent pages. These pages are inter-linked as described by Figures 6.2 to 6.5 inclusively. The root document is the home page (see Figure 6.6 at the end of this chapter), which contains four icons; an instrument alarm, performance fault, systems manual or index icon. Selecting the "Instrument Alarm" icon displays a menu of possible alarm types (see Figure 6.7). Clicking on the appropriate alarm type invokes a page which displays the severity class of the alarm and lists the likely alarm causes (see Figure 6.8). Clicking on hypertext links on this page launches the user directly into the systems manual should more information be required as to the function of individual components.

6.9.2 Performance Faults

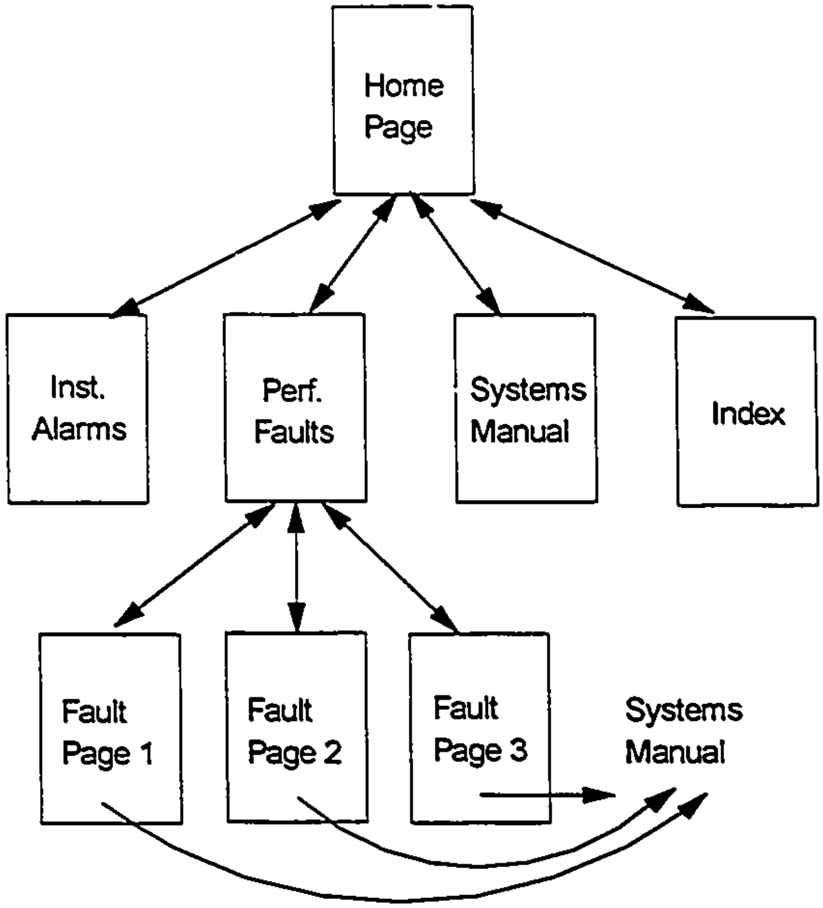

Figure 6.3 Performance Fault Pages

Selecting the "Performance Fault" icon displays a menu of possible performance faults. Clicking on the appropriate fault type invokes a page which displays the severity class of the fault and lists the likely fault causes. Clicking on hypertext links on this page also launches the user directly into the systems manual should more information be required as to the function of individual components.

6.9.3 Systems Manual

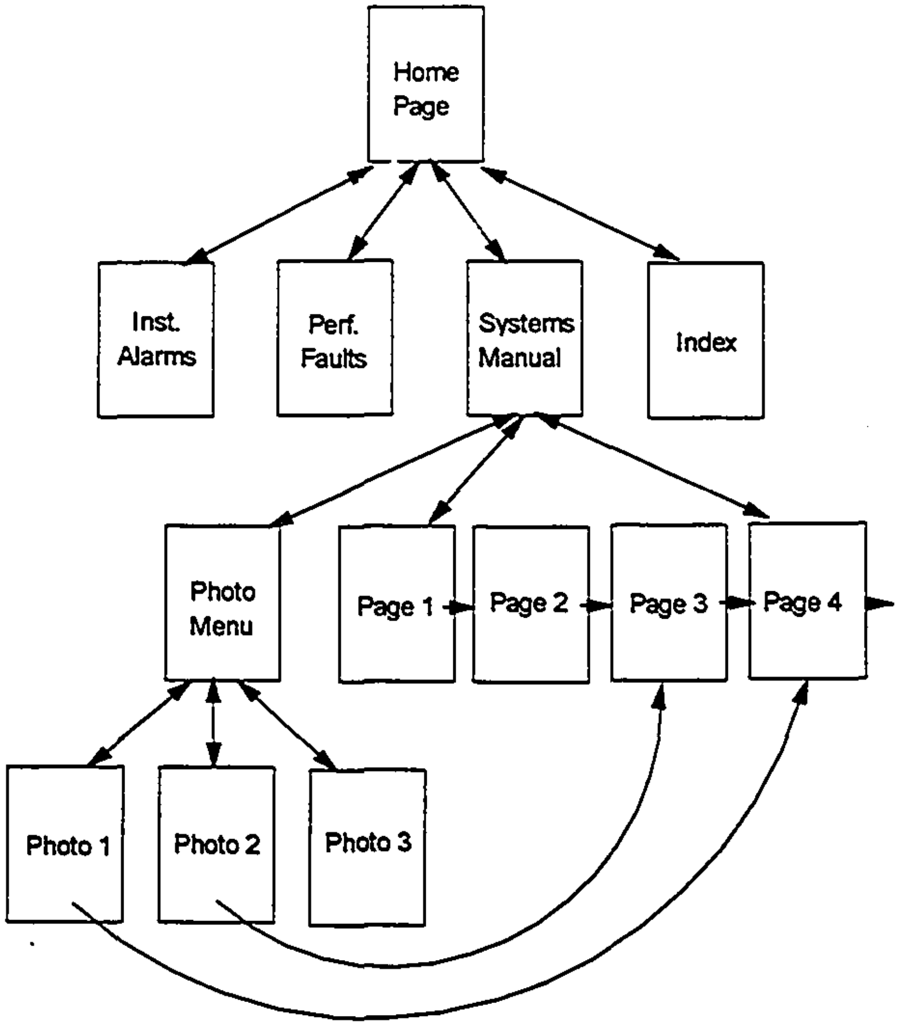

Figure 6.4 Systems Manual

The systems manual is an electronic copy of the Atlas Copco Wagner systems manual[6] which is used to train ST-8B mechanics and electricians. Unlike the instrument alarm and performance fault sections of "First Level", it can be browsed in linear fashion. Links are provided to sections dealing with major subsystems. In addition, a section of photographs showing ST-8B subsystems was included as a training aid to people unfamiliar with the vehicle (see Figure 6.10). Each photograph provides links to the appropriate pages of the systems manual.

---

[6] Reproduced with the permission of Wagner Mining Equipment Co., 1993.

6.9.4 Index

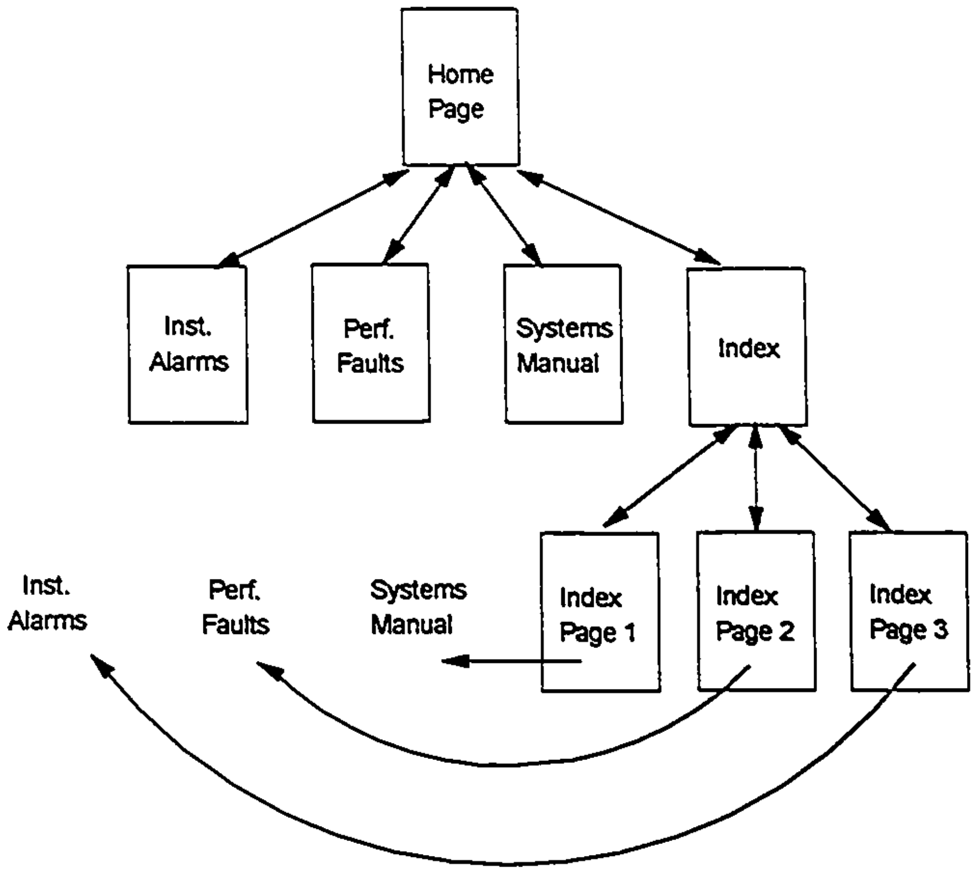

Figure 6.5 Index Pages

The index pages provide a quick and easy way of finding any of the 141 pages in the "First Level" system. Each page has a unique name. These names are listed in the index section. Clicking on the appropriate page name launches the user into that page.

6.9.5 Integration with SCADA Dashboard

"First Level" is designed to be interfaced with SCADA based instrument dashboards via the addition of a DIAGNOSTICS button written into the SCADA display. Activating this button invokes the Web browser as an external program. The browser is configured to automatically display First Level's home page.

6.10 Sample Consultation

Figures 6.6 to 6.12 follow a sample consultation from the completed decision support system. Supposing that a low oil pressure warning for the engine is observed. By invoking the diagnostics button on the virtual dashboard screen, First Level's home page (Figure 6.6) is displayed. Since advice is required for an instrument alarm, the user selects the corresponding icon to display the instrument alarm menu (Figure 6.7). Each underlined phrase represents a hypertext link to another page of the web document. The user selects "engine oil pressure low" under the list of powertrain faults, causing an alarm page to be displayed (Figure 6.8). Low engine oil pressure is rated as a high severity failure, since continued operation could cause serious damage to a diesel engine. This is reflected through the use of a graphical traffic light indicator which indicates red for high severity (a yellow lamp is used for medium severity and a green lamp for low severity). Similar to Caterpillar's VIMS system (see Chapter 2), three severity levels are used for which action policies can be formulated. In the event of a high severity fault such as low engine oil pressure, the appropriate action policy might well be to shut down immediately. "First Level" does not explicitly state this procedure; this remains the responsibility of each mine to formulate.

Below the severity level, a list of likely causes is provided (see Figure 6.8). Likelihoods are indicated in square parentheses. The DSS indicates that the most likely cause is low oil level, due either to a leaking oil cooler or filter or excessive crankcase pressure resulting in leaking oil gaskets. Below the list of possible causes, a list of diagnostic tests is provided (not visible in Figure 6.8). Advice is given to check the oil level first, then to inspect the oil filters and air cleaners for blockage. If the problem is of a reoccurring nature, then advice is given to verify that the oil pressure gauge is reading correctly by connecting an external pressure gauge to an engine test port.

As an example of another consultation type, suppose that a trainee mechanic wishes to learn more about the hydraulic components situated under the mid-ship access hatch nearest the operator. As for the previous example, he/she invokes the home page (Figure 6.6). This time, the systems manual is selected, which brings up the systems menu (Figure 6.9). The mechanic selects "system photographs" and the photograph menu is displayed (Figure 6.10). Small thumb-nail pictures are used to represent the current library of eleven photographs available to First Level. Selecting "Midship Hydraulics" displays an annotated photograph of the hydraulic system components (Figure 6.11). Each hypertext link in this screen connects the user to the appropriate page in the systems manual. Selecting "Transmission Control Cover" invokes the screen explaining how the control cover regulates oil flow to the transmission clutch packs (Figure 6.12). Selecting "Steering Control Valve" displays the screen illustrated in Figure 6.13.

6.11 Future Development

Future development envisages the interfacing of a Maintenance Management System (MMS) to "First Level". One advantage of this would be to provide the user with accurate work order statistics, rather than the qualitative fault likelihood information which is presently built into the system. Interfacing "First Level" to a MMS is a little more complex than linking the system to the SCADA instrument display. Firstly, a web server must be installed on either the same computer hosting the MMS database or on a computer networked to this host. Next, small programs called gateway scripts [see Graham, 1995] must be written to link the web server with the MMS. Gateway scripts are also commonly called CGI (Common Gateway Interface) scripts since this is the method that NCSA web servers originally employed in UNIX. Figure 6.14 illustrates how these gateway scripts work. The browser sends a URL request to the server. This URL request activates the appropriate gateway script, which sends SQL calls to the MMS database to retrieve data. The processed data is passes back to the gateway script, to the server and back to the browser. The browser formats the resulting data and displays it using an HTML "form". To achieve integration with a MMS, "First Level" requires modification through the addition of HTML forms, and many of the existing URL tags will require changing to reflect the network address of First Level's files.

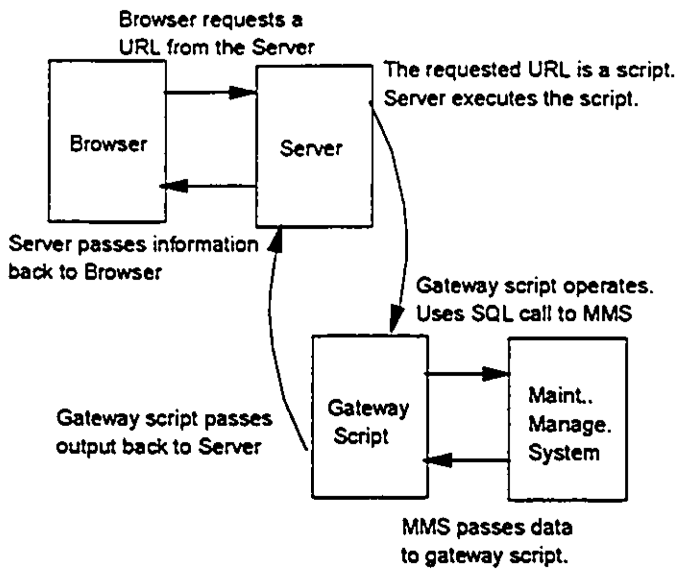

Figure 6.14 "First Level" Integration with a MMS [after Lemay, 1995]

```
<HTML>
<HEAD>
<TITLE>Home Page</TITLE>
</HEAD>
<BODY>
<P>Home Page</P>
<HR>
<H1>First Level ST-8B Diagnostics</H1>
<IMG SRC= "home.gif" ALIGN=MIDDLE ALT="[Picture of an ST-8B Load/Haul/Dump Vehicle]">
<HR>
<P>Select appropriate icon:</P>
<P>
<A HREF="alm_menu.htm"><IMG SRC="iconinst.gif" ALIGN=MIDDLE ALT="[Icon]"></A> Instrument Alarm
<A HREF="flt_menu.htm"><IMG SRC="iconcyl.gif" ALIGN=MIDDLE ALT="[Icon]"></A> Performance Fault
<A HREF="Sys001.htm"><IMG SRC="iconsys.gif" ALIGN=MIDDLE ALT="[Icon]"></A> Systems Manual
<A HREF="ind_menu.htm"><IMG SRC="iconindx.gif" ALIGN=MIDDLE ALT="[Icon]"></A> </P>
<HR>
<ADDRESS>Last Revised 17 July 1995, P.F.Knights, Dept. Mining & Metallurgical Engineering, McGill
University.</ADDRESS>
</BODY>
</HTML>
```

Table 6.6 Sample HTML File for "First Level" Home Page

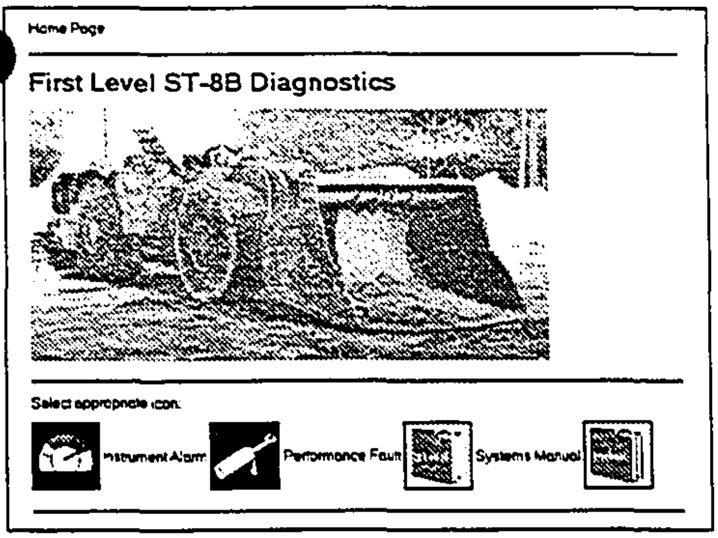

Figure 6.6 "First Level" Home Page

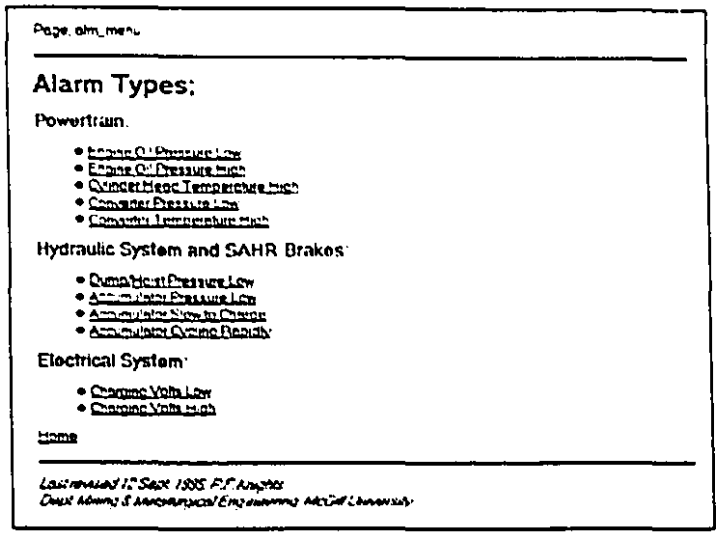

Figure 6.7 "First Level" Alarm Menu

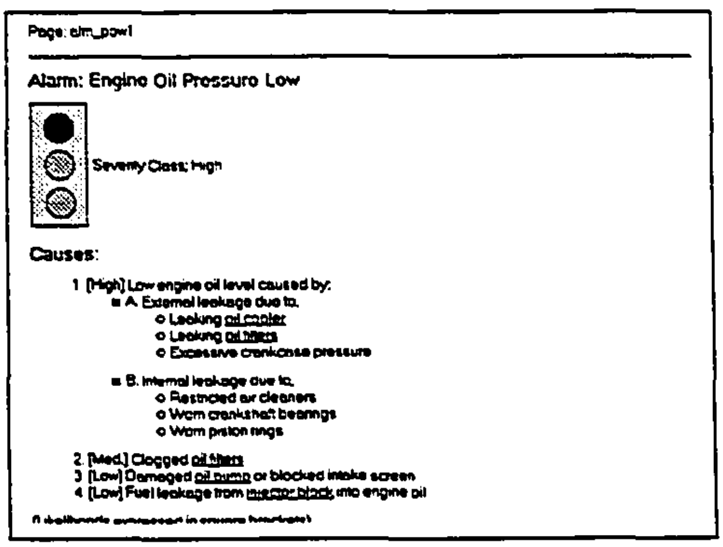

Figure 6.8 "First Level" Alarm Page

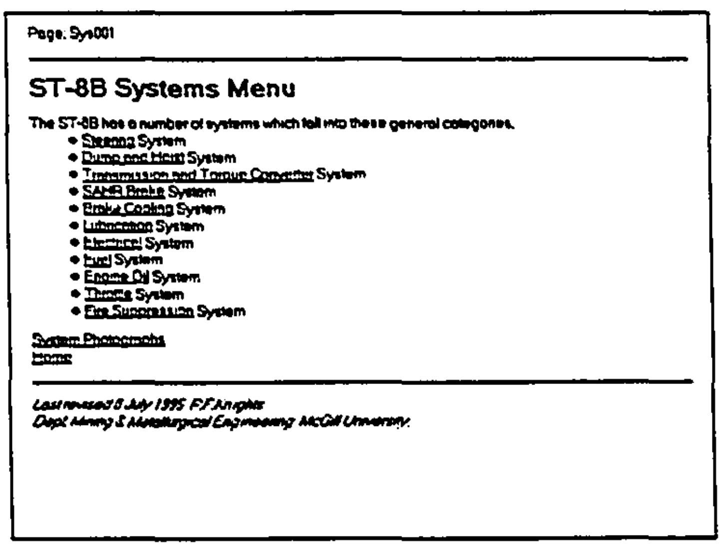

Figure 6.9 "First Level" Systems Menu

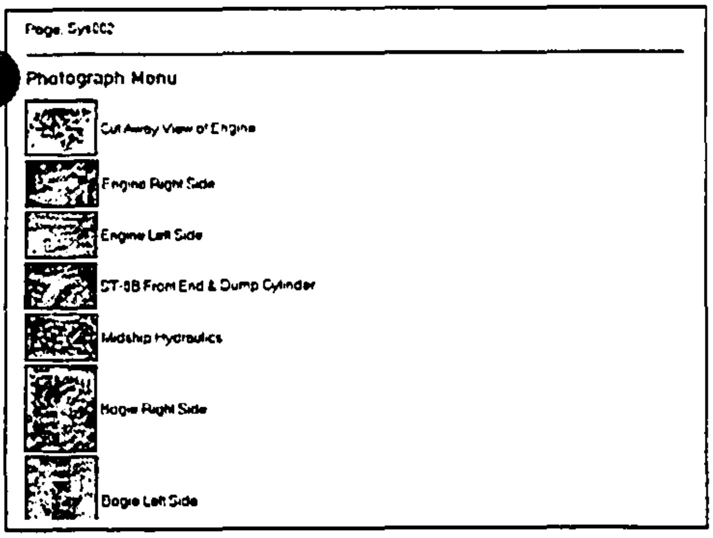

Figure 6.10 "First Level" Photograh Menu

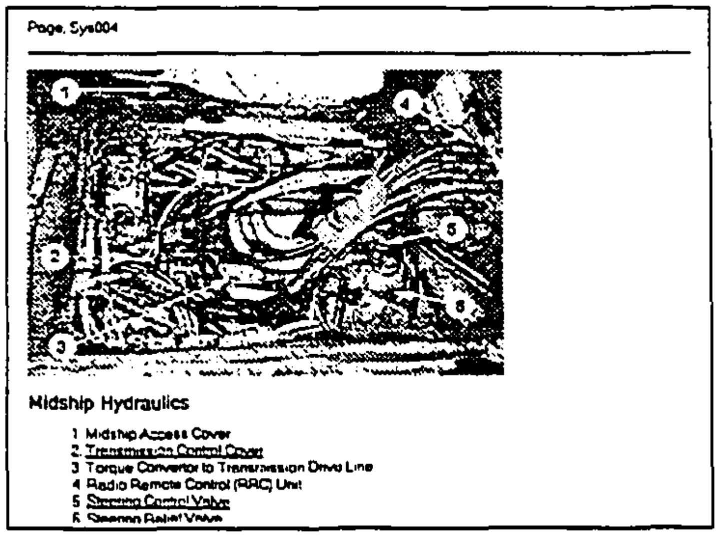

Figure 6.11 "First Level" Annotated Photograph

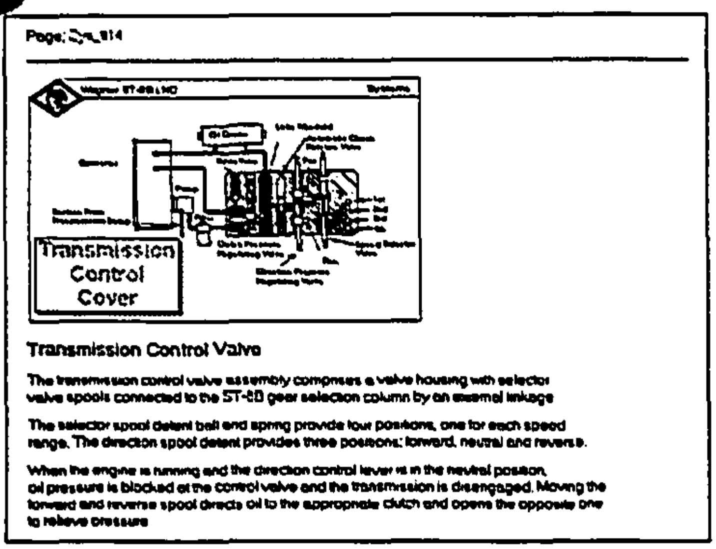

Figure 6.12 "First Level" Systems Page - 1

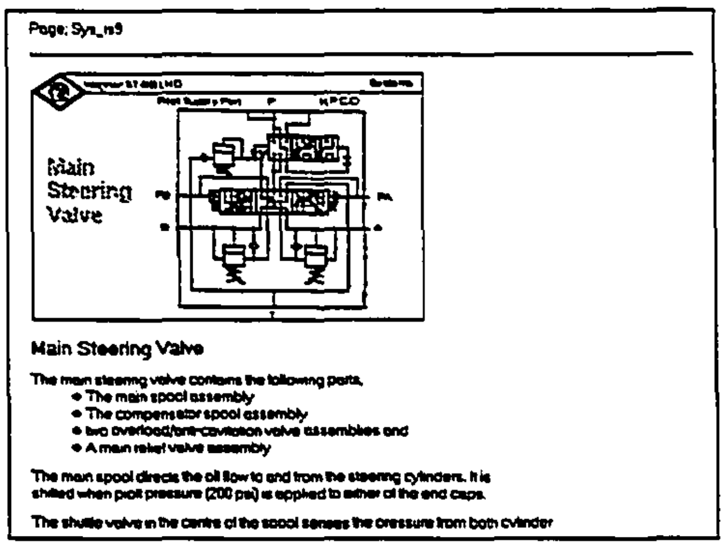

Figure 6.13 "First Level" Systems Page - 2

7. Benefit-to-Cost Evaluation

As with any other type of engineering project, an examination of alternatives and detailed cost justification should be undertaken prior to developing a diagnostic decision support system. Whilst traditional engineering economy measures can be applied to the evaluation of a DSS project, accurate estimation of project benefits and development, implementation and maintenance costs are key to successful investment decisions. This chapter examines the quantification of cash inflows and outflows over the life of a diagnostic DSS, and provides a number of heuristic measures to guide the estimation process. In addition, a simple mathematical model is presented for estimating potential production increases resulting from implementation of a DSS for equipment troubleshooting.

7.1 Investment Indicators

Traditional measures from engineering economy and capital budgeting focus on cash inflows and outflows focus over a study period, and rank projects according to value [Grant et al, 1990]. Four measures are commonly employed in evaluating engineering projects. These measures are;

- Internal Rate of Return (IRR); inflows versus outflows are measured over the life of a project to arrive at a rate of return. An acceptable IRR must be greater than the combined cost of capital and risk margin.
- Net Present Value (NPV), or Net Worth (NW); a minimum attractive rate of return for a project (discount rate), is used to discount project cash flows to a baseline. For projects of unequal lives, an Equivalent Annuity (EA) is often used to evaluate alternatives [Smith and Dagli, 1990].
- Payback Period; Does not assume a life for a project, but measures the expected time to break-even with a project. Can be evaluated with discounted or non-discounted cash flows.

Benefit to Cost Ratio, or Profitability Ratio; is equal to the sum of discounted inflows divided by the sum of discounted outflows.

Each of these indicators requires a detailed estimate of yearly cash inflows and outflows during the life of the project. The remainder of this chapter is concerned with how to establish these estimates.

7.2 Benefit Evaluation

COSTS	BENEFITS
One Time	Quantifiable
Software Shell Purchase	Improved Decision Speed
Software Development	Improved Decision Quality
Other Software Purchase	Improved Decision Consistency
Hardware Lease or Purchase	Automation of Tasks
Communication Equipment	Ability to Perform New Tasks
Office Space and Furnishings	Shorter Employee Training Time
Training and Documentation	
Ongoing (Recurrent)	Non-Monetary
Operating Personnel	Synergy with Other Projects
Communication Lines	Expanded Long Term Opportunities
Hardware Maintenance	Strategic Positioning
Software Upgrades	Job Enrichment
Office Space and Utilities	Recording of Knowledge

Table 7.1 Typical Expert System Costs and Benefits [Smith & Dagli, 1990]

Table 7.1 lists the typical costs and benefits of implementing an expert system [Smith & Dagli, 1990]. These factors are of equal applicability for knowledge-based and hypertext decision support systems. On the benefit side of the table the effect of improved decision speed is perhaps easier to quantify than the effect of improved decision quality (and consistency). This is because the mean time to repair (MTTR) mobile mining equipment serves as a benchmark for evaluating the effect of improved diagnostic decision speed, but no benchmark exists for evaluating the effect of improved decision quality (i.e. it is difficult to isolate the effect of poor maintenance decisions from existing maintenance costs). On the cost side of the table, two factors in particular deserve attention beyond the coverage provided by Smith and Dagli. These are the cost of software development, and the ongoing cost of software upgrades (software maintenance).

7.2.1 MTTR Reduction

A key benefit in implementing a DSS is an expected reduction in the time to repair (TTR) breakdown failures (see Chapter 1). Various researchers [Harjunpää, 1993; Vagenas, 1991a] suggest that diagnosis can occupy as much as 80 percent of the time to repair a failure. A first step in evaluating the production benefits of reduced breakdown repair times is to estimate the potential reduction in MTTR due to the introduction of a diagnostic DSS. Whilst the causes of some breakdowns will be immediately determinable and not require the assistance of a diagnostic support system, others such as hydraulic system faults may be more difficult to diagnose. These diagnostically difficult failures would typically account for a proportion of the failures requiring medium to long repair durations. One can conclude, therefore, that the true potential of a diagnostic DSS lies in reducing the TTR for medium and long duration repairs. To estimate the reduction in MTTR, we therefore require a knowledge of the distribution of repair times.

In 1989 Kumar [1989] published the results of a reliability analysis performed on repair data obtained for one year's operation of a fleet of diesel powered Toro LHD units at LKAB's Kiruna Mine. Kumar concluded that;

- time between failures (TBF) and TTRs were mutually exclusive and identically and independently distributed,
- The best fit model for the distribution of TBF data was a Weibull function, given by:

$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad \text{for } t \geq 0, \alpha \geq 0, \beta \geq 0 \qquad \text{equation (7.1)}$$

where α = Scale parameter,
β = Shape parameter,
t = time duration.

- The best fit model for TTR data was a lognormal distribution, given by:

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left[-\left(\frac{\ln(t)-\mu}{2\sigma^2}\right)\right] \quad \text{for } t \geq 0, \mu \geq 0, \sigma \geq 0 \quad \text{equation (7.2)}$$

where μ = mean of ln (t),
σ = standard deviation of ln (t).

If it is assumed that TTR data commonly follows a lognormal distribution (which is sometimes approximated as a negative exponential distribution [Jardine, 1973] and is strongly skewed towards shorter duration repairs) it can be concluded that, even if large time savings (e.g. 20 percent) are expected for medium to long duration breakdown repairs, the actual reduction in MTTR will be much smaller (circa 2 to 5 percent). This reduction assumes no change in the service and idle time portion of the cumulative equipment TTR.

Reduced breakdown repair times can be leveraged in one of two ways. Firstly, if existing maintenance staffing levels are maintained, increased equipment availability should translate into increased mine production. Secondly, under certain circumstances, maintenance staffing levels can be reduced, saving on labour and associated training costs whilst maintaining equipment availability at unchanged levels. In this second scenario, improved breakdown repair times may be offset by increased idle times as machines wait upon labour resources. The estimated production increase due to a diagnostic DSS will be examined first;

Equipment availability can be defined as;

$$Avail_0 = \frac{MTBF_0}{MTBF_0 + MTTR_0} \qquad \text{equation (7.3)}$$

where

subscripts $\begin{cases} 0 \text{ represent baseline conditions and} \\ \kappa \text{ represent conditions due to a reduction in MTTR} \end{cases}$

and TBF and TTR data are measured over scheduled hours only.

Equation (7.3) can be re-arranged to obtain;

$$\frac{MTTR_0}{MTBF_0} = \frac{1 - Avail_0}{Avail_0} \qquad \text{equation (7.4)}$$

The mean time to repair can be expressed as

$$MTTR_0 = \underbrace{(1-\gamma)MTTR_0}_{Service + Idle} + \underbrace{\gamma MTTR_0}_{Breakdowns} \qquad \text{equation (7.5)}$$

where

γ = fraction of total repair time due to breakdown repairs

Under the assumption that a DSS leads to a fractional decrease of κ in the total time spent on breakdown repairs, the following equation can be written;

$$MTTR_\kappa = (1-\gamma)MTTR_0 + (1-\kappa)\gamma MTTR_0 \qquad \text{equation (7.6)}$$

Rearranging equation (7.6) gives;

$$MTTR_\kappa = (1-\kappa\gamma)MTTR_0 \qquad \text{equation (7.7)}$$

Recalculating the availability of the machine for the reduced MTTR gives;

$$Avail_\kappa = \frac{MTBF_0}{MTBF_0 + (1-\kappa\gamma)\, MTTR_0} \qquad \text{equation (7.8)}$$

Substituting the ratio established in equation (7.4) into (7.8) gives;

$$Avail_{\kappa} = \frac{Avail_0}{1 - \kappa\gamma(1 - Avail_0)} \qquad \text{equation (7.9)}$$

If it is assumed that equipment utilisation remains unchanged both before and after the implementation of the diagnostic DSS, then the percentage increase in mine production can be written as;

$$\text{Production Increase (\%)} = 100\left(\frac{Avail_{\kappa} - Avail_0}{Avail_0}\right) \qquad \text{equation (7.10)}$$

Substituting equation (8.9) into (8.10) leads to;

$$\text{Production Increase (\%)} = 100\left[\frac{1}{\kappa\gamma(1 - Avail_0)} - 1\right]^{-1} \qquad \text{equation (7.11)}$$

As an illustration as to how equation (7.11) can be applied, consider the example introduced in Figure 1.2 in Chapter 1. Here, the fraction of repair time spent on breakdown maintenance of three ST-8B vehicles was measured to be 68 percent . Availability of the three LHDs averaged 85 percent over the year for which repair data was recorded. If reductions in breakdown MTTR in the order of 2.5 to 10 percent are assumed, then;

$$\gamma = 0.68$$
$$0.025 \leq \kappa \leq 0.10$$
$$Avail_0 = 0.85$$

The resulting range of possible production increases are as indicated in Figure 7.1. Results have also plotted for equipment availabilities of 80, 90 and 95 percent, in each case assuming 68 percent breakdown maintenance. From the graph, it can be seen that;

- for a 5 percent decrease in breakdown MTTR, the possible increase in production varies between 0.17 and 0.68 percent, and
- diagnostic decision support systems offer more potential for increasing production where equipment availabilities are currently low (circa 80 percent).

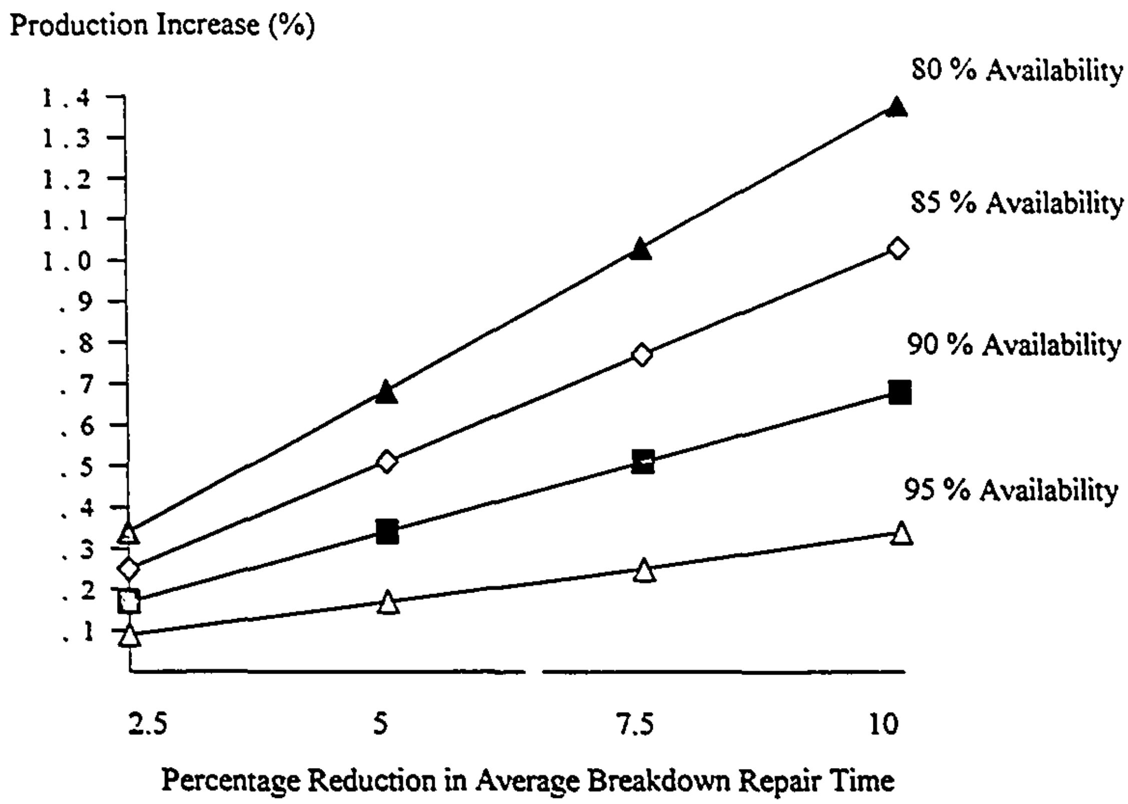

Figure 7.1 Production Increase Versus Reduction in Breakdown Repair Time

7.2.2 Personnel Reduction

Under certain circumstances, a mine might elect to down-size its maintenance work force and save on labour and associated training costs by introducing a diagnostic DSS. In other cases, both personnel down-sizing and production increases might be possible if, for example, a significant reduction in equipment failure frequency was experienced due to a reduction in the number of incorrect diagnoses or the introduction of on-line monitoring system. Potential labour savings can be estimated by considering the ratio of staff to total fleet repair time. Thus;

$$\frac{STAFF_0}{freq_0 \times MTTR_0} = \frac{STAFF_\kappa}{freq_\kappa \times MTTR_\kappa}$$ equation (7.12)

where $MTTR$ is calculated across an entire equipment fleet and
$freq$ is the average failure frequency for each machine.

On the assumption that the average failure frequency does not significantly change, and that fleet numbers remain unchanged, then by substituting equation (7.7) into (7.12) the number of staff following the implementation of a diagnostic DSS can be estimated in the form of a real number as;

$$STAFF_\kappa = (1 - \kappa\gamma) STAFF_0$$ equation (7.13)

The actual personnel reduction can be calculated by truncating the resulting difference in staffing levels;

$$\text{Personnel Reduction} = \text{int}\,[\kappa\gamma\, STAFF_0]$$ equation (7.14)

For example, suppose that prior to the implementation of a DSS a team of 40 mechanics is required to maintain a fleet of 12 ST-8B vehicles in operation for two shifts per day. Using the same figures as before, current breakdown maintenance levels are high (68 percent) and the DSS is expected to reduce breakdown repairs by 5 percent. It would be possible to lay off 1 person ($\text{int}\,[0.05 \times 0.68 \times 40]$) and still maintain equipment availabilities at unchanged levels.

7.2.3 Training Value

The value of a diagnostic DSS as a training tool can be realised both as a reduction in the need for skilled maintenance personnel and a decrease in time necessary to train new personnel. On the former point, decision support systems enable equipment troubleshooting expertise to be captured and disseminated to all maintenance personnel. This is of particular importance to mines where equipment diversity is an issue, since maintenance personnel cannot be expert in diagnosing all equipment types and models. For the latter point, reduced training time can translate into reduced training expenses, through either decreasing contract training expenditures or a possible reduction in instructor numbers.

7.3 Cost Estimates

Having dealt with how to estimate some of the cash inflows associated with implementing a DSS for equipment diagnosis, the cost side of the equation must now be considered. Apart from the obvious one-time costs listed in Table 7.1, the costs that require most careful analysis and consideration are software development and maintenance costs. Knowledge acquisition is a critical factor in these costs.

7.3.1 Size of System

The first task in estimating the development cost of a DSS is to assess the size of the knowledge-base required for the project. Knowledge base size will determine the labour resources and time necessary to develop the system. Not all DSSs are rule-based systems. It is suggested, however, that the size of a knowledge-base be evaluated according to the number of equivalent rules necessary to represent it. For example, if the knowledge-base established in chapter 6, (Tables 6.2 and 6.3) were expressed in IF ...THEN production rules, it is relatively straight forward to calculate that about 330 rules would be required. This is a medium sized knowledge-base when compared to expert systems which have been implemented for controlling mineral processing circuits which typically consist of 50 to 75 production rules [see Bowen, 1995], and when compared to expert systems such as PITCH EXPERT (see Chapter 1) which has approximately 1200 rules and 3000 schemata [Kowalski et al, 1993].

Category	No. Equivalent Rules
Small	≤ 150
Medium	$150 < Rules < 600$
Large	≥ 600

Table 7.2 Suggested DSS Categories Based on Knowledge-Base Size

This discussion leads to a suggested rating scale for Decision Support Systems based upon the estimated size of a system's knowledge base (see Table 7.2). These size categories can be used to estimate development costs, as discussed in the remainder of this chapter. Note that the knowledge base established in Chapters 5 and 6 contains knowledge on ST-8B fault causes, fault likelihoods, fault severities, and some probing (test) knowledge. It does not contain knowledge concerning repair procedures, failure histories, part numbers or part availabilities. To implement a complete maintenance DSS would therefore require a large knowledge-base containing well in excess of 600 equivalent rules.

7.3.2 Development Resources

DSS Size	Manager	Knowledge Engineer	Domain Expert
Small	0 or 1	1	1 or 2
Medium	1	≤ 2	≥ 2
Large	1	≥ 2	≥ 2

Table 7.3 Suggested DSS Development Team Numbers

The estimated size of a DSS knowledge-base permits labour resources to be assigned to the development task. Table 7.3 lists suggested DSS development team numbers. These numbers compare favourably with team numbers suggested by Guida and Tasso [1994], with the exception that Table 7.3 does not consider conventional software programmers should custom interfaces need to be written for the DSS. In the case of medium to large sized DSS knowledge bases, it is recommended that a project manager be dedicated to the task of developing and implementing the DSS. A small DSS may well be able to be managed by the knowledge engineer who also performs the task of eliciting and formalising knowledge. Medium to large sized DSSs require more labour for the knowledge acquisition process, hence two or more knowledge engineers are recommended. The costs incurred by removing a domain expert from normal duties to conduct knowledge acquisition interviews must also be factored into software development costs. For smaller DSS developments, eliciting knowledge from one or two well-chosen experts is recommended. Larger knowledge-bases may require input and verification from a two or more domain experts.

7.3.3 Number of Prototype Stages

The development of knowledge-based systems has been found to be an iterative process involving a number of rapid prototyping stages, whereby functionality and knowledge are continually added to a prototype until satisfactory system performance is achieved. As discussed in Chapter 1, rapid prototyping does not fit well with the traditional waterfall life cycle model applied to the development of conventional software. A survey of 23 KBS developers conducted in 1991 found that most developers base their underlying life cycle model on a spiral development model [Fenn & Veren., 1991].

Figure 7.2 illustrates the spiral model of software development first introduced by Boehm [Boehm, 1988]. Essentially, the model is a polar plot of cumulative development cost plotted against stages of project completion. Each quadrant represents distinct prototyping stages. Thus, one commences by conducting a requirements plan, and rapidly constructs a demonstration prototype (as in the case of the Comdale/X expert system prototypes discussed in Chapter 6). Following examination of the prototype, next level development plans are formulated, and the

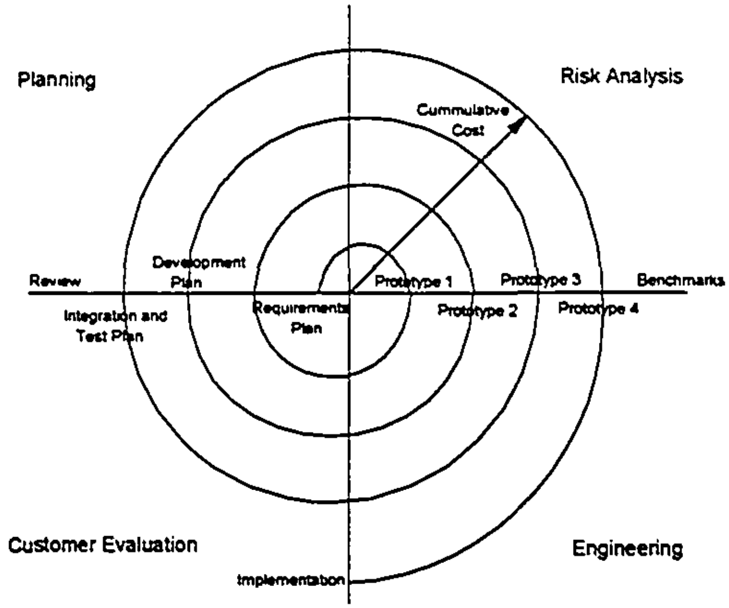

Figure 7.2 Spiral Model of Software Development [Boehm, 1988]

processes of knowledge elicitation, representation, prototyping and testing (see Figure 1.6) are repeatedly iterated during development of each successive prototype.

DSS knowledge-base labour development costs are a combination of the unit cost of labour resources multiplied by development time. The estimation of the number of prototype stages through which a project must progress is key in determining development time. Dependent on the DSS application, knowledge-base prototypes can be user-evaluated by field implementation or expert-evaluated prior to field deployment. Fenn and Veren [1991] recommend a minimum of three prototyping stages; demonstration, pilot and fully functional DSS prototypes. For larger applications, a US Air Force and Army KBS contractor recommends at least five prototype stages [Gates, 1990].

It is important to note that the both development time and labour may not be equally distributed throughout the prototyping stages; more knowledge acquisition effort will be required at the initial stages than the later stages. The contributor set theory outlined in this thesis, if applied to assist in the acquisition of causal knowledge, has the potential both to reduce the number of prototyping stages necessary to develop a DSS, and reduce the development time (and hence cost) of initial prototyping stages.

7.3.4 Knowledge Representation Type

As shown in Figure 1.6, the knowledge acquisition process is an iterative one requiring the elicitation, representation, prototyping and validating of knowledge. Time and labour resources should be allocated to each of these four stages. The process of knowledge elicitation is common to both knowledge-based and hypertext decision support systems. However, dependent on the type of DSS, the resources required to represent and prototype a knowledge-base can differ markedly. The selection of DSS type limits the selection of available knowledge representation methods. Some means of knowledge representation demand more analytical work than others, and hence add to project development costs. For example, ranked in order of increasing analytical complexity, five commonly used means of knowledge representation are;

- look-up tables
- decision charts
- semantic networks
- production rules, and
- rules and frames (schemata).

The knowledge-base in Tables 6.2 and 6.3 is in the form of a look-up table. Expert and knowledge-based systems require knowledge to be in the form of either production rules or as a combination of frames and rules. If a KBS system is selected as the target DSS, it is suggested that the labour resources (in terms of person-hours) allocated to the knowledge representation process be at least double those allocated for equivalent hypertext-based look-up table or decision chart formats.

7.3.5 Software Maintenance

The preceding sections have discussed how to estimate costs incurred during the development phase of DSS project. Software maintenance forms part of the ongoing costs of DSS. As discussed in Chapter 6, knowledge-base maintenance is necessary during the life of a system both to add or refine rules, and to reflect physical design changes made to equipment. In addition, the knowledge-base constructed and implemented in "First Level" used failure likelihoods to discriminate between hypotheses. During the life of the system likelihoods may change as the environment in which equipment is working changes. For example, if higher density muck was encountered, ST-8B stabilizer (dump) cylinder maintenance may become more prevalent due to increased bucket break-out forces. The knowledge-base of "First Level" would have to be updated to correctly reflect this change. For "First Level", this maintenance can be performed by site personnel. If an expert system had been implemented in place of an HTML-based system, it is doubtful that site personnel would be able to effect knowledge-base maintenance, since changing a rule-base can effect the inference chaining process of a KBS in unpredictable ways. It is recommended, therefore, that maintenance of a knowledge-based (expert) system be conducted by the system developer. For this reason, software maintenance should be factored at a higher rate for knowledge-based decision support systems than for systems such as First Level.

7.4 Summary

This chapter has presented an outline for estimating capital inflows and outflows associated with developing a decision support system for troubleshooting mobile mining equipment. Benefits and costs must be evaluated over the life of a DSS project. Quantifiable DSS benefits are associated with increased equipment availabilities leading to increased mine production, or savings arising from reduced maintenance labour numbers. Equations have been established to estimate the magnitude of possible production increases or labour savings.

Costs are associated with each of the development, implementation and maintenance phases of a DSS. Heuristic measurements were established to estimate the size of a DSS in terms of the number of equivalent production rules necessary to establish the knowledge base. The size of a DSS dictates both the labour resources and number of prototyping stages necessary to develop a system. Each prototyping stage involves four stages of elicitation, representation, prototyping and testing of knowledge. The cost of knowledge representation is expected to be greater for knowledge-based systems than for modular, easily editable systems such as "First Level".

8. Conclusions

8.1 Conclusions

The objectives of this thesis are;

- to adapt AI model-based diagnosis techniques to fault diagnosis of mobile mining equipment without developing computational simulation models, and
- to demonstrate that, by reducing dependency on compiled knowledge sources and by reducing the number of prototyping stages necessary to develop a knowledge-base, the resulting analytical methodology can be applied to accelerate the development of diagnostic decision support systems, and
- to provide guidelines for estimating the benefits and costs of developing, implementing and maintaining a decision support system for mobile mining equipment troubleshooting.

This work has addressed these objectives by;

1. in chapter 2, conducting a review of decision support systems for mobile mining equipment troubleshooting. The review found that failure indicator approaches are well suited to electrical systems because of the ease of establishing voltage measurements, but that decision support systems are appropriate for hydro-mechanical systems where retrofitting sensors can be costly and intrusive. Multistage prototyping and manual knowledge acquisition approaches where used to develop all but one of the systems reviewed. In this exception, model-based qualitative simulations were used to establish a knowledge base.
2. in chapter 3, conducting a review of model-based diagnostic techniques in artificial intelligence. This chapter introduced contributor, normality and hypothesis sets. A contributor set contains entities, which, if faulty, explain abnormal behaviour observed at a

single system output, independent of the behaviour of other outputs. A normality set contains entities which must be functioning normally in order to observe expected behaviour at a single system output. A hypothesis set contains entities which, if faulty, explain overall observed system behaviour.

3. in chapter 4, demonstrating how contributor and normality sets can be constructed without necessitating development of computational simulation models. The trace-back method of generating contributor and normality sets was shown to possess a number of inadequacies, which were addressed by considering flow path coupling, low power subsystems and intermediate sensor placement in flow lines. Set theory algorithms were presented for generating hypothesis sets for the assumptions of both single and multiple faults present in a system.
4. in chapter 5, applying the resulting analytical techniques to the hydraulic system and the Deutz FL-413-FW diesel engine of an Atlas Copco Wagner ST-8B Load-Haul-Dump vehicle.
5. in chapter 6, undertaking a manual knowledge acquisition exercise to add knowledge to discriminate between hypotheses, and implementing the developed knowledge-base as a decision support system using HTML, the standard language of the world-wide-web.
6. in chapter 7, presenting guidelines for estimating the benefits and costs of developing, implementing and maintaining decision support systems for diagnosing mobile mining equipment failures. Decision support systems can reduce breakdown repair times and increase equipment availability and mine production, reduce the labour requirements necessary to maintain an equipment fleet, decrease maintenance training expenses and disseminate knowledge to enable unskilled labour to perform skilled tasks.

The work is original and provides a number of contributions to the body of knowledge in the mining and related equipment industry as listed below. The first three points are of generic significance. It;

- is the first work to apply set theoretical concepts to structural models of mobile mining equipment in order to diagnose faults,

- provides significant modifications to the trace-back process used to generate contributor and normality sets,
- illustrates how the resulting analytical technique can be used to reduce the time, cost, and number of prototyping stages necessary to develop a decision support system,
- is the first mining-related work to implement a diagnostic decision support system in HTML, and to demonstrate how HTML and web browsers can be used to implement low-cost, maintainable decision support systems,
- is the first work to suggest disseminating equipment diagnostic and maintenance knowledge over company wide internets ("intranets"), and
- provides heuristic guidelines for estimating the costs and benefits of implementing diagnostic decision support systems for mobile mining equipment.

8.2 Practical Benefit of Work

The work provides a number of practical benefits, including;

1. introducing an analytical technique to reduce the dependency on compiled knowledge sources and accelerate the development of diagnostic decision support systems,
2. development and implementation of a diagnostic decision support system to reduce breakdown repair times, training expenditure and dependence on skilled labour necessary to maintain a semi-automated ST-8B LHD vehicle,
3. demonstration of the use of HTML and web browsers as a cost-effective, maintainable means of authoring and disseminating equipment diagnostic and maintenance knowledge.

8.3 Limitations of Approach

1. Application of the set theoretical diagnostic techniques described in chapter 4 is limited to systems where the number of non-redundant observable outputs exceeds the number of input subsystems. A resolution index (RI) is provided in chapter 5 to help characterise suitable systems.

2. Application of HTML as a means of formalising and presenting diagnostic knowledge is limited to systems which have a limited finite number of faulty or normal output behavioural combinations. This is of little concern for mobile mining equipment mechanical and hydraulic subsystems, which are typically designed to perform a limited range of functions.

8.4 Future Work

Future work could include;

1. development of a graphics-based software package to facilitate the development of structural models and automate the hypothesis generation process. Present techniques can be time consuming, which precludes the iterative application of contributor set theory to, for example, determining optimal sensor location.
2. investigation of the use of assumption-based logic to develop normality sets. For some system failure modes, diagnostic resolution may be improved if certain components are assumed to be functioning normally and included within normality sets. This would require a means of tracking assumptions similar to the ATMS reasoning mechanism developed by de Kleer and Williams [1987].
3. application of the set theoretical diagnosis technique to other fields. To date, an industrial manufacturer in Toronto has expressed interest in applying contributor set theory to the hydraulic system of an injection moulding machine. One application area of particular interest is software debugging and reliability analysis, since flow charts are a form of structural diagram in which process flow is data or information, and components are blocks of code. Software reliability is likely to grow in importance as the mining industry continues to automate and delegate control and monitoring functions to microprocessor-based systems.

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Appendix 1:

Atlas Copco Wagner ST-8B Specifications

WAGNER MINING EQUIPMENT CO.

P.O. BOX 20307 • PORTLAND, OREGON 97220 • U.S.A.

SPECIFICATIONS FOR

MODEL ST - 8B

4-WHEEL DRIVE SCOOPTRAM®
SPECIFICATION NO: 643403

MARCH, 1989

CAPACITY (S.A.E. RATED):

	lbs	(kg)
Static Tipping Load Straight Ahead	69,000	(31,360)
Breakout Force	51,100	(23,180)
Hydraulic Breakout Force	51,100	(23,180)
Tramming Capacity	30,000	(13,640)

BUCKET (STANDARD):

Capacity, S.A.E. Rating

Nominal Heaped	8.5 cubic yards	(6.5 cubic m)
Struck	7.0 cubic yards	(5.4 cubic m)
Boom Raising Time	7.4	Seconds
Boom Lowering Time	3.0	Seconds
Bucket Dump Time	6.5	Seconds

VEHICLE SPEEDS, LOADED:

Forward or Reverse

Gear	1st	2nd	3rd	4th
Speed in mph	3.0	5.2	8.7	14.6
Speed in km/h	4.8	8.3	13.9	23.4

GRADEABILITY: SEE PERFORMANCE CURVE

ENGINE:

Deutz Diesel (4-Cycle),	Model: F12L-413FW	
MSHA Sch. 24 Power Rating @ 2300 rpm:	277 hp	
Maximum Torque @ 1500 rpm	674 ft-lb	(93.2 mkg)
Number of Cylinders	12 in "V"	
Displacement	1168 cu. in.(19.1liters)	
Cooling	Air	
MSHA Ventilation	24,000 cfm	(679 cu. m /min)

ELECTRICALSYSTEM: 12/24Volts

TORQUE CONVERTER:
Single Stage, Clark C-8,000 Series

TRANSMISSION:
Full Power Shift, 4 Speeds Forward and
4 Speeds Reverse, Clark 5,000 Series

AXLES:
Spiral Bevel Differential, Full-Floating
Planetary Wheel End Drive
Clark 75,000 Series

STANDARD BRAKES:
Service: Hydraulically Applied,4-Wheel, Force Cooled
Fully Enclosed Wet Disc Brakes.
Parking: Spring Applied, Hydraulically released
Multiple Wet Disc Brake, Driveline Mounted.

TIRES:
Tubeless, Nylon, Smooth Tread Design,
For Underground Mine Service, on Demountable rims.
Tire Size, Front & Rear: 26.5 x 25, 32 Ply, L-5S

STEERING:
Articulated, Hydraulic Power Steering
Pilot operated, Mono-Stick control
Turning Angle 85° (42-1/2° each way)
System Pressure: 2,000 psi

HYDRAULIC SYSTEM:
Dump and Hoist Control: Single lever
Cylinders, Double Acting with Chrome Plated Stems

Steering Cylinders	(2)	Diameter 6.0"	(152 mm)
Hoist Cylinders	(2)	Diameter 9.0"	(228 mm)
Dump Cylinder	(1)	Diameter 9.0"	(228 mm)

Pumps, Heavy Duty Gear Type

Dump & Hoist	60+60 gpm (456 l/m) @ 2300 rpm
Steering	60 gpm (227 l/m) @ 2300 rpm
Filter	Suction Line 25 Micron
Filter	Partial Return 10 Micron

TANK CAPACITIES:

	U.S. Gal	(liters)
Fuel	100	(380)
Hydraulic Oil	95	(360)

OSCILLATION:
Rear Axle, Trunion Mounted, Synthane Bushings
Degree of Oscillation Total 18 Degrees

EXHAUST CONDITIONER:
Catalytic Purifier plus Exhaust Silencer

OPERATOR'S ARRANGEMENT:
Side Entry and Side Seating For Bi-Directional Operation
and Maximum Visibility.

WEIGHT: (APPROXIMATE)

	lbs	(kg)
Operating (Empty Vehicle)	78,750	(35,720)

MANUFACTURED WITH A MSHA TITLE 30, PART 32 (SCHEDULE 24) CERTIFIED ENGINE

WAGNER MINING EQUIPMENT CO.

P.O. BOX 20307 • PORTLAND, OREGON 97220 • U.S.A.

PRINCIPAL FEATURES AND BENEFITS OF WAGNER SCOOPTRAM® MODEL

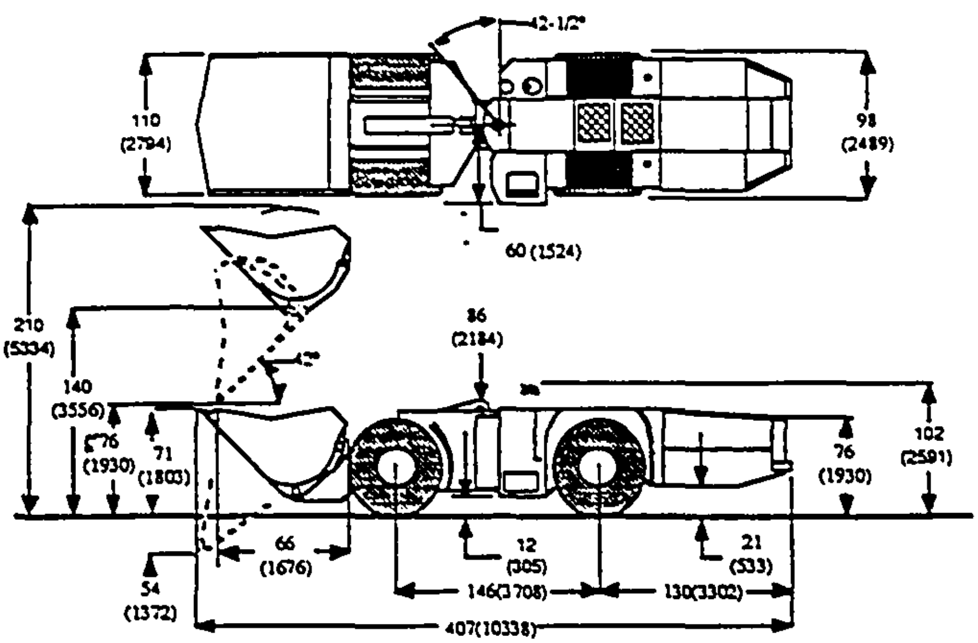
ST-8B

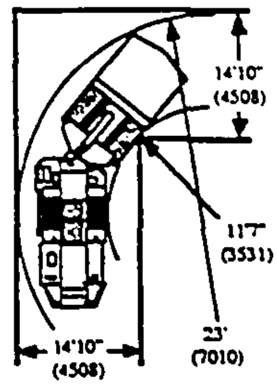
MARCH, 1989

1. 30,000 Lbs. (13,640 Kg) TRAMMING CAPACITY
   - Can carry material weighing 3,500 lbs/cubic yard (2.1 T/M^3) in the standard 8.5 cubic yard (6.5 cubic meter) bucket.
   - Can be equipped with larger or smaller buckets to match its tramming capacity to different material weights.
2. 68,000 Lbs. (30,900 Kg) OF USEABLE BREAKOUT FORCE WITH BUCKET HEEL DESIGN
   - Contributes to one pass loading and full heaped bucket load.
3. MODULATED SHIFT TRANSMISSION
   - Can save up to three seconds on each directional change. Full throttle can be maintained when changing directions.
   - Reduces stresses on drivelines, axles, transmission & bearings. Can increase component life by 15%.
4. SERVICE BRAKES ARE FULLY ENCLOSED, MULTIPLE WET DISC BRAKES IN ALL 4 WHEELS
   - Brakes are applied hydraulically, with dual circuits for front and rear axle brakes (eliminating any air system components and their frequent maintenance requirements).
   - Brake life has exceeded 10,000 hours.
   - Brakes are hydraulically cooled through external circuit.
   - Protected against entry of abrasive dirt, water, rocks, etc.
   - Can save up to 80% on parts and labor over the life of the machine, compared to other brakes.
   - Brakes can be rated for 150,000 lbs. (68,000 Kg) gross vehicle weight, 45% greater than the loaded weight of the ST-8B.
5. HEAVY DUTY BOGIE STRUCTURE
   - Increased life expectancy through an average 30% increase in material cross-sectional area.
6. MASSIVE PIN JOINTS WITH REPLACEABLE STEEL INSERTS
   - Load bearing surfaces increased 50% to 150%.
   - Pin life expected to increase 3 to 4 times.
   - Replaceable inserts protect pin bores and eliminate need for reboring.
7. ADJUSTABLE, SELF-ALIGNING, SPHERICAL THRUST BUSHINGS AND REPLACEABLE STEEL INSERTS IN THE ARTICULATION
   - Life of thrust bushings is twice that of roller bearings or solid bronze bushings.
   - Any wear can be easily compensated for by adding shims and retorquing four bolts.
   - Steel inserts protect, and eliminate the need to reweld & rebore the hinge plates. This can save up to 20 man-hours in labor and reboring expense.
8. HYDRAULIC SYSTEM DESIGNED AND COOLED TO KEEP OPERATING TEMPERATURES BELOW 70° F (21°C) OVER AMBIENT
   - Extends life of hydraulic system components.
9. HYDRAULIC HOSES WITH PRESSURE AND TEMPERATURE RATINGS 50% OVER NORMAL
   - Aeroquip High Pressure hoses rated up to 4000 psi (275 bar) for the steering and dump & hoist systems.
   - Aeroquip High Temperature hoses rated up to 300°F (150 °C) for the transmission/converter circuits.
10. PILOT OPERATED MONOSTICK STEERING
    - Minimizes operator effort.
    - Simplified circuit and valves for easy maintenance.
11. PILOT OPERATED DUMP AND HOIST CONTROL
    - Allows for better operator control with minimal effort.
    - Reduces high pressure hoses across the articulation from 4 to 1.
12. HYDRAULIC TRANSMISSION SHIFT CONTROL
    - Allows for easier operator control.
    - No mechanical linkage to wear.
    - Provides positive spool detent on control valve.
    - Provides positive clutch engagement for longer transmission clutch life.
13. CENTRALIZED LUBRICATION
    - All grease points, except drivelines, have been plumbed to two centralized lubrication panels in the articulation area where they are conveniently serviceable.

The manufacturer reserves the right to change the design and/or specification of this vehicle at anytime without notice.

MODEL ST-8B





NOTES: • DIMENSIONS INSIDE PARENTHESES ARE SHOWN IN MILLIMETERS.
• HEIGHT OVER THE OPERATOR IS ADJUSTABLE DEPENDING ON APPLICATION.
• ALL HEIGHT DIMENSIONS ARE BASED ON A TIRE RADIUS OF 34.4" (874 MM)

STANDARD SPECIFICATION

Engine Hour/Service Meter
Engine Oil Pressure Gauge
Engine Temperature Gauges
Engine Low Oil Pressure/High Temperature Audio-Visual Alarm
Engine Primary and Secondary Fuel Filters
Engine Oil Filter
Dry Type Aircleaners
Converter Oil Cooler
Converter Temperature Gauge
Additional Fuel Filter with Water Separator

Pilot Operated Hydraulic Transmission Shift Controls
Modulated Shift Transmission
Clutch Pressure Gauge
Transmission Oil Filter with Indicator
NoSPIN® in Rear Axle
Straight Hydraulic, Multiple Wet Disc Brakes
Single Lever Pilot Operated Dump & Hoist Control

Two Batteries of 170 Ah each
Alternator, 90 Amps
Lights, Halogen, 12 Volt (4 Front & 4 Rear)
Voltmeter
Battery Isolation Switch
Neutral Start Protection
Automatic Brake Application with Low Converter Oil Pressure
Fuel Shut-Off Valve
Swivel Hinge Lock Arm
Centralized Lubrication Panels
Remote Pump Pressure Test Ports

NOTE: The manufacturer reserves the right to change the specifications and/or design of this vehicle at any time without notice.

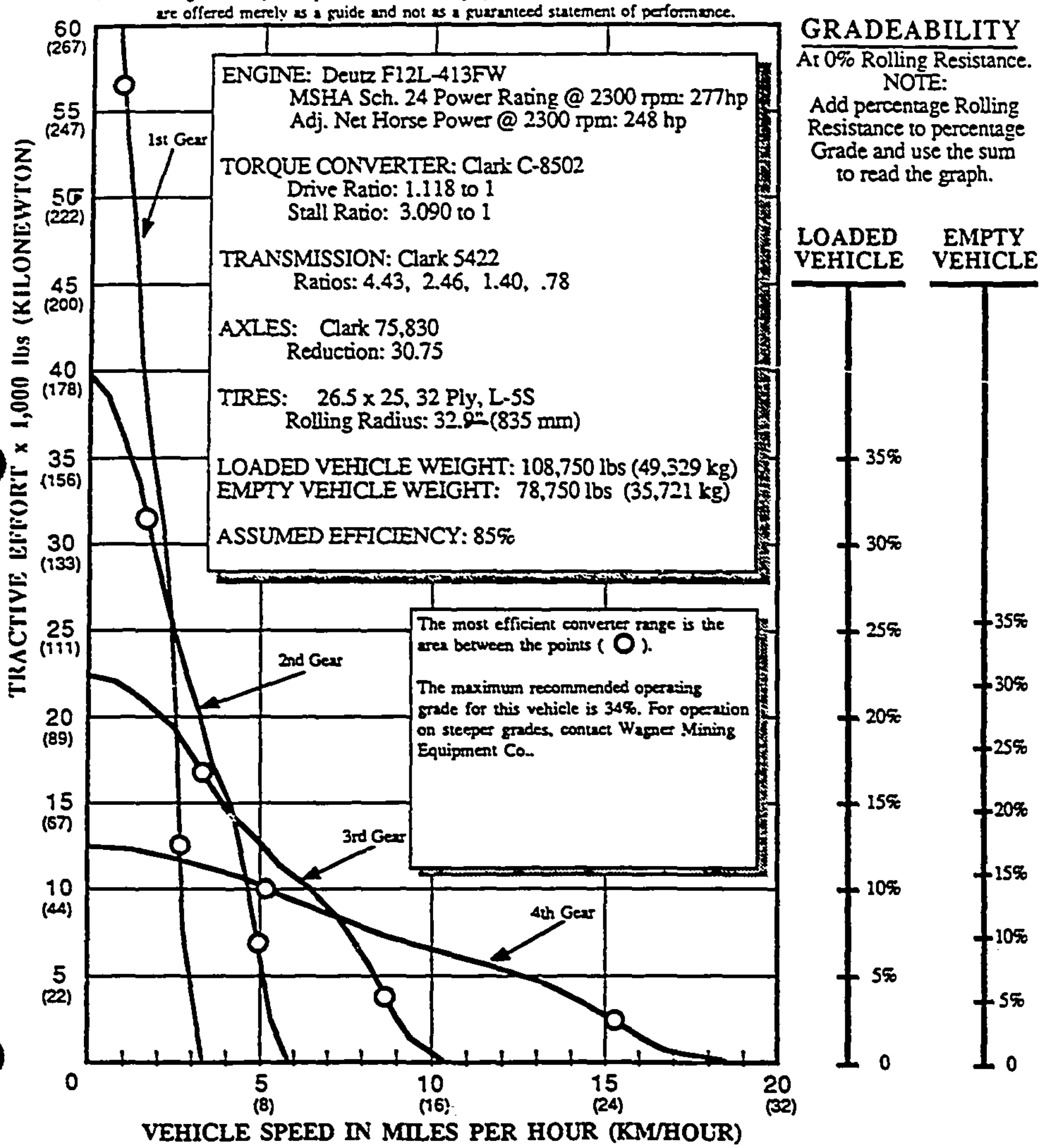
WME RSR 3/89

WAGNER MINING EQUIPMENT CO.

P.O. BOX 20307 • PORTLAND, OREGON 97220 • U.S.A.

PERFORMANCE CURVE
MODEL ST-8B
NO. 643403-1
DECEMBER, 1988

NOTE: The gradeability and speed curves on this graph are based on assumed variables and are offered merely as a guide and not as a guaranteed statement of performance.



Appendix 2:

Analysis of ST-8B Repair Times

Analysis of ST-8B Repair Times

A2.1 Explanatory Note

An analysis of the downtime accrued by three Wagner ST-8B LHDs at an underground metalliferous mine in Canada was undertaken in March 1993 to determine the types, severity and frequencies of typical mine-site repairs. To enable the analysis, maintenance reports for the period 19 February 1992 to 16 February 1993 for LHD units 831, 832 and 833 were transferred to a Lotus 123 spreadsheet. At the time of the analysis, each LHD had logged approximately 3000 operating hours. Since the three machines were among the first ST-8B's produced by Wagner Mining Equipment Co. (now Atlas Copco Wagner), a number of design related repairs undertaken by the mine were removed from the analysis to reduce bias. The analysis has been included in an appendix, rather than the main body of the thesis, because it primarily relates to the work presented in Appendix 3. In addition, it provides an interesting comparison and verification of the fault likelihoods established during the manual knowledge acquisition process described in Chapter 6.

A2.2 LHD Availabilities

Figure A2.1 illustrates the monthly availabilities of each of the three LHD vehicles. Availabilities have been calculated on the basis of two eight hour shifts scheduled for each working day of a month. Lowest availability occurs in May for Unit 833 (114 hours of downtime) which can be attributed to a damaged hydraulic tank and an engine change, and in October for Unit 832 (94 hours of downtime) due to a rebuild of the midship bogie bearing support (point of articulation). A similar midship repair was performed on Unit 831 at the end of August, but since work carried over into September monthly availability was not affected to the same extent as that for Unit 832.

A2.3 Total Downtime

In total, between 19 February 1992 and 16 February 1993, 1517 hours of downtime were accrued by the three LHDs (this figure includes hours billed to the mining company only, and not those accredited to the equipment supplier). Figure A2.2 indicates that inspection ("Insp") is the downtime category to which most hours are attributed. This category includes regular preventative maintenance of the scoops such as washing and engine and transmission oil changes. In descending order of magnitude, the next four downtime categories are; "Eng"; engine repairs, "Drive"; drivetrain repairs, "Stru"; structural repairs and "Hyd"; hydraulic repairs.

Figure A2.3 shows how downtime is divided between the three machines. Of particular note is the downtime spent on hydraulics for Unit 833 (94.9 hours), which is largely due to repairing a damaged hydraulic tank (33.8 hours) and unusually frequent repairs to the unit's autolube system (23.3 hours). In addition, units 831 and 832 show high downtime hours for structural repairs due to the midship bearing rebuilds undertaken on each of these machines.

A2.4 Adjusted Downtime

The ST-8B is a new addition to Wagner Mining equipment's range of LHD vehicle. As such, several design-related faults were discovered in the three machines. Two repairs were carried out on Units 831 and 832 for poorly designed midship bearing supports which necessitated a total of 85.9 hours downtime, and a repair job was undertaken on Unit 831 for a faulty forward/reverse clutch pack (16.9 downtime hours). To enable a more accurate picture of the distribution of ST-8B repairs, these non-representative repairs were subtracted from the total downtime. In addition, downtime due to inspection and "idle" time (waiting upon replacement parts, labour or garage space), were excluded from further analysis.

The resulting adjusted downtime distribution is shown in Figure A2.4, and the repair frequency distribution is as illustrated in Figure A2.5. The graphs indicate that, although the most frequent repair jobs are electrical, engine problems are the largest source of downtime. The next highest sources of downtime are hydraulic and drivetrain repairs. On average, the most time consuming repair jobs are the relatively infrequent bucket changes, closely followed by drivetrain repairs (transmission, torque converter and axle).

A2.5 Engine Downtime

The distribution of downtime spent on engine related problems is as illustrated in Figure A2.6. Surprisingly, approximately 23 percent of engine downtime is related to problems with the fuel system. This category includes fuel leaks which occurred at the fuel pump, shut-off solenoid, filter and injector lines, a damaged fuel tank and repairs and adjustments to the fuel shut-off linkage and solenoid. Broken teeth on ring gears accounted for another 17 % of downtime, whilst the "Eng" category includes compression testing and adjustments to engine valves and motor mounts, brackets and bolts. Problems with the engine lubrication system, ("Oil"), include leaks which occurred at oil filter o-rings and connecting hoses. Cooler related repairs mostly entailed cleaning and/or replacement of the engine cooler and frame. Leaking throttle pedals and damaged throttle linkage pins contributed to the "Thtl" category, whilst "Exh" includes blocked PTX scrubbers and leaks which occurred in the exhaust system. Each ST-8B is fitted with a Deutz F12L-413-FW engine which is air-cooled by a blower fan. The majority of blower problems ("Blow") were worn blower bearings and damaged blower grills. The remaining three categories are; "Air"; damaged air filter covers, "Alt"; replacement and tightening of alternator belts, and "Sens"; replacement of the tachometer and engine temperature sensors.

A2.6 Hydraulic Downtime

Figure A2.7 illustrates the distribution of downtime spent on hydraulic maintenance repairs for the three scoops. 21 percent of downtime was spent on hydraulic tank repairs which is in large part due to a ruptured hydraulic tank on Unit 833. Maintenance of auto-greaser hoses ("AutG") as well as boom and cylinder grease fittings account for a further 20 percent of downtime. Leaking o-rings, and frequent cracking of the midship steel line ("Mdshp") to the main control valve (MCV) demanded 16 percent of all hydraulic downtime. Leaking relief valve, o-rings and hoses connected to the hoist, dump and steering cylinders accounted for the majority of downtime in the "Hst", "Dmp" and "Steer" categories. "MCV" downtime accounts for leaking o-rings at the main control valve, and "Tow" downtime mainly consists of time taken to bleed and test the towing system. Leaking o-rings and dirty valve seats contributed to hydraulic pump repairs ("Pump"), whilst a very small percentage of downtime was spent on fixing loose joystick controls ("Cntl"). The miscellaneous category ("Misc") includes maintenance such as draining excess oil and timing the midship drive line.

A2.7 Drivetrain Downtime

The distribution of downtime spent on drivetrain maintenance is shown in Figure A2.8. The largest source of drivetrain downtime is due to axle repairs ("Axle"), mainly consisting of repairs to leaking brake cooling hoses, hub seals and planetary cover seals[1]. The transmission and converter oil cooler ("Cool") necessitated repairs to leaking feed hoses and cooler brackets, and, in some instances, cooler replacement. The "Cltch" category includes replacement of the forward/reverse clutch pack and retainer, whilst "Whl" repairs are due to the replacement of wheel studs. Leaking o-rings and supply hoses to the torque converter account for "Torq" faults, as well as some charging pump ("Pump") and oil filter ("Filt") repair and replacement problems. Cracks in the transmission pan account for "Tran" repairs, whilst maintenance of breather valves and oil changes account for differential ("Diff") repairs.

[1] In this analysis, the brake system was considered part of the drivetrain system. In fact, if correctly treated as part of the hydraulic system, hydraulic system repairs can be concluded to be the most significant source of ST-8B downtime.

A2.8 Electrical Downtime

When mucking, scoop lights are particularly prone to damage. It is not surprising then, that repairs to the scoop lights ("Light") and light wiring account for approximately 24 percent of the downtime spent on electrical repairs. Figure A2.9 illustrates the distribution of service time spent on electrical repairs, not including repairs to the scoop remote control systems. Starter motor faults ("Start") account for a further 19.6 percent of downtime. These include loose connections, sticking solenoids, and faults resulting in replacement of the starter motor. Replacement of warning lights and repairs of breakers and shorts in the dash wiring ("Dash") account for 13 percent of downtime, whilst a further 12.8 percent of downtime was spent on replacing faulty master switches ("Mastr"). Battery repairs include battery replacements, loose and dirty battery terminals, and broken ground cables. The remaining five categories include; "Sens"; replacement of engine and torque converter over-temperature and pressure sensors,; "Alt"; replacement of faulty alternators, brackets and loose wiring; "Horn"; replacement of the horn and tightening of ground wiring; "AutG"; replacement of fuses, program cards and wiring at the auto-greaser; "Fuel"; replacement of wiring to the fuel shut-off solenoid, and; "Glow"; wiring repairs to the engine pre-heat (glow) plugs.

A2.9 Other Downtime

Approximately 50 percent of the downtime recorded for structural repairs was due to the two midship repair jobs undertaken on Units 831 and 832. The remainder of the structural downtime was spent on welding wear pads at the hoist cylinder anchor pins, checking for cracks in the boom, welding boom and bucket stops and repairing damaged fenders.

Figure A2.4 shows that a relatively large number of repairs were recorded for the LHD remote control systems. The majority of these, however, were solved by simply replacing the remote control unit with a refurbished unit.

The ST-8B uses a SAHR (spring applied, hydraulic release) braking system, and is fitted with an automatic brake applicator (ABA) system which automatically applies the service brakes if either the engine or torque converter lose oil pressure or the unit loses electric power. The SAHR braking system is a "wet" brake system housed within the axle enclosure, and hence, it is not surprising that the majority of brake problems are leaks which occur in the hub seals and cooling hoses. Two instances were also recorded of brake pedals which required replacing.
Figure A2.4 shows that, on average, bucket repairs ("Bckt") require 3.2 hours of downtime. This is due to fitting and cutting drain holes in new buckets. Regular testing and service of the Ansul fire suppression system ("Ansl") on the three machines required the least maintenance during the year of operation.

A2.10 Summary

Maintenance data was analysed for one years operational experience with three ST-8B LHD vehicles. The most frequent repairs were found to be electrical in nature, however engine, hydraulic and drivetrain repairs demand the most downtime. The largest source of engine downtime were fuel system problems which included a damaged tank, adjustments to the fuel shut-off linkage and leaks at the pump, filter and injector lines. The most significant source of drivetrain problems occurred at the axles, with typical problems being leaks at brake cooling hoses and hub and planetary cover seals.

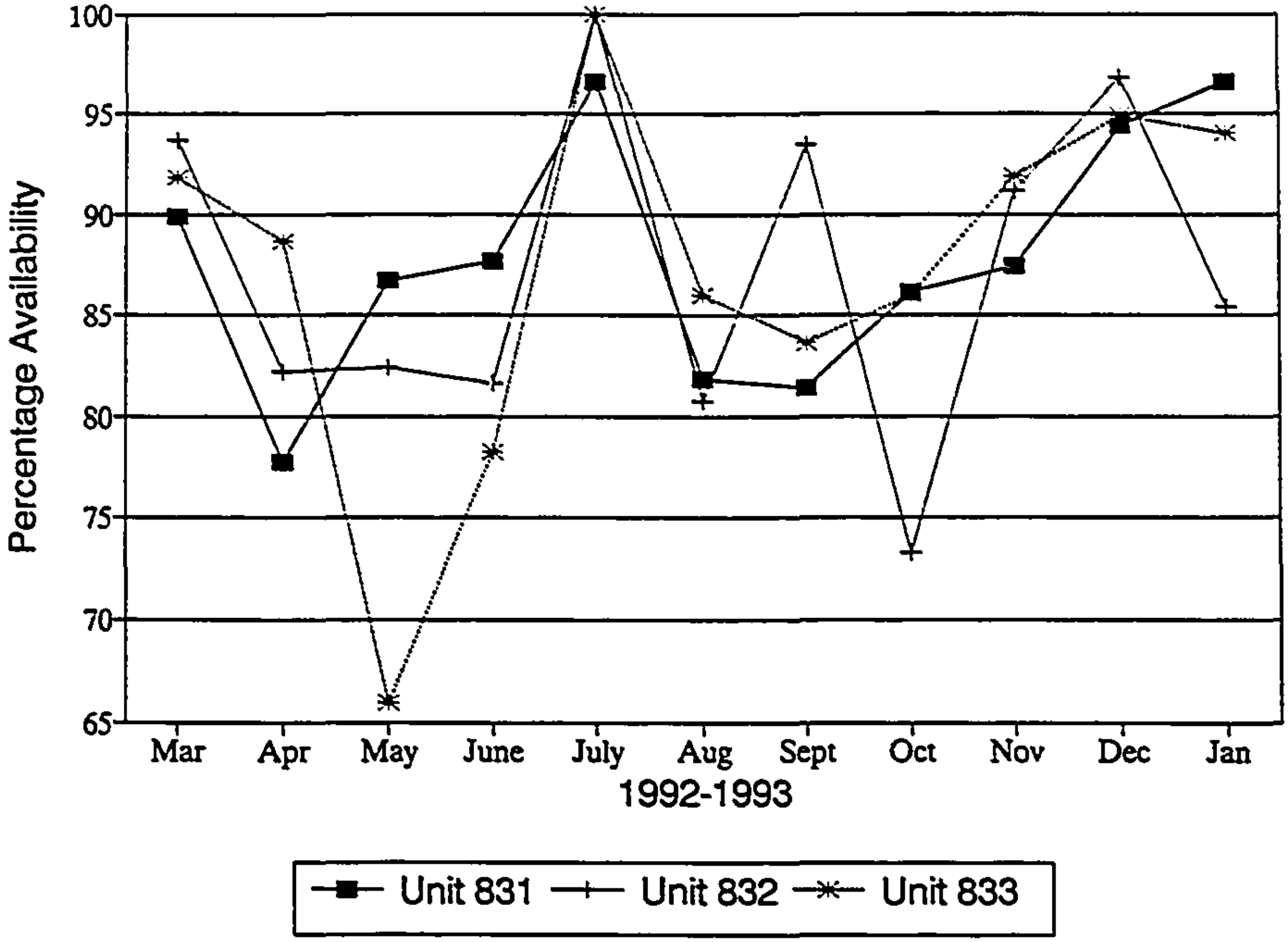


Figure A2.1 ST-8B Availabilities

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

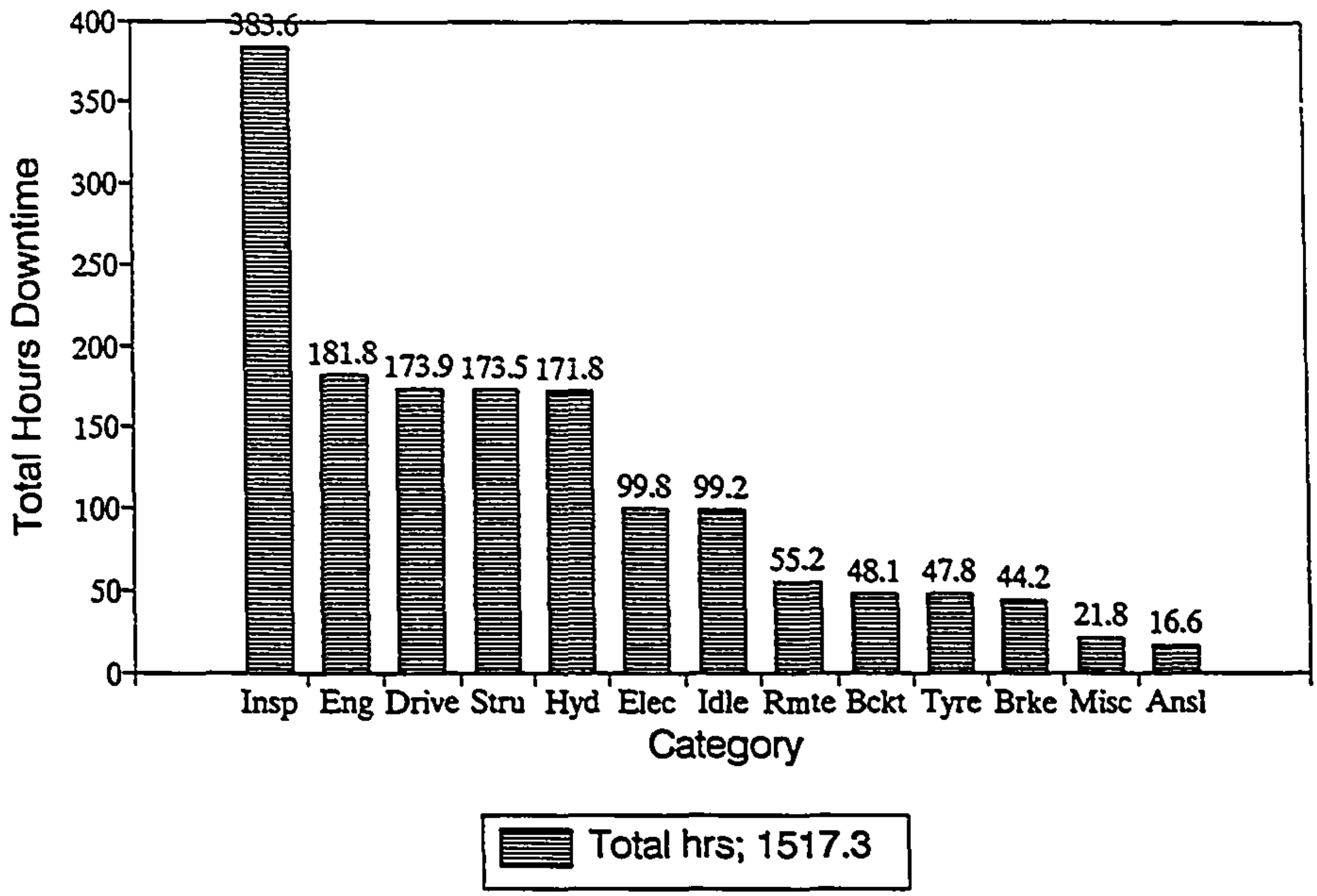


Figure A2.2 Total ST-8B Downtime

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

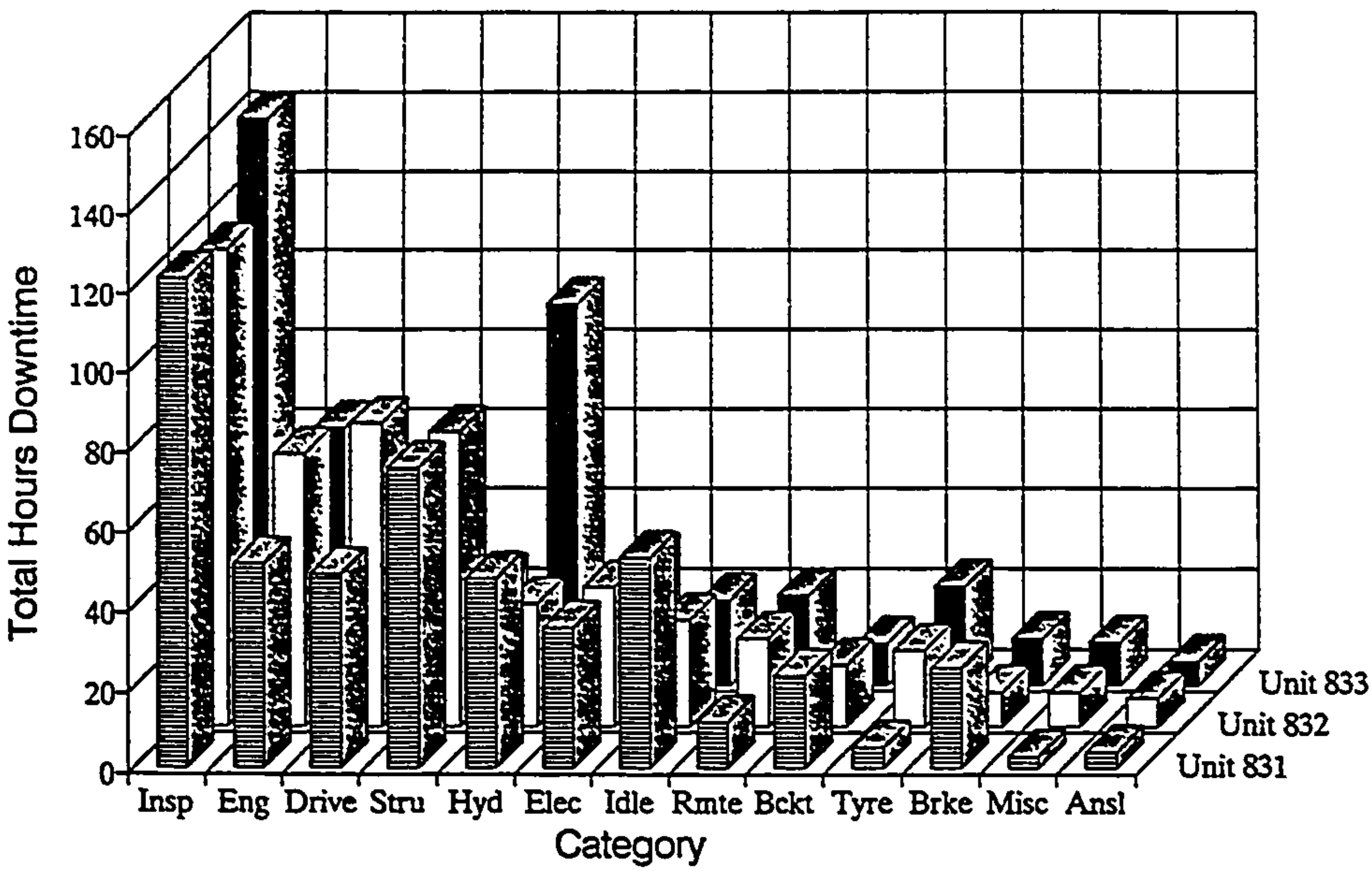


Figure A2.3 Downtime by ST-8B Unit

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

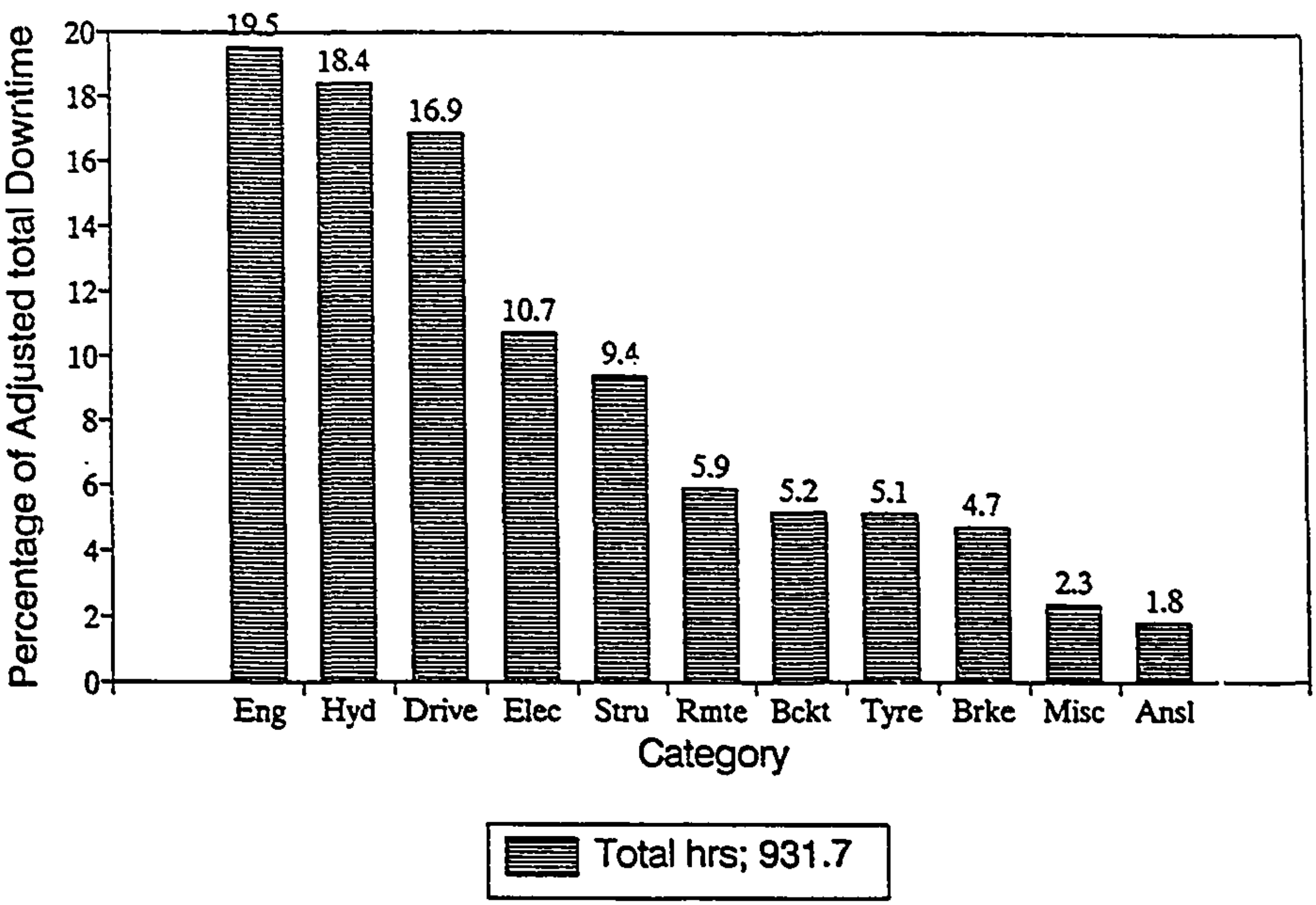


Figure A2.4 Adjusted Total ST-8B Downtime

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

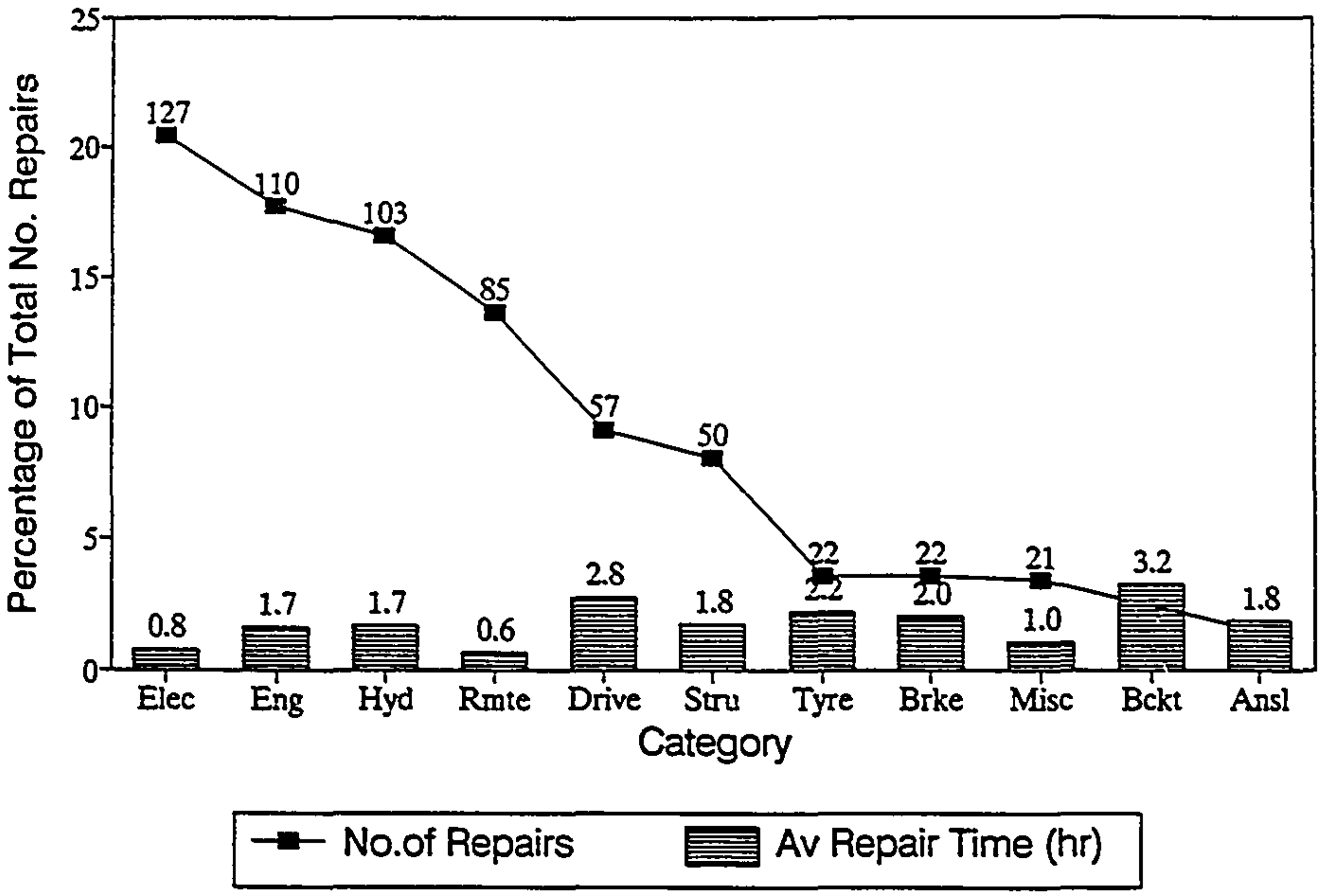


Figure A2.5 Adjusted ST-8B Repair Frequencies and Average Durations

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

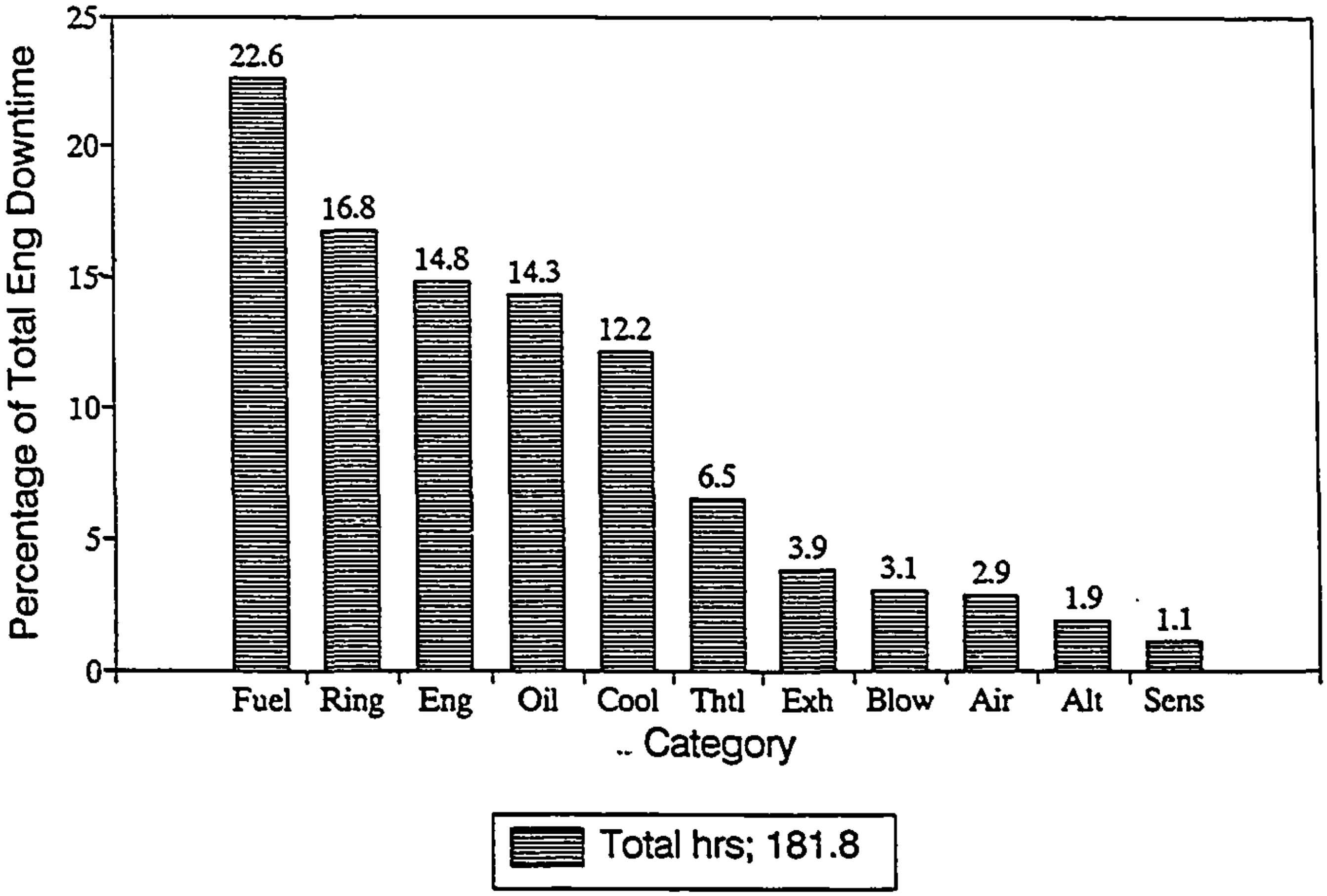


Figure A2.6 Deutz FL-413-FW Engine Downtime Distribution

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

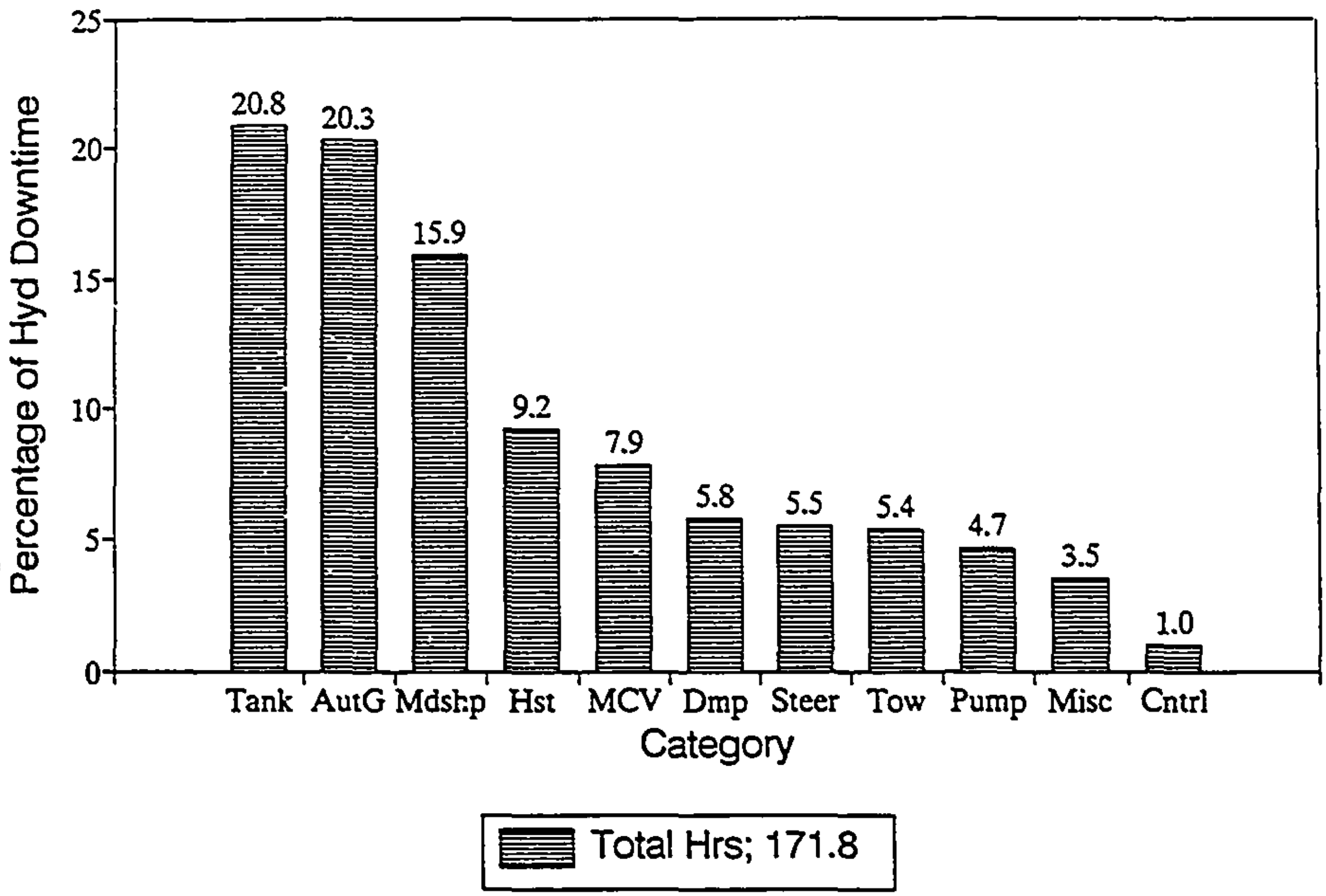


Figure A2.7 ST-8B Hydraulic System Downtime Distribution

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

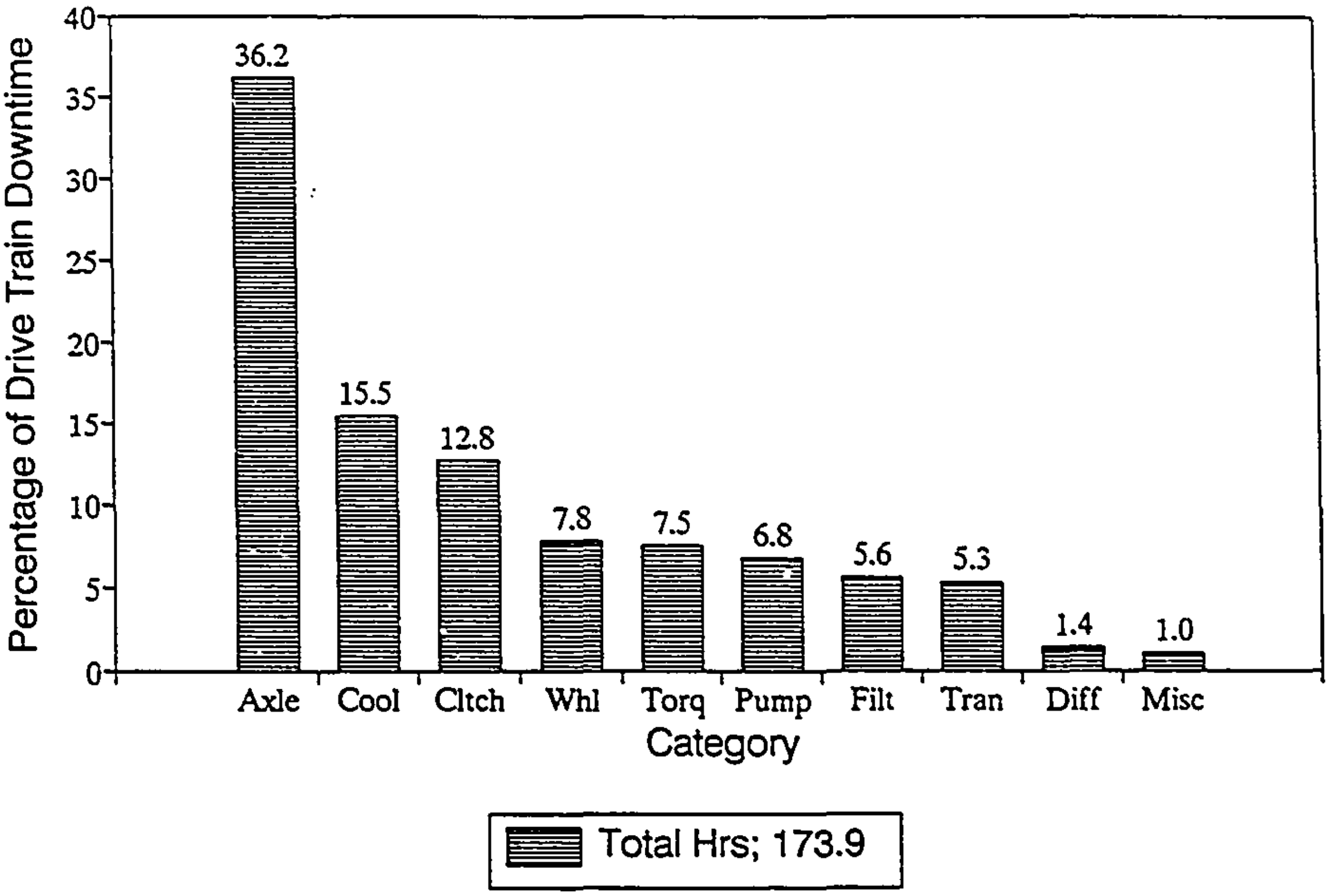


Figure A2.8 ST-8B Drivetrain Downtime Distribution

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

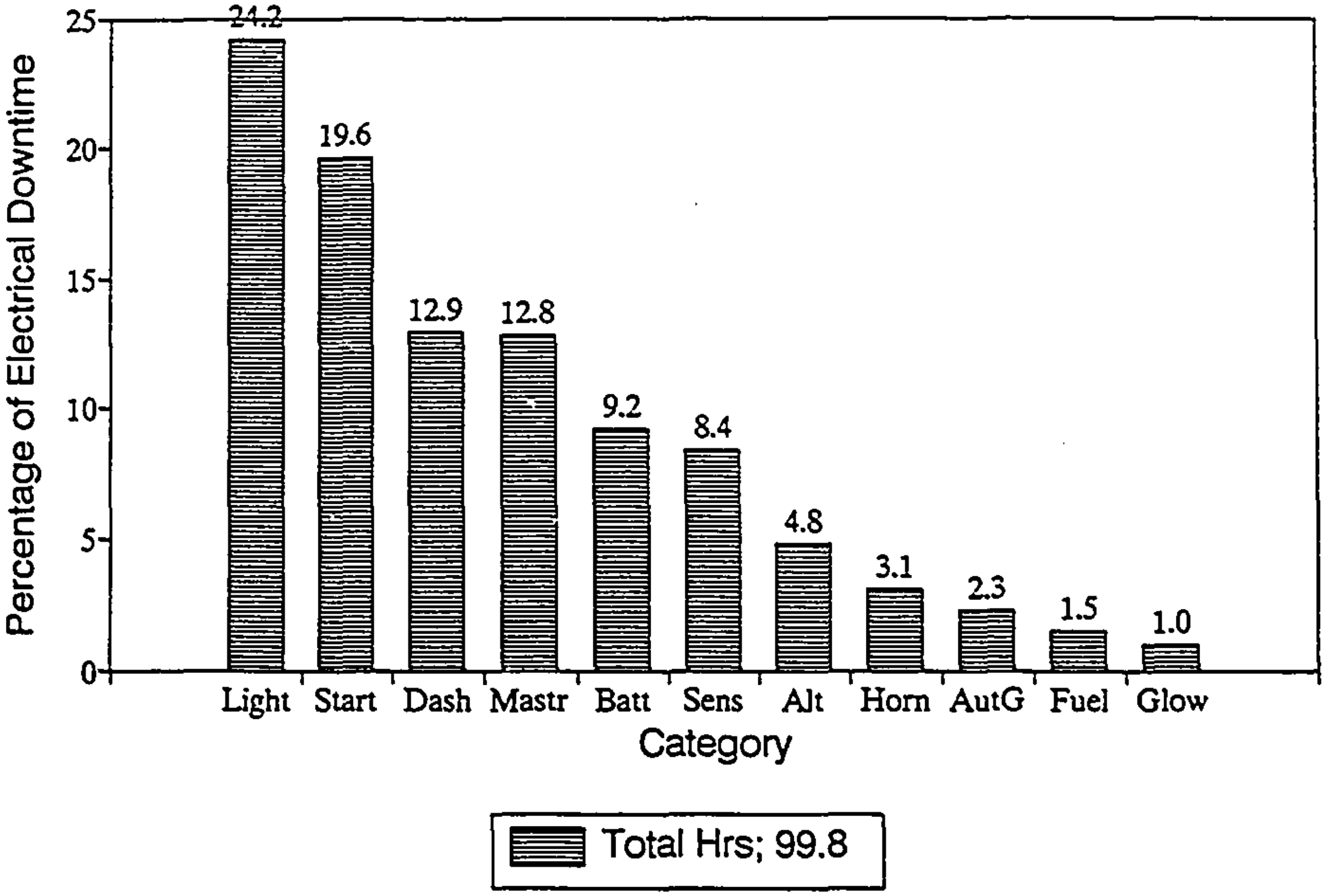


Figure A2.9 ST-8B Electrical System Downtime Distribution

Units 831, 832, 833, 19 Feb. 1992 to 16 Feb. 1993.

Appendix 3:

Sensor-based Symptom Detection in ST-8B Vehicles

Sensor-Based Symptom Detection in ST-8B Vehicles

A3.1 Explanatory Note

This appendix outlines a list of recommended condition monitoring parameters, sensors and sensor positions for detecting faults in semi-automated ST-8B vehicles. The term "semi-automated" is used here to describe operations in which the LHD is automatically controlled during tramming and remotely controlled from the surface during loading and dumping. The work was conducted for INCO Limited, and resulted in the submission of a report in December 1993 [Knights, 1993a]. The work has been included as an appendix because it relates to symptom detection (fault detection), and not to hypothesis generation which is the major focus of the thesis. The work was conducted prior to the development of the set theoretical techniques outlined by the thesis, and thus causal knowledge was drawn from the ST-8B service manual [Wagner Mining Equipment Co., 1991] and an analysis of ST-8B repair data conducted in March 1993 (see Appendix 2).

A3.2 Engine

A3.2.1 Critical Parameters

During a brief tour of INCO's Divisional Shops at Copper Cliff in February 1993, the Foreman in charge of Central Maintenance was asked what he perceived to be the major causes of Deutz FL-413-FW engine failures. Without hesitation he replied that the two major causes of engine damage were (i) dirt build-up on the engine leading to overheating and (ii) dirty oil leading to bearing, piston and sleeve wear [Catalano, 1993].

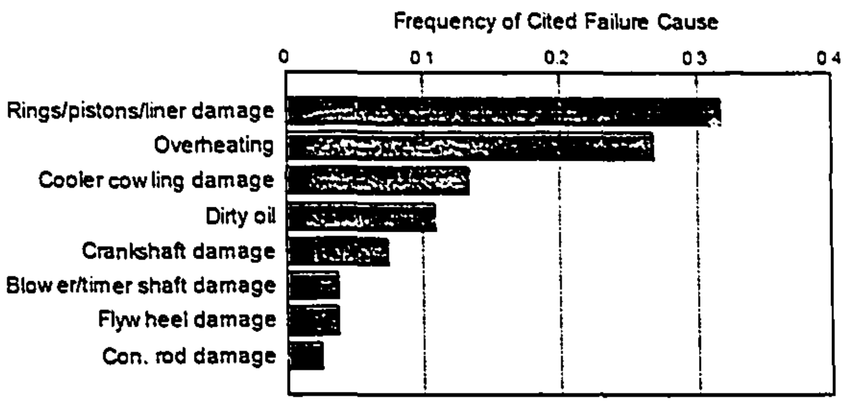


Figure A3.1 Deutz F12L 413 FW Engine Failures (Div. Shop Records, 16 Feb. 88 to 13 Feb. 93)

Figure A3.1 is a histogram of the major fault causes cited in all Divisional Shops failure reports for FL-413-FW engines over a five year period. Most damage to rings, pistons and liners can be attributed to poor engine cooling, poor lubrication or wear due to dirty oil. Damage to the rings, pistons, cylinder heads, liners and crankshafts commonly occurs in the form of scored, cracked or burnt components. Damage to the crankshaft and blower/timer shafts includes worn or broken bearings, and the "flywheel" category consists of broken ring gear teeth and damaged housings. The graph generally confirms the Central Maintenance Foreman's previous diagnosis.

With this information in mind, it appears that the most critical engine performance parameters to monitor during engine operation are;

(i) cooling system effectiveness
(ii) lubrication system effectiveness, and
(iii) oil quality.

At peak engine loads, both the cooling and lubrication systems must work at peak efficiencies. The job of the cooling system is to transfer heat away from the engine's cylinder sleeves, head and exhaust manifolds. The cooling system for the Deutz engine also has the auxiliary function of cooling the engine oil, hydraulic oil and transmission and converter oil. The Deutz FL-413-FW engine is air cooled by a blower fan mounted at the rear of the vehicle (the blower fan is coupled to the engine camshaft by a hydraulic clutch and gear train, and is activated when a thermostat in the exhaust manifold opens a control valve and directs engine oil flow to the clutch). Exhaust temperature, cylinder head temperature and engine oil temperature can all be monitored for signs of engine overheating. Engine exhaust temperature variations are in part due to engine speed [Kessler, 1993], but will respond more rapidly to cylinder overheating problems than either head temperature or engine oil temperature signals. It is recommended, however, that since measurement points are already in place on the FL-413-FW engine, cylinder head temperature be monitored for "top end" temperature problems. Engine oil temperature should also be monitored since overheating resulting from "bottom end" problems (such as crankshaft journal bearing wear) are not readily detectable from either exhaust or cylinder head temperature signals.

The lubrication system of the Deutz engine performs the dual function of both lubricating and cooling engine components. Oil is pumped from the sump at high pressure, cooled through a heat exchanger and distributed through a filter bank to various lines or "galleries" throughout the engine. Crankshaft journal bearings are lubricated via passages drilled within the crankshaft, and rocker arm bearings via hollow pushrods. The fuel injector pumps are also lubricated with engine oil. A stream of oil is sprayed onto the underside or "skirt" area of each piston to provide essential cooling. If the source of pressure that is supplying the piston cooling oil fails, the piston crowns and skirts will overheat very rapidly. At full load, loss of piston cooling oil can result in piston seizure in a matter of seconds rather than minutes [York, 1986]. If the piston does not seize, scuffing of the piston and/or sleeve will commence leading eventually to scoring. The lubrication function of oil as required by all bearing surfaces is equally important but not as time-critical as piston cooling. It is therefore essential to monitor engine oil supply pressure to the piston cooling ducts. The existing oil pressure gauge is tapped into the main oil gallery which delivers oil to the cooling ducts and camshaft bearings. The oil duct connecting to the gauge provides a suitable location for an analogue pressure sensor to measure oil pressure. Oil pressure, however, is a function of engine speed, and it is therefore necessary to measure engine RPM and to establish the nature of the RPM-pressure relationship (a flywheel magnetic pickup or an alternator pickup can be used to measure RPM).

Figure A3.1 indicates that wear of pistons, rings and cylinder linings is a common occurrence in FL-413-FW engines. Cracked, scored or broken pistons, rings and sleeves all result in excessive engine blow-by (pressure loss during combustion to the crankcase). The condition is evident by momentary increases in pressure in the crankcase before venting takes place through the crankcase breather valve. Flight Systems Corp., a Pennsylvania based company which currently manufactures the "Engine Saver 550" diesel engine monitoring unit, recommend the installation of a crankcase pressure sensor to detect cylinder blow-by. The monitoring point is located high above the oil away from any breather outlet. The pressure sensing line drains downwards for its entire length to prevent condensing oil vapour from blocking the line and causing false alarms [York, 1986]. It is recommended that this approach be adopted for sensing cylinder blow-by in FL-413-FW engines.

Oil quality is most commonly assessed by laboratory testing of oil samples. Measuring oil quality (dirt content) on line presents a challenging task. The Haulpak Division of Komatsu Dresser Company manufacture an oil monitoring system known as the "Metalert" warning system which employs magnetic particle sensors which can be fitted into existing vehicle oil drainage plug ports [Dresser-Haulpak Co., 1993]. The main limitation of this system is that it will only detect the presence of ferrous metallic particles in the oil (many of the Divisional Shop engine failures listed as being due to dirty oil were found to be contaminated by sand-fill). In addition some mining companies have found the system to give false alarms leading to unnecessary machine downtime [Kincaid, 1993]. Monitoring the differential pressure drop between the inlet and outlet of the twin cartridge oil filters presents another way of detecting dirt build-up within the engine oil. The FL-413-FW oil filter arrangement consists of two oil filter cartridges mounted in parallel and a further centrifugal filter at the blower coupling. Each filter cartridge contains a relief valve to ensure oil cooling flow to the engine should the filters become plugged. It is recommended that a differential pressure switch be installed over the filters, and pressure setting of the switch should be the same as the relief valve setting of the oil filter cartridges.

The previous discussion has centred on the cooling and lubricating systems of the engine during operation. Equally important to the running of an engine is the ability to ensure;

(iv) uninterrupted fuel delivery,
(v) uninterrupted delivery of air for combustion,
(vi) uninterrupted removal of engine exhaust, and
(vii) reliable starting performance.

A survey of the repair downtime accumulated during one year's operation of three ST-8B vehicles at McCreedy West mine indicated that the fuel delivery system was responsible for approximately 23 percent of all engine related machine downtime (see Appendix 2). Some of this downtime was due to problems with the fuel shut-off solenoid and linkage, a design problem which was later rectified, and some downtime was due to a ruptured fuel tank. 19 percent of all fuel related engine problems involved repairs to leaking or blocked fuel injectors. Monitoring of mechanical fuel injection systems prevents significant challenges, however Aachen University of Technology have experimented with high pressure pulse sensors clamped around the distribution hoses leading to the fuel injectors [Burgwinkel and Kessler, 1993]. To date, sensing has been accomplished on an off-line basis and the durability of the sensors during normal operations is questionable [Kessler, 1993]. Consideration was given to mounting a flow meter within the upstream fuel line, however, it was decided that this would not adequately detect the presence of either fuel leaks or blocked fuel injectors.

Restriction of either fuel supply or air supply to the engine will result in a decrease in power developed by the engine (see Section A3.8). For a conventionally operated LHD this power loss is easily evident to the operator. However, for an automated LHD, a loss in engine power may not be quite so noticeable. A knowledge of both the throttle setting and RPM of an operating diesel engine can be used to predict the torque output of an engine. A universal mathematical model of diesel engine performance using just these two operating variables was developed by H.D.Harris and F.Pearce [1990]. It is suggested that the dynamometer facilities at INCO's Divisional Shops could be used to test an FL-413-FW engine to establish the nature of the throttle setting/speed/torque relationship. In practice, throttle settings on the automated LHD can be indirectly measured by monitoring the PLC signals sent to activate the hydraulic slave valve in the ST-8B throttle line. In an operating environment, the throttle setting/speed/torque relationship can be used to estimate engine torque output as a function of either time or distance travelled during production cycles (distance travelled can be calculated by multiplying engine speed, gear ratio and wheel diameter). It is suggested that engine torque be statistically monitored during tramming, loading and dumping phases of the production cycle to determine negative trends in engine performance. To the best of the author's knowledge, this presents a new approach to engine monitoring, and, if successful, should be able to detect restrictions or irregularities in both the fuel and air supply. Nonetheless, it is recommended to install pressure switches in the downstream suction side of each air filter to monitor for air restriction essentially to provide a check on torque model predictions during development.

Blocked catalytic converters in the exhaust system can cause a build-up of back-pressure in the exhaust manifold which may either result in leaks in the exhaust system or blow-by in the engine cylinders. In the latter case, the crankcase pressure sensor should detect the exhaust blockage. Leaks in the exhaust system are usually apparent to an operator by unusually excessive noise. Since audio feedback is being used with the automated LHDs, it is likely that a remote operator will be able to detect a severe exhaust leak. However, a minor exhaust leak may still go undetected, and, since exhaust particle emissions are strictly regulated in an underground mining environment, it is recommended that pressure switches be installed in the exhaust lines upstream of the catalytic converters. For fully manless mining these sensors may not be necessary.

Typical failures of the engine starting system are due to faulty starter motors, faulty batteries or shorted wiring to the preheat plugs (see Section A3.8). Low battery charge can in turn be due to a faulty battery, faulty alternator or loose or slipping alternator belt. It is therefore essential that both the battery voltage and charging voltage be monitored (see Section A3.5).

Finally, when considering either surface-controlled or unmanned LHD operation, sensors must be provided for measuring machine parameters which are currently monitored during pre or post-shift operator checks. These include sensors to monitor engine oil level and fuel level.

A3.2.2 Discussion

Engine faults such as worn journal bearings and mistimed, burnt or stuck valves lend themselves to diagnosis through the use of accelerometer-based vibration measurements. A literature search revealed that, whilst some experimental work has been undertaken on vibration-based diagnosis of reciprocating engines [DeJong et al., 1987, and Courrech, 1990], vibration monitoring has mostly been confined to laboratory environments and there are few examples of real-time vibration monitoring of mobile mining equipment in production environments. It is concluded that the major drawback in the adaptation of accelerometers to either engine or transmission fault detection is that a comprehensive data set is necessary in order to correctly characterize and identify frequency response signals obtained from accelerometer readings. Usually this necessitates artificial inducement of faults to the engine or transmission in order to obtain vibration responses, a scenario which is better suited to a laboratory environment and which demands considerable time and financial commitment to develop.

Another means of diagnosing combustion irregularities is to use a high resolution speed sensor to monitor flywheel output speed. By comparing the measured speed signal with a reference timing signal (obtained by measuring the angle of rotation of the camshaft), small speed fluctuations can help locate and pinpoint combustion irregularities which may occur in one or more cylinders. This technique forms the basis of the "Mechanic's Stethoscope" system developed by the Noranda Technology Centre [Dasys, 1993]. A similar system has also been developed by the University of Aachen and is currently in the process of being commercialized [Kessler, 1993]. Both these systems employ onboard sensors which can be connected to off board analysis equipment in the maintenance garage. Whilst such systems may prove extremely effective for engine testing in a workshop environment, the primary requirement of the LHD sensor system is to determine the presence of an engine fault in a production environment. As such, development of off-board diagnostic equipment lies outside the scope of work of this project, but should nonetheless be noted as having the potential to provide major savings in workshop related downtime.

One further technique for engine fault diagnosis is the analysis of engine oil sump acoustic signals. Engine faults are usually a source of noise which tends to propagate through the oil system to the sump. In at least one engine manufacturing plant, General Motors employs just such an acoustic probe to test the integrity of new engines [Trépanier, 1993]. As for the case for applying accelerometers above, the development of such a system requires a complete set of fault data and requires commitment beyond the existing scope of the project. Nevertheless, attention is drawn to the potential of this technique for future reference.

A3.2.3 Summary Table

SENSOR	TYPE	RANGE	No.
oil pressure (main gallery)	analogue	40-120 PSI	1
oil temperature (cooler outlet)	analogue	100-300 degrees F.	1
cylinder head temperature	analogue	200-350 degrees F	2
crankcase pressure	switch	10-20 PSI adjustable	1
throttle position (PLC signal)	discrete	idle/half/full	1
RPM	analogue	500-2800 RPM	1
oil filter differential pressure	switch	max = oil filter relief valve setting	1
oil level	analogue	empty-full (0-29 litres)	1
fuel level	analogue	empty-full (0-380 litres)	1
engine exhaust pressure	switch	15 PSI (25" water) adjustable	2
air filter downstream pressure	switch	13 PSI adjustable	2

Table A3.1 Summary of Sensors Recommended for the FL-413-FW Engine

The above table summarizes the sensors recommended for the Deutz FL-413-FW engine. Included beside each sensor are the sensor type (analogue, discrete or binary switch), the estimated measurement range of each sensor and the required number of sensors. As discussed previously, the air filter pressure switches are recommended for experimental purposes only, and may not be required as part of the final monitoring system. This means that there are a minimum of twelve sensors recommended for adequate monitoring of the FL-413-FW engine. The effectiveness of this sensor array is discussed in Section A3.8.

Sensors should be selected on the basis of accuracy, robustness, response time and insensitivity to temperature drift. Each sensor should be able to withstand the range of operating temperatures and pressures likely to be encountered in the engine environment (including possible pressure spikes). At this stage, a scan rate around 1 Hertz (one reading every second) for each sensor is considered reasonable. This would generate around 115 bits per second of data to transmit over the mine-wide communications system for the engine health information alone.

A3.3 Powertrain

A3.3.1 Critical Parameters

A3.3.1.1 Torque Converter and Transmission

The ST-8B powertrain consists of a Clark C-8502 torque converter and a Clark 5422 powershift four speed transmission with modulated forward and reverse shifting. Three separate driveline systems transfer torque from the torque converter to the transmission and from the transmission to the forward and rear axles. The rear axle is mounted on a trunnion support which permits a limited degree of oscillation.

The torque converter and transmission function together through a common hydraulic system. Oil in the transmission/converter system essentially performs four functions; (a) hydraulic coupling between the converter impeller and turbine, (b) hydraulic actuation of clutch piston plates, (c) cooling and (d) lubrication. Oil is drawn from the transmission sump by a charging pump driven from the converter output shaft by means of a gear train. The oil is passed through a set of filters before entering a control cover located on top of the transmission. The clutch pressure regulating valve within the control cover directs oil both to the transmission clutches and to the torque converter. If we follow the oil flow to the converter, the oil enters the converter and is directed through a stationary stator to a rotating impeller. The fluid is accelerated both radially and tangentially and passed into a turbine. The resulting reaction transfers torque to the turbine and from there to an output shaft via a gear train. A pressure regulating valve at the converter outlet ensures a minimum operating pressure within the converter. Oil from the converter outlet flows the transmission/converter cooler located on top of the Deutz engine. Cooled oil flows back into a manifold in the transmission control cover whereby it is directed through a number of lubricating hoses to cool and lubricate transmission elements before returning to the transmission sump.

Following the flow of oil from the clutch pressure regulating valve to the transmission, oil first passes through two selector spool valves in the transmission control cover. The first of these valves directs oil to either the forward or reverse clutches. The second directs oil to either the 1st, 2nd, 3rd or 4th gear clutch packs. Each clutch pack consists of an annular piston and several alternating friction and reaction discs splined alternatively to the drive gear and separated by springs. When oil is directed to the rear of the clutch piston it causes the friction and reaction discs to mesh and engages the selected output gear connected to the clutch drum. Typical transmission problems arise due to broken or worn clutch piston sealing rings which cause excessive clutch leakage and may cause overheating and slow clutch response. For these reasons it is essential to monitor the following variables;

(i) transmission clutch pressure,
(ii) forward and reverse clutch pressures,
(iii) 1st and 2nd clutch pressures,
(iv) transmission lube oil pressure,
(v) convertor oil temperature,
(vi) transmission oil level, and
(vii) oil filter differential pressure.

Transmission clutch pressure should be monitored to ensure correct oil supply to both the torque converter and transmission clutches. The existing pressure gauge can be adapted for this purpose or alternatively measurements can be made at the port provided in the transmission control cover. Once a drop in clutch pressure is detected, gear position must be known in order to correctly identify which clutch pack is faulty. Gear position is best identified by installing pressure switches in the pressure lines to the forward and reverse clutch packs and to the 1st and 2nd clutches (present speed control on the automated LHD does not utilize 3rd and 4th gears). Transmission lube oil pressure should also be measured, since low lube oil pressure can indicate a leaking or plugged oil cooler, whilst high lube oil pressure can indicate a blocked transmission lube port. Lube oil pressure can easily be monitored from the check port provided in the transmission control cover.

The transmission/coverter oil cooler, like the engine, is prone to dirt accumulation. A proposal was made to measure the differential temperature over the cooler as a means of detecting dirt accumulation. This requires two temperature sensors, one at the cooler inlet and outlet. To minimize the number of sensors on the LHD, a better proposition is to monitor only oil temperature at the cooler outlet. Hot oil can indicate a variety of problems, including cooler dirt accumulation, worn sealing rings, low oil level or air leaks in the pump suction line (see Section A3.8). Transmission oil level should be monitored since the monitoring system is intended for use on remotely controlled or automated LHDs where visual pre or post-shift operator checks may not be possible. Finally, as is also the case with the engine, oil impurities can be a problem for the transmission. For this reasons, it is recommended that the differential pressure across the oil filters be monitored.

A3.3.1.2 Differentials and Planetary Drive Axles

The ST-8B is commonly fitted with two Clark 75830 axles, each of which consists of a free floating spiral bevel differential and two wheel hubs driven by planetary gear trains. Both the differential and wheel hubs require oil for lubricative purposes. During regular operation the oil levels in the differentials and planetary hubs are checked and, if necessary, replenished every 250 operating hours. Although the survey of ST-8B repairs identified leaking planetary hub seals as a cause of powertrain related downtime (see Appendix 2), monitoring of the oil level in the hubs presents a difficult task due to the requirement of maintaining a signal link to a sensor over a rotating hub.

A3.3.2 Discussion

Accelerometer-based vibration measurements were considered for fault detection in the LHD transmission. However, as the case for vibration-based diagnosis of the engine, vibration-based diagnostics require considerable laboratory testing which is currently beyond the scope of this project.

A3.3.3 Summary Table

SENSORS	TYPE	RANGE	No.
1st and 2nd clutch pressure	switch	140 PSI	2
forward/reverse clutch pressure	switch	140 PSI	2
Transmission clutch pressure	analogue	180-220 PSI	1
Transmission lube pressure	analogue	15-35 PSI	1
Convertor oil temperature	analogue	60-250 degrees F	1
Oil filter differential pressure	switch	max = oil filter relief valve setting	1
Transmission oil level	analogue	max 57 litres	1

Table A3.2 Summary of Recommended Sensors for the ST-8B Powertrain

A3.4 Hydraulic System

A3.4.1 Critical Parameters

The hydraulic system of the ST-8B includes four main interrelated systems which fall into the following categories;

- steering system
- dump and hoist system
- brake system, and
- brake cooling system.

These systems share a common reservoir, heat exchanger and pilot pressure regulating circuit. A brief description of the operation of each system will now be presented.

A3.4.1.1 Steering and Dump/Hoist Systems

Pressure to the steering and dump/hoist systems is supplied by a tandem hydraulic gear pump driven off the Deutz engine timing shaft. The front section of the pump supplies the steering system with oil (60 GPM at 2400 RPM) and the rear section supplies the dump/hoist system. When the steering system is not being used, oil from the front section of the pump flows through a high pressure carry over port on the main steering valve (MSV) to the dump/hoist system providing a total of 120 GPM for quick response of the dump/hoist system. A pilot pressure valve draws oil from the brake accumulator charging valve and maintains the steering and dump/hoist pilot control circuit at 200 PSI. The main steering valve controls the flow of oil in the steering system and directs oil to and from the two steering cylinders. The INCO machines utilize a monostick steering arrangement whereby a stick control is used to direct pilot oil pressure through a steering pilot valve to the MSV. As oil pressure extends a steering cylinder on one side of the vehicle, it retracts the cylinder on the opposite side enabling the vehicle to turn about its central bogie pin. The MSV also contains port relief valves through which oil is directed when the steering cylinders reach the limit of their extension.

Similarly, the dump and hoist operations are controlled by a stick with two degrees of freedom. The stick directs a pilot control valve which sends pilot oil pressure to the main control valve (MCV). The MCV in turn directs high pressure oil to and from the twin hoist cylinders and single dump cylinder. Port relief valves in the MCV redirect oil flow once pistons reach their end stops.

The survey of ST-8B repairs found that 44.3 % of downtime spent on hydraulic repairs was due to leaking relief valves, o-rings and hoses in the steering and hoist/dump circuits. Some 16 % of this downtime was due to cracking of the midship steel lines to the MCV valve, a fault which was later found to be design related and subsequently corrected. To monitor the health of the steering and hoist/dump circuits, it is recommended to monitor the following variables;

(i) pilot supply pressure
(ii) main steering valve inlet pressure
(iii) main control valve inlet pressure
(iv) cooler outlet temperature, and
(v) hydraulic fluid level.

Pilot pressure should be measured downstream of the pilot regulator and monitored for pressure drops which most likely indicate leaking valves or seals in the pilot circuit. The pressure sensors at the MSV and MCV inlets can be used to run regular diagnostic tests on the hydraulic circuit. These tests would entail bringing the engine to 2300 RPM and fully extending the hoist, dump and steering cylinders for both no load and full load conditions (if available, bucket load information would more accurately define the full load condition for the hoist circuit). Cylinder response times can be indirectly obtained from the MSV or MCV pressure signals. Commencement of flow to a cylinder results in a measurable drop in CV inlet pressure. When the piston reaches the cylinder end stop, the resulting pressure build-up opens a port relief valve and restores full supply pressure to the valve. Response time can be measured as the time interval between these two events.

Statistically slow response times will indicate the presence of faults in the hydraulic circuit (see Section A3.8).

Hydraulic oil temperature is another important parameter to monitor as hot oil measured at the cooler outlet can indicate a variety of problems, including a defective pump, cylinder flow-by, overheating brake assemblies or dirt accumulation on the hydraulic cooler. As was the case with the monitoring of the converter oil temperature, measurement of the temperature differential over the hydraulic oil cooler was considered, but the idea was rejected for reasons of minimizing the number of sensors on the LHD.

A3.4.1.2 Brake and Brake Cooling Systems

The ST-8B's operated by INCO employ Wagner Mining Equipment's SAHR (spring applied, hydraulic release) brake system on all four wheels. This system reverses the usual process of engaging and disengaging brakes. Springs apply the brakes, and hydraulic pressure release them. The wheel hub is splined to, and rotates with several friction discs. Sandwiched between the friction discs are steel reaction plates splined to the axle housing. The disc pack is enclosed from the environment and immersed in oil. An annular disc is forced against the plates by the pressure of industrial coil springs arranged around the annulus. Oil, drawn from the main hydraulic reservoir by a single gear pump, is supplied through a charge valve to two gas charged accumulators which maintain sufficient brake pressure during tramming operations to permit disengagement of the friction plates. If oil supply pressure is lost, or if a foot pedal control valve is actuated, the SAHR brakes automatically engage.

When not charging the accumulators, oil is directed by the accumulator charge valve to the hydraulic oil cooler located on top of the engine directly over the cylinder heads. Cooled oil then flows to the front and rear brake assemblies and past the friction plates to dissipate heat generated as a result of braking applications.

To enable tramming of the LHD, it is essential to ensure sufficient oil supply pressure to the brakes. For this reason, accumulator supply pressure should be monitored. Severe drops in pressure indicate either problems in the charge circuit or leaks in the braking circuit. At the same time, the survey of ST-8B repairs identified damaged brake cooling hoses as major source of drivetrain-related downtime. Pressure switches located in the return cooling lines of both the front and rear cooling circuits are recommended to monitor this problem.

A3.4.2 Summary Table

SENSOR	TYPE	RANGE	NO.
Pilot pressure	switch	180 PSI	1
Main CV inlet pressure	analogue	1000-2300 PSI	1
Steering CV inlet pressure	analogue	1000-2300 PSI	1
Cooler outlet temperature	analogue	50-150 degrees F.	1
Hydraulic fluid level	analogue	empty-full (0-360 litres)	1
Brake accumulator pressure	analogue	1600-2100 PSI	1
Brake cooling return pressure	switch	20 PSI adjustable	2

Table A3.3 Summary of Recommended Sensors for the ST-8B Hydraulic System

A3.5 Electrical System

A3.5.1 Critical Parameters

The electrical system of the ST-8B is a dual 12/24 Volt system and consists of six main sub-circuits. These sub-circuits are for;

- charging,
- starting,
- cylinder preheating
- instrumentation,
- lighting, and
- auto-lubrication.

Power supply to the electrical system of the ST-8B is via two 12 volt batteries. The starting motor sub-circuit requires the full 24 volt capability of the two batteries, whilst all other sub-circuits require only a 12 volts supply. In testing for faults in any electric circuit, it is first necessary to test the integrity of the supply voltage. For this purpose, battery supply voltage should be monitored. Secondly, the charge voltage from the alternator should be monitored to distinguish between battery and alternator faults (a voltmeter currently exists in the charge circuit for this purpose).

When the contacts on the main starting switch are closed on the 12 volt starting circuit, two solenoids are activated; one, located in the governor housing on the fuel injector pump, opens the fuel line and another closes the contacts of the 24 volt starter motor circuit. The survey of ST-8B repairs indicated that starter motor faults and sticking or damaged fuel shut-off solenoids were the most common form of starting problems. The fact that a vehicle will not start is indicative enough of problems in the starter circuit. Any sensor installed in the starter system would perform a purely diagnostic function, and, for simplicity of the LHD sensor system, fault diagnosis is best handled by a decision support system.

The preheat sub-circuit is used to heat glow plugs, located in the pre-combustion chambers of each cylinder, to aid starting in cold engines. On a conventionally operated machine, two filament indicators are used to indicate that current is flowing in each bank of plugs. On a remotely operated vehicle, a fault in the preheat sub-circuit will also make starting difficult. Following the same reasoning as above, from a fault detection viewpoint little can be gained by providing sensors for current in each bank of glow plugs. Fault diagnosis is once again best left to a decision support system. Similarly it is not thought necessary to provide sensors for faults in the LHD lighting system; a faulty light should be obvious to a remote operator.

Greasing of critical wear points on the ST-8Bs such as the boom pins and bogie joint is achieved via a "Bijur" auto-lubrication system which is retrofitted to the vehicle [Bijur Lubricating Corp., 1992]. Power supply for the system's controller card comes from the ST-8B ignition system. The ST-8B repair survey classified autogreaser problems as part of the ST-8B hydraulic system, and found that problems with the auto-greasing unit were a major source of downtime (see Appendix 2). The Bijur system controller card includes a flashing LED which is used for indicating lubricating system pressure faults. It is recommended that the voltage over this LED be monitored to notify a remote operator of problems which may occur in the auto-lubrication system.

The integrity of each of the sensors in the LHD monitoring system should also be considered in an LHD monitoring system. Rather than employing additional hardware for this purpose, sensor integrity can be tested by examining both the signal average and standard deviation over a period of time and comparing these to previous values. A stationary signal indicates either an external fault in the LHD subsystem or a sensor failure. This system of sensor integrity checking has been successfully employed by Monsanto Co. in at least one production facility [Biachin, 1993].

Finally, fault detection facilities for the control and communications modules of automated LHD vehicles are beyond the scope of this study, but should nonetheless be considered for future automated mining applications.

A3.5.2 Summary Table

SENSOR	TYPE	RANGE	NO.
Battery voltage	analogue	0-24 Volts	1
Alternator charging voltage	analogue	12-24 Volts	1
Bijur Fault Indicating LED	Switch	LED Voltage	1

Table A3.4 Summary of Recommended Sensors for the ST-8B Electrical System

A3.6 Tyres

A3.6.1 Discussion

The ST-8B utilizes tubeless nylon tyres with a smooth tread design and demountable rims. On conventionally operated LHDs, tyres are usually examined every shift for tread wear and damage. Automated LHD operations require that vehicles have some means of detecting a punctured tyre. Two suggested means for detecting the presence of punctured tyre are to; (i) use remote infra-red pyrometers located above each tyre to detect abnormally high heat output from a rubber tyre, and (ii) to examine the frequency (and magnitude) of steering correction error signals sent to the steering controller of the machine when under automatic guidance. This latter method is based upon the supposition that an LHD with a punctured tyre will tend to steer in the direction of the side of the vehicle having the damaged tyre. The steering controller would have to work harder in this event, resulting in an increase in the frequency and possibly magnitude of the steering correction signals.

Of the two approaches, the latter is considered more appropriate, since it requires that no additional sensors to be installed on the machine. A controlled experiment, in which an LHD under automatic guidance is deliberately fitted with a flat tyre, may be the best way to test the feasibility of this idea.

A3.7 Comparison of INCO Monitoring System with Other Systems

A comprehensive survey of technical and business sales literature was undertaken to establish the state-of-the-art of LHD monitoring systems. The following systems were identified;

(i) Tamrock Loaders Ltd. (formerly Ara Inc.) manufacture and market the CECAM (Computerized Equipment Control And Monitoring) system for LHD vehicles [Laurilla, 1989]. This system is designed for both production and maintenance monitoring and has the capability of handling data from up to forty sensors.

(ii) Caterpillar manufacture the Cat EMS (Electronic Monitoring System), which has the capability of monitoring ten critical machine parameters [Caterpillar, 1992]. Elphinstone Ltd. of Australia are making use of this system on their LHD vehicles powered by Caterpillar engines.

(iii) VMC (Vehicle Monitoring Company) are currently developing an LHD maintenance monitoring system for Wagner Mining Equipment. The prototype unit will be fitted to an ST-8B scheduled for delivery to Inco Ontario Division late in 1993 [Van Schoiack, 1993].

(iv) The German manufacturer MAN has developed a condition monitoring system for its range of LHD vehicles [Anon., 1989].

(v) Flight Systems Corp. manufacture and market an engine monitoring unit called the "Engine Saver 550". This system is in use in over 1000 diesel engines in a wide variety of applications to protect against overspeed and other damage. All of the pressure sensors used by the system are mounted inside the system's electronics enclosure which makes it easy to retrofit to engines [Lego, 1993].

(vi) The Detroit Diesel Allison division of General Motors have released an upgraded version of their engine control and monitoring system called DDEC-II [Hart et al., 1987). This system employs a specially designed processor chip interfaced with engine monitoring points, and is capable of providing engine diagnostics as well as fault detection functions.

Tables A3.5 to A3.9 list the parameters monitored by each of the these systems. The proposed ST-8B monitoring points are compared against the variables monitored by both these systems and the existing ST-8B dashboard instruments (listed under the category "ST-8B"). The noticeable areas of difference are the hydraulic system, where the proposed system is designed to detect faults via a series of system tests, and the brake system, where the SAHR brake system is used in place of conventional calliper brakes.

Subsystem	Parameter	ST8B	Toro	Cat	VMC	MAN	Flight	DDEC	Inco
Fuel	Fuel temperature							A	
	Fuel pressure							A	
	Fuel level			DS	x				A
	Throttle position							A	DS
	Fuel shut-off	DS							
Air Filter	Air Suction pressure					DS		x	DS
Combustion	Crankcase pressure						A	A	DS
Power transfer	Engine RPM				DP	A	DP	x	DP
	Vehicle Speed					A		x	
Exhaust	Exhaust temp.								
	Exhaust pressure								DS
	Scrubber temp.								
Timing	Reference signal							x	
	Synchronous signal							x	
Lube oil	Oil pressure	DS	x	DS	A	DS	A	A	A
	Oil temperature	DS	x		A	DS		x	A
	Oil level				DS			x	A
	Filter diff. pressure				A				DS
	Hourmeter	A	x					x	
Cooling	Cyl. head temp.	A				A			A
	(Coolant pressure)*			DS			A	A	
	(Coolant temp)*			DS			A	A	
Starting	Starter switch	DS						x	
	Alarm overide	DS							
	Preheat indicator	DS							
Control	Accelerator pedal	A						A	
Legend;	(A) Analogue sensor. (DS) Discrete switch sensor. (DP) Digital pulse sensor. (x) Unknown sensor type.				* Water cooled engine only				

Table A3.5 Comparison of Engine Monitoring Points

Subsystem	Variable	ST8B	Toro	Cat.	VMC	MAN	Inco
Converter &	Conv. Oil pressure	A	x		A	DS	A
Transmission	Oil filter diff. pressure			DS			DS
	Oil temperature	A	x	DS		A	A
	Oil level						A
	Trans. Lube pressure						A
	Gear position						DS

Legend; (A) Analogue sensor
(DS) Discrete switch
(DP) Digital pulse sensor
(x) Unknown sensor type

Table A3.6 Comparison of Powertrain Monitoring Points

Subsystem	Variable	ST8B	Toro	Cat.	VMC	MAN	Inco
Tank	Cooler oil temperature		x	DS	A	DS	A
	Hydraulic fluid level		x		x	DS	A
	Pump pressure		x				
	Return pressure					DS	
Pilot System	Pilot pressure						DS
Steering	Steering cyl. pressure		x		A		
	Steering Valve Inlet Press.						A
Hoist	Hoist cyl. pressure		x		A		
	MCV Inlet Pressure						A

Legend; (A) Analogue sensor
(DS) Discrete switch
(DP) Digital pulse sensor
(x) Unknown sensor type

Table A3.7 Comparison of Monitoring System Hydraulics Sensors

Subsystem	Variable	ST8B	Toro	Cat.	VMC	MAN	Inco
Battery	Charging Voltage	A		DS		DS	A
	Battery Voltage						A
Lights	High beam warning	DS					
Horn	Horn	DS					
Autolube	Fault LED						DS

Legend:
(A) Analogue sensor
(DS) Discrete switch
(DP) Digital pulse sensor
(x) Unknown sensor type

Table A3.8 Comparison of Electrical System Monitoring Points

Subsystem	Variable	ST8B	Toro	Cat.	VMC	MAN	Inco
Service brake	Brake fluid temp.		x				
	Brake fluid level			DS			
	Accumulator pressure	A			A		A
	Service brake pressure		x			DS	
	Brake pilot pressure				A		
	(Brake air pressure)*			DS			
	Brake cooling pressure						DS
Park brake	Park brake pressure			DS		DS	

Legend:
(A) Analogue sensor
(DS) Discrete switch
(DP) Digital pulse sensor
(x) Unknown sensor type

* Air operated brakes

Table A3.9 Comparison of Brake System Monitoring Points

A3.8 Effectiveness of Proposed Monitoring System

Tables A3.10 to A3.13 are charts of possible faults for the ST-8B's engine, powertrain, hydraulic and electrical systems. The fault charts have been derived as a result of both the ST-8B repair survey and trouble shooting guides found in the ST-8B service manual. The sensors recommended for each LHD subsystem are listed to the right side of each fault diagram. The ability of a sensor (or combined set of sensors) to indicate performance degradation as a result of a particular fault is marked by an "x" in the relevant sensor column(s).

The number of times that a particular fault was repaired during the ST-8B repair survey is listed to the right of each fault listing. This number gives an idea as to the expected frequency of a particular fault occurring. The number of specific hydraulic system faults which occurred during the survey period was difficult to categorize and an "x" is used to indicate the occurrence of a fault. Similarly, faults cited by the Divisional Shops maintenance staff as causing engine failures are also indicated by "x"s.

The fault charts provide a means of gauging the effectiveness of the monitoring system, in terms of which faults will be able to be detected and which will not. An accurate picture can also be gained as to whether frequently occurring faults are covered by the monitoring system.

Deutz FL 41[illegible] Engine Fault Chart

Problem	Cause	Cause	Cause	Engine RPM	Oil Level	Oil Pressure	Oil Temperature	Oil filter Diff. Press.	Cyl. Head Temp.	Crankcase Pressure	Air Filter Pressure	Exhaust Pressure	Fuel Level	Throttle Position	Battery Voltage	Charging Current		# McCreedy Repairs	Divisional Shops
1. Hard starting	Low cranking speed	Improper lube oil																	
		Low battery output	Poor or shorted connections												x			4	
			Undercharged or B.O. battery												x	x		7	
			Low ambient temperature												x				
		Defective starter motor or loose connections														x		9	
	Low compression	Improper valve adjustment																3	
		Valves sticking or burnt																	x
		Compression rings worn or broken																	x
		Cylinder head gasket leaking																	x
	Insufficent fuel to engine	see 2. "Insufficient fuel"																	
	Insufficient combustion air	see 3. "Machine lacks power"																	
2. Insufficient fuel to engine	Fuel tank empty or ruptured												x					1	
	Fuel pressure low	Air leaks	Loose connections or B.O. lines between tank & pump	x										x				2	
			Damaged primary fuel filter gasket	x										x					
		Flow obstruction	Shutoff valve not fully open	x										x				9	
			Shutoff lever on aneroid not in up position																
			Primary or final fuel filters restricted	x										x					
			Damaged lines between charge pump & injection pump	x										x				2	
		Worn or damaged charging pump		x										x					
	Fuel pressure normal	Throttle linkage damaged or improperly adjusted		x										x				1	
		Boost pressure line B.O. or loose		x										x				1	
		Aneroid damaged or improperly adjusted																	
		Injection nozzles restricted		x										x					
		Injection pump plungers sticking		x										x				1	

Appendix 3

Deutz FL 413 FW Engine Fault Chart

Problem	Cause	Cause	Cause	Engine RPM	Oil Level	Oil Pressure	Oil Temperature	Oil filter Diff. Press.	Cyl. Head Temp.	Crankcase Pressure	Air Filter Pressure	Exhaust Pressure	Fuel Level	Throttle Position	Battery Voltage	Charging Current		# McCready Repairs	Divisional Shops
3. Machine lacks power	Improper engine adjustments	Injection pump linkage B.O. or improperly adjusted		x										x				1	
		Injection pump improperly timed		x										x					
		Improper valve adjustments		x										x				3	
	Insufficient fuel to engine	see 2. "Insufficient fuel"																	
	Insufficient combustion air	Air cleaner restricted		x										x				8	
		Low compression	Valves sticking or burnt	x										x					x
			Compression rings worn or B.O.	x						x				x					x
		Excessive exhaust back pressure		x									x	x				2	
	Non-engine related problem	Service brake dragging		x										x					
		Park brake dragging																	
		Torque convertor slipping		x										x				5	
		Transmission clutch pack slipping		x										x				4	
4. Exhaust smoke analysis (Engine must be at normal operating temperature)	Black or grey (Incompletely burnt fuel)	Insufficient combustion air	see 3. "Machine lacks power"																
		Excess fuel or irregular fuel delivery	Anerold damaged or improperly adjusted																
			Injection pump improperly timed																
			Injection nozzle restricted	x										x				1	
		Improper grade of fuel																	
	Blue (Lube oil in combustion chamber)	Excessive air cleaner restriction																	
		Excessive crankcase pressure								x									x
		Poor oil control at cylinders			x					x								1	
	White (Cylinders not firing properly)	Improper grade of fuel																	
		Injector pump plungers sticking		x										x				1	
		Cylinder head gasket leaking																	x

Appendix 3

Deutz FL 413 FW Engine Fault Chart

Problem	Cause	Cause	Cause	Engine RPM	Oil Level	Oil Pressure	Oil Temperature	Oil filter Diff. Press.	Cyl. Head Temp.	Crankcase Pressure	Air Filter Pressure	Exhaust Pressure	Fuel Level	Throttle Position	Battery Voltage	Charging Current		# McCreedy Repairs	Divisional Shops
5. Excessive crankcase pressure	Cylinder blow by	Piston or sleeve damaged								x									x
		Piston rigs worn or broken								x									x
	Breather restriction	Breather B.O. or obstructed								x									
	Excessive exhaust back pressure	Obstruction at catalytic convertor or muffler								x		x						2	
6. Low engine oil pressure (Engine must be at normal operating temperature)	Oil	Low oil level		x	x	x													
		Incorrect oil viscosity		x		x													
		Oil dilution	Injector pump leakage	x		x												2	
			Charging pump leakage	x		x													
	Pressure guage	Faulty gauge		x		x													
		Guage line restricted or leaking		x		x													
	Circulation	Filters clogged		x		x												1	
		Pressure regulating valve malfunctioning		x		x													
		Oil gallery plug missing		x		x												1	
		Excessive wear of crankshaft bearings		x		x													x
	Oil pump	Intake screen partially clogged		x		x													
		Air leak at pump outlet		x		x													
		Pump worn or damaged		x		x													
7. High lube oil consumption	External leakage	Gasket or oil seal leakage			x													8	x
		Excessive crankshaft pressure causes leaks			x					x									
	Internal leakage	Oil cooler core leaking			x		x											2	x
	Oil control at cylinders	Oil control rings worn or broken		x	x	x													x
		Piston pin retainer loose			x														
		Scored sleeves or pistons			x					x									x
	Excessive air cleaner restriction										x							8	

Appendix 3

Deutz FL 413 FW Engine Fault Chart

Problem	Cause	Cause	Cause	Engine RPM	Oil Level	Oil Pressure	Oil Temperature	Oil filter Diff. Press.	Cyl. Head Temp.	Crankcase Pressure	Air Filter Pressure	Exhaust Pressure	Fuel Level	Throttle Position	Battery Voltage	Charging Current		# McCready Repairs	Divisional Shops
8. High engine oil	Lube oil pressure low	see 6. "Low lube oil pressure"																	
temperature	Lube oil presssure normal	Dirt build up on cooler		x		x	x		x										x
		Blower failure		x		x	x		x									1	x
	Lube pressure high	Oil cooler blockage		x		x	x		x									1	x
9. Excessive engine	Internal source	Improper engine adjustment	Injection pump linkage B.O. or																
vibration			improperly adjusted																
			Injection pump improperly timed	x										x					
			Improper valve adjustment	x										x				3	
		Irregular or restricted air supply	Valves sticking or burnt	x										x					x
		Irregular or restricted fuel supply	Injection nozzle restricted	x										x				1	
			Injector pump plunger sticking	x										x					
		Irregular combustion	B.O. compression rings							x									x
	External source	Broken or loose engine mounting																8	
		bolts																	
		Broken or loose cooler frames																3	x
		Worn blower bearing																1	x
		Damaged blower grill																1	

Clark 5000 Series Powershift Transmission & C8000 Series Torque Convertor Fault Chart

Problem	Cause	Cause	Converter Inlet Press	Trans. Clutch Press	Fwd/Rev. Valve Pos.	1st to 4th Gear Pos.	Trans. Lube Press.	Cooler Outlet Temp.	Diff. Filter Pressure		# McCreedy Repairs
1. Low clutch pressure	Normal clutch leakage	Low oil level		x							
		Broken spring in transmission regulator valve		x							1
		Clutch pressure regulator valve stuck in open position		x							
		Faulty charging pump	x	x							1
	Excessive clutch leakage	Broken or worn clutch piston sealing rings		x	x	x					3
		Clutch drum bleed valve stuck in open position		x	x	x					
		Broken or worn sealing rings on clutch support		x	x	x					
		Low convertor charging pump output	x	x							1
2. Low convertor charging pump output	Low oil level		x	x					x		
	Sump screen plugged		x	x							
	Air leaks at pump intake or connections or collapsed hose		x	x							2
	Oil pump B.O.		x	x							1
3. Low flow through cooler	Low convertor in pressure	Defective safety by-pass spring	x								
		Convertor by-pass valve partially open	x								
		Excessive convertor internal leakage (Check conv. lube flow)	x								
		Broken or worn sealing rings in transmission clutches	x	x	x	x					3
	High convertor out pressure	Plugged oil cooler (indicated if trans. lube pressure is low)					x		x		
		Restricted cooler return line					x				
		Lube oil port in transmission plugged (Trans. lube Press. high)					x		x		
4. Overheating	Worn oil sealing rings (Check conv. & trans. leakage)							x			
	Worn oil pump							x			
	Low oil level							x			
	Pump suction line taking air							x			
5. Noisy convertor	Worn coupling gears										
	Worn oil pump		x	x							
	Worn or damaged bearings						x				
6. Lack of power	Low engine RPM at conv. stall										
	See 4. "Overheating"										

ST8B Hydraulic System Fault Chart; General Faults

Problem	Cause	Pilot Pressure	MCV Inlet Pressure	MSV Inlet Pressure	Hydraulic Oil Level	Cooler Outlet Temp.		# McCreedy West
1. Poor hydraulic system performance or failure	Defective pump		x	x				x
	Dirt in relief valve		x	x				x
	Relief valve defective		x	x				
	Worn cylinders		x	x				x
	Load to heavy		x	x				
	Internal crack		x	x				
	Plunger not in full stroke							
	Reservoir low on oil				x			
	System filters clogged		x	x				x
	Restrictions in line		x	x				x
2. Excessive oil foaming	Incorrect viscosity or type of oil							
	Excessive bypassing of oil over relief valves							x
3. Excessive oil temperature	Sustained maximum pressure operation with bypassing of oil over relief valve					x		
	Incorrect viscosity or type of oil					x		
	Worn hydraulic pump					x		
4. Foreign material in reservoir screens	Lint - worn, frayed or damaged cylinder packing		x	x				x
	Chips - worn pump or damaged cylinders		x	x				
5. System pressure build-up	System relief valve set too low		x	x				
	Worn pump components causing internal leakage		x	x				
6. Low pressure in hoist circuit	Damaged, worn or improperly adjusted hydraulic relief valve		x					x
	Bypass in cylinders		x					x
	Hydraulic pump worn		x					x
7. Low pressure in dump circuit	Refer to causes for (6) above		x					
8. Low pressure in steering circuit	Damaged, worn or improperly adjusted steering circuit relief valve			x				x
	Bypass in steering cylinders			x				x
	worn steering pump			x				

ST8B Hydraulic System Fault Chart - Main Control Valve

Problem	Cause	Pilot Pressure	MCV Inlet Pressure	MSV Inlet Pressure	Hydraulic Oil Level	Cooler Outlet Temp.		# McCreedy West
9. Difficult operation or sticking of control valve plungers	Overheated hydraulic oil (see 3)					x		x
	Dirt in valve bores, plungers and/or oil		x					x
	Valve warped from incorrect mounting procedure		x					
	Fittings too tight							x
	Excessively high temperature in valve							
	Linkage binding		x					
	Plunger bent		x					
	Detent or return spring damaged		x					x
	Spring or detent binding		x					
	Valve not in thermal equilibrium							
10. Unable to move plunger in or out	Dirt in valve		x					x
	Plunger cap full of oil		x					
	Bind in linkage		x					
11. Detent control fails to hold	Worn detent cam							
	Spring or ball broken or deformed							x
	Excessive vibration							
	Plunger stroke restricted		x					
12. Load drops when plunger moves from neutral	Dirt in check valve							x
	Scored check valve poppet or seat							
13. Load will not hold	Cylinder leaking or worn		x					x
	Oil bypassing valve plunger		x					x
14. Leaking seals	Paint on/under seal		x					
	Excessive back pressure							
	Dirt under seal		x					x
	Scored plunger		x					x
	Loose seal plates		x					
	Cut or scored seal		x					x
15. Anti-void valve inoperative	Sensing hole in small poppet plugged							
	Poppet sticking		x					
16. No pressure	Pressure relief large poppet stuck open		x					
	Check valve poppet stuck open		x					x
	Pilot poppet stuck open	x						
	Dirt under valve seal		x					x
17. Erratic pressure	Pilot poppet seal damaged	x						
	Small poppet sticking in large poppet							
18. Relief valve pressure setting incorrect	Wear due to dirt		x					x
	Jam nut and adjusting screw loose		x					
19. Leaking relief valve	Damaged seats		x					x
	Worn o-rings		x					x
	Parts sticking due to dirt		x					x

ST8B Hydraulic System Fault Chart; Pump

Problem	Cause	Pilot Pressure	MCV Inlet Pressure	MSV Inlet Pressure	Hydraulic Oil Level	Cooler Outlet Temp.		# McCreedy West
20. Pump does not deliver fluid	Shaft sheared or disengaged		x	x				
	Reservoir-to-pump intake line restricted		x	x				
	Fluid viscosity too heavy for pump to pick up prime							
	Relief valve stuck open		x	x				x
	Vanes stuck in rotor slots							
21. Noisy pump	Low oil supply				x			
	Cavitation in hydraulic pump		x	x				
	Air in pump oil supply		x	x				
	Excessive fluid foaming		x	x				
	Vortex or spiral in oil circulating in reservoir							
	Excessive pump speeds							
	High engine speed with cold hydraulic oil							
	Hydraulic oil viscosity too high							
	misalignment							

ST8B Hydraulic System Fault Chart; Steering Control Valve

Problem	Cause	Pilot Pressure	MCV Inlet Pressure	MSV Inlet Pressure	Hydraulic Oil Level	Cooler Outlet Temp.		# McCreedy West
22. Hard steering when turning slowly	Low fluid in reservoir				x			
	Low oil pressure due to kink in hose			x				x
	Low oil presssure due to foreign object stuck in hose			x				
	Pressure loss in cylinder(s) due to worn piston packing and/or rod packing			x				x
	Steering control valve leaks			x				x
23. No effort required to turn	Loose or worn valve			x				
24. Poor steering return	Sticky valve spool			x				
25. LHD loads to one side or the other	Unbalance or badly worn valve (steering will be light in the direction of load and heavy in the oppposite direction)			x				
26. Momentary increase in effort when turning wheel fast	Insufficient oil supply to pump			x				
27. Excessive wheel kick-back or loose steering	Air in system			x				

ST-8B Electrical System Fault Diagram

Problem	Cause	Charging Voltage	Battery Voltage		McCreedy West
1. Charge too low or no charge at all	Defective battery	x	x		5
	Slipping generator belt drive	x			
	Defective generator	x			3
	Malfunctioning regulator	x			
2. Charge too high; overcharged battery	Malfunctioning regulator	x			
	Incorrect pulley used on generator	x			
3. Battery uses an excessive amount of water	Charging rate too high	x			
	Incorrect pulley used on generator	x			
4. Rapid burn-out of light bulbs	Charging rate too high (see 2.)	x			
5. Cranking motor operating slow or not opening at all.	Battery discharged		x		
	Defective cranking motor				4
	Corroded, loose or defective cables				1
	Defective solenoid				1
6. Low or intermittant generator output	Dirty or worn generator commutator	x			
	Brush(es) sticking	x			
	Weak brush springs	x			
	Slipping belt drive	x			
	Malfunctioning regulator	x			
7. Lights are dim	Batteries low		x		
	Poor ground		x		
	Loose connections				
8. One electrical gauge not operating	Gauge defective				3
	Sensor Defective				
	Bad connection or connector plug				6
9. Ignition ON - no gauges or lights working	Dead battery		x		5
	Loose connection from battery to ammeter				
	Broken wire between battery & ammeter				
10. Ignition ON - no electrical gauges or lights working	Bad connection between ammeter circuit breaker or ignition switch to gauges				
11. All electrical gauges working - no lights	Loose connection between ammeter and switch				6
	Bad light switch				

A3.9 Summary of Recommended Sensors

SENSOR	TYPE	RANGE	No.
engine oil pressure (main gallery)	analogue	40-120 PSI	1
engine oil temp. (cooler outlet)	analogue	100-300 degrees F.	1
cylinder head temperature	analogue	200-350 degrees F	2
crankcase pressure	switch	10-20 PSI adjustable	1
throttle position (PLC signal)	discrete	idle/half/full	1
engine speed (RPM)	analogue	500-2800 RPM	1
eng. oil filter differential pressure	switch	max = oil filter relief valve setting	1
engine oil level	analogue	empty-full (0-29 litres)	1
fuel level	analogue	empty-full (0-380 litres)	1
engine exhaust pressure	switch	15 PSI (25" water) adjustable	2
engine air filter suction pressure	switch	13 PSI adjustable	2
trans. 1st and 2nd clutch pressure	switch	140 PSI	2
trans. fwd/rev clutch pressure	switch	140 PSI	2
transmission clutch pressure	analogue	180-220 PSI	1
transmission lube pressure	analogue	15-35 PSI	1
convertor oil temp. (cooler outlet)	analogue	60-250 degrees F	1
trans./conv. oil filter diff. pressure	switch	max - oil filter relief valve setting	1
transmission oil level	analogue	max 57 litres	1
hydraulic pilot pressure	switch	180 PSI	1
Main CV inlet pressure	analogue	1000-2300 PSI	1
Steering CV inlet pressure	analogue	1000-2300 PSI	1
Hyd. cooler outlet temperature	analogue	50-150 degrees F.	1
Hydraulic fluid level	analogue	empty-full (0-360 litres)	1
Brake accumulator pressure	analogue	1600-2100 PSI	1
Brake cooling return pressure	switch	20 PSI adjustable	2
Battery voltage	analogue	0-24 Volts	1
Alternator charging voltage	analogue	12-24 Volts	1
Bijur Fault Indicating LED	Switch	LED Voltage	1
TOTAL NO. SENSORS			34

Table A3.14 Summary of Recommended LHD Sensors and Monitoring Points

Appendix 4:

Transcript of Interviews Conducted at Stobie Mine

Transcript of Interviews Conducted at Stobie Mine

April 19th 1995.

(M) Mike, Leading Hand Mechanic, 2400 Level

(P) Peter Knights, McGill University

M; If the brakes apply, most of the time it's the brake hoses. Brake hoses break all the time. We lose our brake pressure and we can't release our brakes. Slow to apply would be a break in the modulator. that'll jam or stick for some reason, contamination ....

P; Your modulator is what? The treadle valve, is that what you're looking at.

M; No, the valve ...

P; Oh the charge valve

M; No the pedal.

P; OK, this is the pedal here

M; Yes the pedal valve will jam in a position where it's only going to ...it won't release completely. We need 1500 lbs to release and it'll give us maybe 500.

P; Is that generally due to crap that gets around the pedal and the modulator there

M; Yes, the piston on top jams because of the contamination. These drilled parts are OK, mind you, if we can only release the cap better from jamming. What else are we looking at here?

P: just to check that, if you have a jammed treadle valve it means that your brakes will not release fully so you end up with partially pulling a little bit or ....

M; Yes, sort of giving you a pull, because when you step on the pedal, what you're doing is relieving pressure from the wheel ends. So if you're jamming half way up you're only getting a release of maybe ....

P; Then your brakes are going to pull on you

M; Yes. So now the treadle valve, relay valve , accumulators ...Accumulators are pretty basic, you know. if you're not getting the applications you should be getting.

P; So if your brakes are not releasing, again the accumulators are something to look at? I guess that would show up on a pressure gauge pretty well?

M; Yes. All the gauges show is the brake pressure and if you make some applications you're not going to have the backup. You're working your pump all the time.

P; Oh yes, the pump is working all the time but you're charging your accumulators here. have I got that in the right position for a start? This is the accumulator pressure gauge, should it be after the accumulator gauge. I'm just wondering about that actually.

M; Lets see, the brake pump, charge valve.......

P; This is the switch that comes over from the transmission. I believe this comes off your torque convertor, and if you get low torque convertor pressure ...

M; ...your brakes will apply. It won't send any oil to your braking system.

P; Yes, there's a relay valve which cuts of supply and your brakes will automatically apply there. That's what that is. That's also linked to the starter solenoid in your starter circuit. If you start up the machine, that starter solenoid will activate a relay as well because basically there is a pressure switch in here which will cut oil flow to the brakes.

M; Yes, exactly, I know which one you're talking about.

P; And that transmission pressure can actually cut that solenoid as well .....I think I've got that right.

M; Ah ...I think that's engine oil pressure. If you have oil pressure you can't activate your starter so that you don't turn your engine over and engage your starter when the engine is running.

P; Oh OK.

M; I think that's the one you are referring to. I don't think it has anything to do with the brakes.

P; Yes ....but there's a link between here, your torque convertor, because I was just reading up here the inadvertent brake application. If your brakes come on automatically.... Oh, here we go..

M; clutch pressure, brake accumulator pressure ...

P; transmission clutch pressure interlock to the brake accumulator ....and that's your driveline ...that's what I'm calling here your relay valve.

M; No that your wheel end, because we don't use driveline disc brakes on this machine. It just has four independent wheel brakes.

P; These don't have any park brakes, is that right?

M; Well, your park brakes, there are four individual park brakes... that's what they are, because a park brake is a mechanical brake, and all four wheels are all mechanical, so we don't need the driveline brake.

P; OK. So this is what ....

M; What this is here is a latch circuit system that we install so that when you start the equipment that you would start with the brakes on. Release the big button on the release position. You would still have to reset this button

P; (indecipherable)

P; I might just scribble down a copy of that in a little more detail.

M; I don't know. Maybe there is a starter circuit in there, but I don't remember dealing with it.

P; If we can get hold of a service manual we can pull that out and have a look. You've probably got a service manual handy. (Pause) So, I may as well start right at the beginning. Here I separated ....the suction filter and strainer are considered a separate system. So the reservoir contains the oil. OK supposing you had low oil level ...

M; The seals were going and your wheel ends and that

P; So you're getting leakage occurring. That's mostly your cooling circuit ?

M; Yes, but you're probably getting high pressure leaks on your closed circuits. I remember that the old scoops had pressure applied and spring released and the seals would overheat. Your seals would go, they'd overheat and you'd have your heat sensors on the wheel end, and they'd indicate cooling temperatures and give us a red light, cooling temp high or whatever. Now we don't have that anymore because we don't have any problems...

P; If you get a blockage in your cooling circuit how do you first detect that? I mean if your brakes start overheating, how do you first notice it?

M; At one point we used to carry just oil in the wheel end. So if there's oil flowing through the wheel end or even if its just full of bypass, I don't think anyone would notice.

P; Yes, would you get foaming occurring in the reservoir?

M; There's a bypass on the cooler.

P; Oh the cooler's got a bypass.

M; I would imagine they'd have to have some kind of bypass.

P; Yes, I mean, but supposing you had a plugged cooler... how do you know you've got a plugged cooler on a machine? I sounds like a stupid question .....

M; High pressure. High pressure in your ...

P; In your wheel ends? Wouldn't that be low pressure if you're plugged here?

M; Well, your brake cooling is low pressure isn't it?

P; Yes. Very low pressure.

M; If you have high cooling pressure, your face seals are just held together with rubber ..

P; Oh, you're talking about the seal on the actual cooler here?

M; No, on the wheel end.

P; Your high pressure is part of this circuit here, that is brake application. Right here is the cooling circuit. Through here is low pressure, but, what I found hard is that if you have a plugged cooler, it just means that you're not getting any oil flow through the cooler to the brakes here, which would start ....I don't know. As far as I can see there's no temperature indicator on the hydraulics. You don't have a temperature gauge or anything like that. As far as telling that you've got a plugged cooler, the only way you could tell is if you've got a leak on this side, because this side has relatively high pressure when the accumulators are charged. Maybe you'd get a leak at your pilot valve or a leak out from around the cooler?

M; A system in line like that has go to have some kind of bypass. You can't just have a cooler in line like that..

P; Well, that's something we should look into.

M; <u>I remember on 18 we used to have problems with high pressure in the cooling system. You have your drain valve here, a check valve, I think 15 PSI.</u>

P; Yes

M; <u>And when that jams up you get blown face seals. We had problems with that. I've never encountered cooler problems, so that's the question you're asking</u>. Maybe we should look more into the cooler to see what would happen .....

P; So, all right. So we looked at sort of causes of your brakes applying.

M; <u>Well your problems are here; brake modulator and broken hoses, basically all the breaks are the most common breakdown OK. The check valve plugging is not common, but it happens</u>. It will blow your seals so you'll have leakage at the wheel end, and you can detect that.

P; Well from a remote perspective it's difficult.

M; Yeah, you'd run out of oil .....

P; You could have an oil level indicator hooked up, and if you noticed the oil level rapidly dropping you would know you had problems. There's all sorts of questions like that when you start running a roboscoop. A guy on a scooptram ..he's aware of a lot of things that are happening, and it's very difficult to try and put sensors all over the machine to do exactly the same job.

M; Low oil in the reservoir.... where you lose oil could be anywhere in the hydraulics.

P; Absolutely.

M; You want to try and narrow it down to specific causes.

P; What about if your brakes where slow to apply? For example if an operator went to put his brakes on and found them very slow and sluggish. Could that be either an accumulator problem or again a modulator problem?

M; I don't think we've got any of that. If your charge valve is stuck, you'll still get a good application if your accumulators are charged. Well if your machine is running you'll still get good application. The volume is so little...

P; so as long as you're getting pressure pumped up this circuit here ..

M; Yes. So as far as a slow application, it won't happen. It could be a slow application because, like I said it could be restricted application, where we won't be able to release all the pressure.

P; Right. So that was slow application. What if your brakes are slow to release? You've applied them. They work OK and then they are slow to release following this.

M; That would be slow getting pressure to it.

P; Slow getting pressure to it? Yes, because you need positive pressure to release them don't you. So that would be indicative of a brake pump if it was running very slowly. You'd probably know that otherwise though.

M; Yes, I don't think you notice that when your foot come off but you'll know when your system is charging you up... how slow it is or your system won't give you a full charge. When you start up the machine it has to charge up and if it's really slow, there's something wrong.

P; OK. So in other words you'd be watching your accumulator gauge and if your accumulator is really slow to charge ....What happens when you get a plugged suction filter here. Do you get partial flow through the pumps?

M' Yes, you'll get a (indecipherable). But we do get pump cavitation, and you know what cavitation does. Noise, vibration.

P; Yes, you'll get noise, vibration and oil foam, but the only way to really tell is by an operator coming and telling you "I've got a noisy pump".

M; There is positive pressure that we need in the tank that you can sense. There's a valve on the tank to pressurise the tank and sort of supercharge the pump. So if that valve is open it can cause a problem. It can jam. And then we won't get that supercharge any more and at high RPM it will cavitate. Maybe I can let you jot down a few notes and I'll go and .....

P; That's no problem. (Pause). Back again. Just saying that if your brakes are not releasing during operation you may also have a problem with the accumulator charge valve.

M; That's right. That's your source for the brake system. If it's not charging right it's just unloading the tank.

P; OK. And it may be partially restricted, in which case you're not getting your full oil flow through there. I guess you'll also notice it in your accumulator charge gauge?

M; Yes, if it's really slow to charge and as you mentioned earlier you had slow release, that may be one of the problems.

P; And I was just going to say that if you've got slow charging accumulators you're still going to get your brakes operating but you may have problems if you're cycling them.

M; Yes.

P; OK. I was just going to check that. If your brakes are not applying smoothly, and you're getting either a jerky application or snatching application, what is that most likely due to?

M; A jerky application?

P; Do you see that much?

M; With a very jerky application, it is a spring applied brake. As soon as you release the ....it should gradually release.

P; What happens if you get spring problems?

M; Never heard of that. These machines only have, what, 2000 hours on them. Some of them are up to 5000 hours and we don't have brake problems. Since we've had the SAHR brake system, it's been great to us. We've never had to do a brake yet.

P; OK. So they're pretty robust then.

M; Yes, besides the modulator valve and the brake hoses. Those are the two main problems.

P; OK. If we move on down then, and let's look at the pilot circuit, and, if we were going to observe a general failure of the pilot circuit, I imagine that what we'd probably see is that we'd lose our control of the steering, dump, hoist and engine.

M; That's right.

P; So that would be, I would have though, a pretty good indicator that there was something screwy with your pilot sequence valve in here, or a blockage to it? Or you've probably got a leak.

M; Yes, or a drop in pressure if you lose your oil. It could be lack of oil. You would have to check the oil, I guess. There's that sequence valve.

P; Yes.

M; Yes, that sequence valve. That'll charge your accumulator first and than allow it to charge the pilot system.

P; Is that right?

M; Yes, You get your pilot pressure after full accumulator pressure is charged up. So imagine that's your sequence valve. Then you'll allow your pilot pressures to charge up.

P; Right, so.... actually, the way I looked at ..I actually had the training manual which had a bigger schematic of the valve and it showed that if you look at the accumulator charge valve it showed a direct path through to the filter, but then there's the charge valve which come off and if you drop below 1600 PSI it opens and allows the accumulators to charge.

M; That's right.

P; When your accumulators hit 2000, it shuts. There's also, I think, a pressure relief on the other side in case it doesn't shut off.

M; A safety release of some kind?

P; Yes. So it basically sequenced between 1600 and 2000 PSI.

M; Yes.

P; And the pilot sequence valve, or pilot pressure valve here. It goes through and you're supposed to get 200 PSI to your pilot pressure right?

M; Yes, it should allow 200 PSI.

P; And basically any pressure over that it lets out through a relief valve to the cooler. But, if I'm correct in saying it, if you experience a problem in your pilot circuit, it most likely going to be due to a leak, or a rupture somewhere ?

M; You're probably right.

P; I'm probably leading you on, I mean this is a problem.

M; You know, As much experience as I have on this, it's not a hell of a lot. I have experience on hydraulics. I can grab the schematics and go repair this machine. But the faults we have with pilot pressure, the pilot's set too high. People don't know what it is, they set it too high and blow the caps off the end of the valves.

P; So that's a matter of setting that relief valve in the pilot pressure valve?

M; You could build up to 2000 pounds in the end of your valve and blow the caps off. Still pretty dangerous. Your pilot control valves can't handle that kind of pressure anyway. High pressure there would be a real problem.

P; Yes, high pressure there is a problem

M; yes, a higher pressure more than a low pressure. Yes, a malfunction of it may cause high pressure also. I don't think you have any other relief there.

P; If we look at then the throttle master and slave valves here, do you experience many problems with those?

M; We'll change the odd one for internal leakage.

P; Internal leakage, and you just notice that the engine ...

M; Yes, it's not going to give full RPM or it's not going to give a full stroke.

P; From both? both of these will leak? That's the throttle valve and this is the slave on the engine here.

M; Oh the throttle valve, yes that'll leak. That has to be regulated also .It has to be bought down again from 210 to 100 PSI.

P; Really? And that's an adjustment in the slave here?

M; Yes at the throttle valve. But they come in already adjusted. But if they're not, for whatever, this pressure has to be brought down to 100 PSI for the slave cylinder. If you were to run that at 200 you'd probably have problems with the slave cylinder. Every time that I've ever put a throttle on they've always checked the pressure for 110 PSI or 100 PSI.

P; Right, but if you're going to go over that you start blowing some seals and leaking?

M; Yes.

P; So they're the most likely faults that are going to occur there.

M; Yes.

P; That's more like your treadle valve here where you probably experience leaks ...actually do you experience leaks at the SAHR modulator?

M; Not external leaks. Internal leakage.

P; Internal leakage?

M; Yes.

P; What happens if you get internal leakage. How would you see that in your brake system?

M; You'd have a faster cycle time on your accumulator charge, because you're dumping...

P; Do they report that?

M; No, they don't record it. we won't get a report saying "Oh my cycle is going too fast".

P; And they wouldn't tell if there charge time is too fast.

M; Most of the times we'll get it when the accumulators are totally drained and the valve has bypassed for so long that we need to change the valve at that point because its been operating ...You're looking at a combination of problems. If we were to pick it up at the original fault where we say may cycle time is usually 3 minutes and it's now 30 seconds, let's look at it. We could probably maybe change a brake valve and prevent further damage. But it's not happening. I don't think we have the operators trained enough on this new system. Never mind the operators, I don't thing most of the mechanics know about the cycle time. I don't know how critical it would be to have that implemented in your system?

P; Well, that's one of the nice things you can do if you've got that hooked up to instrumentation you can look at things such as cycle time.

M, It could maybe register a warning, "cycle time is short by 2 seconds".

P; So that's one of the nice things you can do with instrumentation. OK. Well, I'll just write that lot up for the time being.

April 21 1995

(R) Rick Mayette - Leading Hand Mechanic, 1800 Level.

(P) Peter Knights - McGill University.

P; It's Friday the 21st April, and I'm talking to Rick Mayette down on 1800 level. OK. If we look at the hoist output here, is it normal that you'd normally get a hoist and dump failure at the same time?

R; Yes.

P; What about if you had a cylinder bypass and you had a bypass problem in either your hoist or dump?

R; If you have a bypass in your hoist, you still have your dump. It runs of your main control valve. If you want the dump, you apply the section on the main control valve.

P; OK. Back again. I've got a loose schematic of the main control valve. Where is it? OK. No. 20 here. Now this is not totally correct, because there are pilot relief valves in here which are not shown, but what I've shown is oil comes up through the dump spool OK ...

R; Yes.

P; And it firstly goes to the dump, so if you activate your dump it gets priority over hoist. And then to hoist when you're not activating the dump. So you're saying that if I was to have a cylinder bypass in the hoist,

R; Yes your system still works kind of not applying to your hoist. And it won't work properly because of the bypass. Now it would have to be really bad, because you've still got the other hoist.

P; Yes, I'm with you. So one hoist cylinder will be working a lot harder than the other.

R; Yes, and it will lift, even there's bypass in the other one. Now if there's a leak like a hose, well I might have a problem because I'm running out of oil. As far as just a bypass, the other one will lift.

P; OK. What about if there's a bypass in the dump?

R; If there's a bypass in the dump, that has nothing to do with the hoist.

P; Yes, so I'd just notice that my dump is really .....

R; __My dump is either falling down or whatever.

P; How frequently does that happen?

R; Not that often. What usually happens, in most cases we end up with a broken dump. Or the seal packing leaks bad enough, that it keeps coming out bad enough and he can't hold it. He's got to put lever on his, weight on his dump lever because he's losing too much.

P; So that's more common that the seal packing leaks on the cylinder. Is that on the hoist cylinder as well?

R; No. The hoist, we usually break them. The eyes break off. Not too often we'll change one because, if it leaks, so it leaks a bit. We don't change them.

P; OK., looking through your stats, the other day, you've had a lot more problems with dump cylinders than you have hoist cylinders.

R; Yes.

P; OK. I've got an idea as to what might help us a little bit here. This is basically the Wagner service manual, and what we're looking at is what Wagner use for troubleshooting, and they deal with a section on the Main Control Valve and the Steering Control Valve. What I thought I'd do is just run through these failures with you, and if you can tell me what the likelihood of these kind of failures occurring is it gives me some idea of the frequency. Not only do I need information on the likelihood, but sometimes it just sort of says, you know "low pressure in dump circuit", and I don't know what kind of symptoms you'd see on the machine as a result of that, and I need to know that for the guys upstairs as well. So we may as well start at the top of this list and we'll take our time working down. It might take a couple of sessions, but we'll take our time and seed how we go. So number 1 up here is "poor hydraulic system performance or failure." It just says, cause: defective pump, dirt in relief valve, relief valve defective ...I'll let you read through those.

R; worn cylinders, load too heavy, internal crack, plunger not in full stroke, reservoir low on oil, system filters clogged, restrictions in line.

P; So, of those, what would be the most common one?

R; Common one?

P; If any. You might have some other ideas too.

R; Relief valve.

P; Dirt in relief valve? What relief valves?

R; Well, dirt in general is a big problem.

P; Dirt in general?

R; Yes. Very seldom, we will change pumps. Most times we don't. The pump is not the problem of a hydraulic system.

P; A low frequency problem.

R; I would say so. When a pump is gone, there's another problem. You run out of oil.

P; OK.

R; Yes. Reservoir low on oil. That's a big problem.

P; That's pretty common?

R; What happens then is now you're working the pump. Now you could have a problem with the pump, but even then, when it gets that bad, we usually just fill it with oil and the problem is cured. The pump is one of the last things that we have to change because the pump is gone. Cylinder problem again, which is most likely packing .. poor hydraulics.

P; Would you say that was a medium likelihood?

R; That's a medium.

P; What I'm doing is categorising this into low, medium, high and unlikely, if you like. The dirt was a high.

R; Dirt is very high.

P; Where does dirt ...? If you get dirt..?

R; If you get dirt in your system you get it on your relief valves,... either in your pump, or your relief in your control valves, or your port reliefs.

P; OK. they're high likelihood areas. How will that show up then? Will that show up in sluggish performance..?

R; ... of the hoist and dump cylinders and poor hydraulics ....hide in the pilot. We'll go down the line. We'll check for proper engine speed, proper stall speed... check that the engine's got the power. If that's OK, then we'll go to the hydraulics. Then again your relief valves or the settings for the valves. have I got a high enough pressure? Have I got a high enough hydraulic pressure? Count it off the specs.

P; OK. To check your hydraulic pressure there, do you attach something to one of the hydraulic ports.

R; That's right. Now, another thing, am I opening that spool on the main control valve, for my dump/hoist? Am I getting enough pilot pressure? Have I got a valve that's leaking? Is it pushing the spool to the other side? Now, if I use the lever I'm overcoming what is a bypass in there, so it might be OK, but maybe in low, very low, like when I'm going at idle, that power I don't have it because maybe I'm getting pressure from the other side of the bypass on the pilot section.

P; Right, I'm with you there. So, Internal cracks?

R; No...I'm just saying now for your pilot plunger stroke - that's what that means ...am I getting enough pilot pressure to make sure that the spool is in full? That another thing.

P; Good.

R; Again, when it comes to these last two, filters clogged and restrictions in lines, you're talking dirt.

P; So this is pretty high likelihood as well?

R; Oh ..yes, we do run into that problem.

P; High? Would you classify it as high or medium?

R; We had one machine we had problems with, and it was the hydraulic oil, it was full of sand fill.

P; How did it get sand there?

R; Because of the sand fill that the pump was drawing. It ran sand fill through the pump. So the pump was ruined.

P; Yes. That was the shotcreting?

R; Yes.

P; So this is what ...system filters clogged is again dirt.

R; Again it's dirt, it's not a common thing but again the problem is that once we get that dirt that's our main problem.

P; They'd have a bypass, wouldn't they, on the filters?

R; Yes. Yes.

P; Well if your filters have been clogged you can bypass and get s..t all the way down through the hydraulic system anyway, so you're more likely going to pick it up and clog in the relief valves...

R; We had a problem where packing of some kind - like we blew a cylinder or whatever - packing got caught. Now, when a guy changed the filter in the main tank, I guess everything stayed in the bottom, so everything went through the pump and to the charge valve. Now you're running into no hydraulic power and the spools in charge valves are plugged

P; OK. I'm with you. Those are these spools?

R; These get jammed. (indecipherable). I don't see it in here. But again with dirt ..

P; It's more likely, if you're running a scoop on remote, you're not going to pick up the fact that your filters are clogged unless you do that on a routine service. So it's more likely that you're going to get restrictions in a line but probably dirt in a relief valve is going to be the common one there.

R; Yes.

P; Because if your filter clogs, it's going to go all the way through.

R; Yes, between that and hydraulic leaks and reservoir low that's when you end up with problems.

P; We were just discussing the charge valve here and the fact that you got that really clogged. What happens here?

R; What happens, OK. first of all it clogs your charge valve. Now you have no proper pilot pressure because that feeds your sequence valve. So right away you figure that your sequence valve is gone, but in most cases no. The charge valve will get it first and will plug up the charge valve. And changing the spools, but we found out by changing the spools, we change the spools and put them back in. No problem. Everything works good and all of a sudden it comes back two hours later, the same problem again. More and more dirt inside them, the spools. So what we do is pull them out and start the machine, let it flush through the charge valve so it should be clean and then we put the spools back in, and that eliminates most of the times the problem.

P; I'm with you. OK. That's pretty good for that first one there. It gives me a good idea of what we can look at there. So basically when we talk about poor hydraulic system performance, we talking about low power and slow, I guess too.

R; Slow, yes, slow.

P; Do you ever get any jerky hydraulics as a result of dirt there?

R; Not really. It's more just slow, and as you say, no power. You have to work your lever to make it fill in the bucket where normally you just go in, push in and roll it back and your bucket's full.

P; OK. Let's move on to the next one down here which is oil foaming. If you get oil foaming occurring, how does the operator know that? How does the machine behave?

R; Foaming oil......

P; Is it a common problem

R; Not normally. You'll get ...most common - now it doesn't have it here - oil foaming, is if you have an air leak. You're sucking air somewhere. Whether it's through an O-ring, or a hose on your suction side. That's when you're going to get oil foaming. Most cases.

P; And if you had a hole on the suction side, and you're getting foaming in there, how would you ...

R; Don't forget, you'll also get cavitation.

P; So you've got noise?

R; You'll hear it. You'll hear it. Especially at higher RPM. When you want it more, that when you'll hear it. That's when you'll hear the pump cavitating.

P; Ah, got you. One of the things that Mike mentioned the other day was a problem with the relief valve on the tank ..

R; Yes.

P; It charges the tank and if that gets s..t jammed in it you can again get cavitation at high RPM.

R; Now again, that machine we had full of sand fill, when I pulled that relief valve it was plugged solid full of sand fill, like sand. It was like grabbing it and pulling it out of a mud hole.

P; So oil foaming is a product of an air leak occurring basically, and that's when you're going to see that. How frequently would you get a leak on the suction side?

R; With these new B's .....we used to have more problems with the A's. The way they're set up now plumbing wise, we don't usually run into that much of a problem.

P; So I'll put infrequent here. And one of the other things it mentions here is excessive bypassing of oil over relief valves. So if you are bypassing over a relief valve, you're getting air ...

R; that' s exactly what you're getting. By bypassing, instead of having steady flow through the system, it's relieving and going somewhere and that' s when you end up with ..

P; But you would notice that with poor performance too and sluggish performance if you were getting excessive bypass.

R; Definitely.

P; So, I mean, I don't know why they haven't got this one up here. "excessive bypassing of oil should really be back up in this list here. This is a problem with the Wagner troubleshooting guide. It's all over the place! Ah ...Number 3, "Excessive oil temperature". How do the guys notice that you've got hot oil? The operators wouldn't know that, would they?

R; The operator? Yes he would. His torque temperature gauge might also go up, by having hot hydraulics.

P; Hot hydraulic oil? How would that push his torque temperature gauge up?

R; Because you're running leaks, to your torque through your hydraulic tank. Running oil from your hydraulic tank to your torque.

P; Is that right? I thought that the transmission was a totally separate system.

R; Yes it is, but you're still running oil through your pumps and your pumps are attached to your torque, and so you're still going to get a heat problem.

P; This is something I have to grapple with. See I also put together one of these diagrams for the whole drivetrain, and I thought pretty much your drivetrain system drew oil through the sump of the transmission and so... I'll try to understand it. I thought it drew from the sump, went up through the charge pump, into the transmission cover, the control valve. These are your clutch packs, in here, forward, reverse, 1st, 2nd, 3rd, 4th, so here's your torque convertor. I didn't know that there was any connection here to the hydraulic tank.

R; See if you have a seal leaking on one of your pumps, on your main hydraulic pump, your steering pump, you're getting oil - hot oil from your tank - going into your torque convertor.

P; Oh OK. So it's really....

(End of Side 1 Tape 1)

R; There again, what you're getting is a effect of just like putting a relief valve. Pressure ... the more pressure, the more heat. You make a restriction, causing heat.

P; If your oil heats, you're more likely to get seal leaks, as you were saying, into your torque convertor, and that will push your torque convertor temperature up.

R; That's right. Yes. This is also one ...incorrect type or viscosity of oil. On some machines, if you were to put (indecipherable) oil in the steering system of a scissor truck, it won't work. I won't get no proper steering, because your oil is not right, it's not thick enough. I'm not getting the right viscosity of oil to make the system work. I'm not saying, in your transmission, for a system on a scoop it won't work, but it'll flaw you definitely, cause sealing problems.

P; OK. This probably shouldn't happen, you know, but it does happen in the mine?

R; Oh yes, I've seen a guy put diesel fuel in the hydraulic tank. Not familiar with the type of machine he's on. He goes on this machine, he'd never seen it before, and he thinks that's the fuel tank.

P; (laugh) ..OK, that's good, we're working our way down there. So, if you have excessive oil temperature, from the point of view of somebody operating a roboscoop up there, the first thing there really going to notice is if they get.... unless there's a temperature sensor on the hydraulic tank, which there's not one on a conventional machine but they could place on a roboscoop, and they probably should ...

R; They should, definitely.

P; The only other way that they'd notice it is if the convertor temperature was high and that could be the indicator?

R; That could be the indicator.

P; So now I'm with you there. OK., so number 4 "foreign material in reservoir screens". I guess this is when you inspect the reservoir and you look at what type of material is there. That's pretty straight forward. It gives you either lint ...which is cylinder packing ending up there, or chips.

R; Worn pumps. That you will get, but not .... This, this is more likely here. Cylinder packing.

P; So this is high likelihood, and this is low ...Actually, what I just noticed, that if we go back to number 3, I didn't put frequencies on this. Worn hydraulic pump is a low likelihood. Incorrect viscosity is probably low?

R; Yes.

P; It doesn't happen ...it shouldn't happen that frequently if things are being run properly. And "sustained maximum pressure operation" giving excessive oil temperature ...

R; It doesn't have here "low oil".

P; Low oil is another one?

R; Yes, if you have low oil. If you have low oil, well your pump has got to work, it's got to cavitate automatically, creating heat, ...

P; And you're not giving that oil time to cool.

R; That's right.

P; Yes, I mean this is one of the problems I have with these Wagner manuals. It's very incomplete.

R; Very basic as far as what are the causes. But again, as a whole, we have 15 of these machine here. In the three years that I've been here, excessive oil temperature is probably nil, or very uncommon, as a whole. This part, like number three, is not a major problem with these machines.

P; Right, so that allows me to put that there. And foreign material in the reservoir screens, I guess you would see that?

R; Yes, that is more often.

P; OK. If we go to number 5 which is "insufficient pressure build-up", and that's when you start the machine, and it give you a couple of options here. I think there are more causes to this, but one is a system relief valve set too low. And I guess that would be a relief valve on your charge valve causing that? Another one is worn pump components causing internal leakage in the pump. But .. system pressure build-up here .....insufficient pressure build up when you start the machine.

R; Again... so what you're saying there is that I don't have enough hydraulic pressure, or power, or whatever?

P; Yes, and again, you'd be noticing low power. So all of these causes can be either ...

R; Dirt, and something went into the relief valve, ah ...maybe it'll do it for an hour and guess what, all of a sudden the piece gets out of there and you don't see it again. On these machines, very seldom do I have to have somebody (indecipherable) the control valve and reset the pressure relief valve. That's a very unlikely problem. We have more of a problem where roll back will crack ....we have more problems setting port relief valves, than your main relief valve. Usually we have high enough pressure. If you have a problem where it's a roll back coming back, or a hoist coming down, and you've got to keep the lever on the hoist, and if you don't, because you're losing it and it starts slowly coming down .....especially under load because you've got a full bucket, in most cases it a port relief valve.

P; So you'd notice that if a port relief is leaking, you won't be able to hold a load and you'd be gradually slipping down ..

R; Yes, we have more problems with the dump port relief, than the hoist port relief.

P; How do you notice the dump? I guess it starts slipping back on the dump there ..?

R; What happens here is that you have to put the machine up for whatever reasons. Or he's scraping back the muck on top of the ore pass, and he goes like this, and what happens is he's got pressure and a soon as he needs to throw that lever the bucket just stays there, and what happens is that it rolls back by itself.

P; That's what I was just seeing Larry try on that machine over the way?

R; that's right. That's our major problem as far as the dump. Hoist ... it does happen, but not as often. Not as often as the dump.

P; OK. Actually, we may as well just finish through this list here, and then I'll let you have a break. "Low pressure in the hoist circuit". Now, if you get low pressure in the hoist circuit, you're going to get again, low power right?

R; Yes, definitely.

P; You see, these b...y things are repeating themselves again. We've got worn pump, we've got bypass in cylinders. I don't know whether we really need to go over that low pressure there.

R; Low pressure in the hoist circuit, "damaged or improperly adjusted hydraulic relief valve" ...when it comes to this relief valve, they're mentioning all the time relief valve problem... Dirt. That's a major cause. I don't think too often we have to change a relief valve because it's damaged. It's normally a dirt problem, or a bypassing problem.

P; OK. If we're looking at the hoist circuit then, we just have low pressure to the hoist, we'd be looking for dirt stuck in the main control valve and a relief valve in there?

R; Yes, we'd go from there, and then back to have I got enough pilot pressure? Am I bypassing through my pilot pressure? Am I getting enough to push that spool all the way?

P; How do you check your pilot pressure by the way? Do you hook in to check the pressure there?

R; On these B's ....yes, we do have a port relief valve.

P; But I guess too, if your steering is fine, and you're noticing that you've just got a hoist problem, you know your pilot pressure's OK unless you've got something in the pilot valve itself.

R; That's right.

P; But I'm just wondering, under that scenario, how you discriminate between a pilot valve here or the main control valve? Supposing you're getting no power to both your hoist and dump ... both are pretty poor, and you narrowed it down ...Your steering's OK so you know your pump's fine, right, So you narrow it down and you say, "OK, the rest of my circuit is fine", so it's either this pilot valve here or the main control valve.

R; Yes, that's right. Am a getting power through that? You've got two systems here. The hoist and the dump. I wouldn't really go for pilot pressure. Why would I be getting two functions, out of that pilot valve, for hoist and dump? Very unlikely. Either I have no pilot pressure, not enough pilot pressure ...

P; In which case you wouldn't have steering ...

R And here, it says, this is more common ...low pressure in hoist circuit, Bypass in cylinders.... means also again, packing, or dirt. But most likely packing.

P; So this is the most common one.

R; And again, hydraulic pump worn ..to me that's the last ...very seldom do you end up changing... having a major problem in changing a pump is running out of oil and burning the pump itself.

P; So, in other word, if you're checking oil level, which you should be on the roboscoop, that'll give you an idea as to whether you're leaking.

R; You have to realise that the amount of muck that these machines are mucking sometimes, you're running with leaks that we never always have to fix because they'll go and muck again and when it gets ...we'll say OK you have a leak. I just put in 20 gallons at the beginning of the shift. Well, during that time, you're losing all that oil and your pump is starting to get hotter because it's running low on oil and you're cavitating, and that's where you run into a problem.

P; OK. So going down to the last one here, Low pressure in the steering circuit, we've got again improperly... probably dirt in the steering circuit relief valve is more likely than that?

R; For the steering circuit.. ah, that's one thing very seldom, with the steering control valve that we end up with a problem with the relief valves. Not too often ... since I've been here, not too often. This is more of a problem, you'll have a steering cylinder bypassing. More frequent than the relief valve. And then again, the last resort again, like we were saying is the steering pump.

Session 2.

P; Now we're onto the main control valve. The main thing I wanted to know from the hoist and dump outputs there are what kind of failures you can observe. I guess we've pretty much discussed sluggish behaviour - lack of power - being dirt, and there's also the failure to hold a load, and you mentioned that that's usually a port relief problem or a cylinder bypass or such. But if we go over this section here, no. 9, "difficult operation or sticking of control valve", how would you notice that, anyway? Would you notice that your cylinders were slow to respond to a manual instruction to hoist?

R; Slow response? No not really. What would happen there is well OK. "sticking of control valve plungers", yes it would be slow to respond. yes. Because if there's a piece of dirt or piece of packing there, you're trying to force it, so your spool is not operating as smooth as it normally would, so the flow will only go through to make the function work. So you would definitely have slow operation.

P; When you look at the causes of that then ..over here, hydraulic oil. I guess you're getting lack of lubrication through there, so maybe even some expansion in the valve assembly from heat. so that may cause some sticking. is that likely .. I mean how frequently do these kind of failures occur?

R; Like again, with overheated hydraulic oil due to whatever, a restriction of some kind which will cause your oil to go through and cause more heat because you're impeding a restriction for whatever.... ah

P; I just wanted to know, in here, it gives you a whole list of bits and pieces and what is your most common cause ...if any are common at all. I mean, it may not be a problem.

R; We've had these here for three years, I don't recall anybody changing a main control valve.

P; Is that right?

R; Yes. I can go back in every book, and if we've changed one, that's it ..

P; What about spools in the valve?

R; Again spools, it's dirt. If anything we change a broken spring, or broken cap on your pilot into your main control valve, but as far as the spool itself? More common in the older machines. Not in these. I don't think I've seen anybody change one here.

P; Like I said, I suspect that this was done for the old A's anyway, so in other words, these are all low likelihood problems.

R; We had more problems in the old times, where we changed more control valves, then than now. We've never changed one.

P; You don't experience problems with bent plungers ..or ?

R; Again, let's say a bent plunger caused by what? Broken metal in the oil? Most likely metal would probably give you ....or a scored plunger. I've seen that, where it's all scratched .

P; But then you get internal leakage in the valve ..

R; That's right, and you're running into problems ..

P; And again you'd notice sluggish performance because of that leakage in the valve.

R; Your oil is going where it's not supposed to being go. You want it to go here, to create this function, and you're losing some of that

P; Yes, and you may get some heating as well, because you're getting oil going back into the reservoir.

R; That's definitely.

P; OK. so, I can say that pretty much all of those are unlikely events, but you've given me some ideas as to what would be the cause of it if something happened anyway. Can't move plunger in or our - dirt in valve, well that's high likelihood.

R; that's more of a cause again. But again, our systems are better what our filters pick up. You won't get it at the valve. You've got your tank ..and you'll get it in your charge valve. If you're having a hydraulic problem, this is where we're going to get it, right here. This is where we're going to get it first. Before we get anywhere past this set-up, it's going to come past here first.

P; Or into either the steering control valve or main control valve. Because that's one path, down through your brake pump, right, but you've also got your tandem pump driving your hoist and steering, so the likely points for sticking of c..p like you said are going to be the accumulator charge valve and probably those two valves. Is that what you experience?

R; No. Again, when we get it from wherever, dirt from filters, the filters don't pick up let's say packing, it will go into the system, it plugs up your charge valve. It doesn't go into this side.

P; I wonder why that is? I may have got this diagram wrong?

R; I'm just looking at that

P; I've got both pumps here sharing a common suction filter and strainer, out of the reservoir, and maybe I've got that slightly wrong?

R; No. the tandem pump comes from there ....But I think the thing is, this is return, from pump to your tank. When you're getting it in here, where your filter is housed inside the tank in the tube, this is where its going to end up, coming through the brake pump.

P; I wonder why that is? Is the brake pump lower than the tandem pump or something like that?

R; No it's not. Your tandem pump is the lowest one. again, you have the tandem pump which is a big pump, which has a pipe like this, so the odds ....

P; But is that pipe, the inlet, if you like, the suction to the tandem pump, is separate to the suction for the brake pump side? So they don't share the same suction filter?

R; No ...Yes, there getting it from the tank, but they're getting it from a different area of the tank. This one is piped from the tank to the brake pump, and this one is piped from the tank to the tandem pump. But like I say, this one here has a big outlet, like a three inch outlet. You'd have to have some pretty big pieces to have a problem going this way.

P; Yes, right.

R; Whilst, here, if it does get in here, that's it. This is where it plugs in.

P; OK. so this is a smaller outlet than these valves here, and that's why you might have a problem here. I just couldn't work out logically why that was ..

R; Definitely, yes.

P; Now I'm with you. So that restricts the flow that the other outlet

R; Even it goes through the pump, and it goes to the main valve, you're going through a valve which has a 24 hose and it just runs back right to the tank. So you have more of a flow, less chance to catch. When you get into this set-up, small ports, this is all, you've got a hose this size.

P; So this is definitely one to ...the accumulator charge valve there.

R; Yes.

P; That's good to know. All right, let's get back to this list here.

R; Unable to move plunger, in and out

P; Plunger cap full of oil ...

R ...which is not common. Where you have this problem is where you have a leakage through your pilot valve to your dump/hoist valve. Then you have oil seeping through the hose when you're not supposed to. and filling the plunger and giving you a harder time to move. And your other function. If you had one leaking on your push side, on your forward side, now it'll be leaking in this plunger and when you want it to go to that side a bit you have oil in there giving you a harder time to move.

P; So, in actual fact, that plunger cap full of oil is more going to be a pilot valve problem.

R; Oh a pilot pressure problem.

P; This is another reason I find ....

R; If you hit a binded link well that's your oil set-up, where you have more problems, again, having leakage problems.

P; See in here, if you fix that then you're just fixing the cause unless you look at the pilot valve problem. Now let's look at the détente control. Is there a détente control in the main control valve? I think what they mean here is a little ball and spring which allows you to select spool positions. does that exist.... is there a détente on the system?

R; Yes... that again, we don't have problems, as a general.....

P; OK ....It mentions here, no. 12 here, the load drops when plunger moved from neutral. This is when you're in neutral and then you activate the thing. You've got two choices; dirt in check valve and scored seat. Judging from what we've said, you're probably more likely that you've got dirt.

R; More likely, yes. Those main control valves are pretty durable. It would take something ...a piece of metal, a good piece of metal to get in there an jam to really effect the valve. I've seen some pieces of pump gears, broken, and stuck in the main control valve. And, pull the spool off, pull the cap off, find out if it's still not working, take the piece out, put it back and ....

P; (laugh) And it didn't score the valve significantly?

R; That's right. Not even so.

P; So how frequently would you notice that you get dirt in a check valve ... I think we've covered that question ....

R; Accumulator charge valve... this machine as a whole, the B, we don't run into too many problems of having dirt in the main control valve itself. Actually, there probably has been packing that goes through the valve, but the valve just moves back and forth, maybe squishing the packing and the next thing you know it goes through the return, and leaves.

P; What causes your port relief to go off then ...is that dirt in the port relief?

R; yes, most likely. The port relief again is a smaller valve behind the valve, and that's what happens. You probably get dirt in it, and then your pressure is ...it's set differently because it pushing ..your spring is not going back all the way to where it should be so what we usually do is we back it all the way off, screw it all the way in, see if we get above what we should get, and then we back it off again. And again, with them ...most causes on port reliefs, is a broken spring. You've got dual springs, a smaller spring and a bigger spring and a poppet, and the spring breaks. So that could be from excessive use ...maybe a chunk that hits that bucket, that's what I was talking about having problems with the bucket and the dump ..

P. Impact loads ....

R; And on that force the spring will break.

P; Right, I'm with you. But I noticed, just looking at Maximo, that's a pretty frequent job that you do.

R; yes ...You noticed that eh?

P; Anti-void valve inoperative on the MCV. Now I'm not sure what they mean here when they talk about an anti-void valve. I think they mean the compensator spool which is the one here ...Oh no. I'm not sure what they're on about.

R; Anti-void valve inoperative?

P; Yes. I'm not sure what they mean here. I don't have all the schematics. I'll just put a question mark here. I'll chase that one up. But I'll have to really look at the schematics there to know what they're on about. OK. No pressure ....I don't know what they mean by no pressure there ...I think... I think that a lot of these problems have been covered. What I'm realising, is that a lot of these are just symptoms of what you observe, which are dirt and metal scraps getting into the valve.

R; That's exactly what this all is. It sticks. It shouldn't stick. It's got a fairly heavy spring. the reason it sticks is that you end up with dirt in the valve. dirt on the valve seat ...pilot poppet stuck open ...Why's it stuck open? Dirt again. All this runs to basically, dirt.

P; When it talks about pilot poppet here, are you talking about the pilot valve back up here, or is there a poppet valve in the main control valve here that ...

R; No ..its a valve probably on the end of your tap valve. It's all done hydraulic now. we used to have a system where the linkage and manual, either a cable, or they used to have a small little hydraulic cylinder, which was pushing the spool still hydraulically but through a little cylinder. Now, it's direct. It goes pilot pressure from a hose to the back of the cap.. and that's what it is now.

P; OK. Erratic pressure - pilot poppet seat damaged, so you're getting leaks out of there. Small poppet sticking in large poppet. Are these frequent things?

R; No, no.

P; This is again on the pilot pressure side of the valve.

R; I find on these machine, you don't have what you'd call poor pilot pressure, you either have pilot pressure, or you don't have pilot pressure. So you're having it, it comes from your charge valve, and your charge valve ...this sequence valve. The sequence valve reduces it from whatever pressure you have in your charge valve to 200, 220 PSI pilot pressure. That's basically all it does. And basically, whatever excess you might have, it's used for cooling brakes. And like I say, we did this once ..we changed the sequence valve, and we still had the same problem. All the time it's the charge valve. Dirt in the spools. There's no such thing as a broken spool ....it's dirt in it. A restriction in the valve.

P; Relief pressure valve pressure setting incorrect.. I think that says pilot poppet problems there, but we've covered those problems. I think that's pretty good. We've covered these things pretty well ....

R; Relief valve pressure setting incorrect ...OK, wear due to dirt, you get dirt, now you're going to get a different setting, then jam nut and adjusting screw loose, that possible.

P; We're talking port relief here, aren't we?

R; Yes. Worn seats, damaged O-rings, parts sticking due to dirt. See again, if you notice, everything is dirt, dirt, dirt.

P; Yes. that's your major cause of problems.

R; Yes ..it's not dirt in general. It's packing, pieces of material, or end caps of hydraulic tanks. a guy takes the five gallon can, with the little plunger there, and he doesn't bother taking it off, he pushes it in the can, he fills the vehicle tank and where do you thing those little things go? We had a problem with the ST 5's where a guy was spitting seeds in the fuel tank. He was having fuel problems. We take the tank cap off; sunflower seeds! That much in the fuel tank!

P; (laughs)

R; It all generates back to dirt. We're starting to have a few problems getting the machines on a ramp ..fuel problems. Now when the machines are getting older we're having either dirt in the tank or collapsed hoses.

P; And that's giving you injector problems because of the filter bypass. OK That gives me quite enough to look at the main control valve. Over the page here, this is the last page on the hydraulic circuit. This deals with pump problems. Both brake pump and the tandem pump. As you said, you rarely have to replace pumps. I don't know whether we really have to go through this a such, because I think we've covered most of it. I mean, if a shaft is sheared, well you're going to know that.

R; That problem will occur, but we don't see it. It's going to be infrequent.

P; Unless you have fatigue of the shaft, some metal problem with the fabrication.

R; Unless you have a really bad dirt in the tank, generated by either bad packing or metal, whatever, you're not going to run into that.

(End of Tape 1 Side 2)

(Tape 2 Side 1)

P; OK, back again, it's the 21st April. I'm talking to Rick Mayette, the leading hand down on 1800 level. We're discussing hydraulic pump problems. Let's see. Where this sheet is out. Vane pump - we're using a gear pump. so it's not even relevant. Fluid viscosity too heavy for pump to pick up prime. OK, when your oil is cold, do you ever experience problems?

R; Yes, when your hydraulics are cold.

P; And the cause can be just a very cold day.

R; Depending on where you are, yes. It may be 10 or 15 minutes before your hydraulic pressure will work properly. If it's -20 or -30, outside, it's very slow.

P; Yes. That's another point. Maybe we should put an ambient temperature sensor on there to tell us what the ambient temperature is, since it can also be a cause of sluggish behaviour.

R; yes, definitely.

P; Shaft sheared, relief valve stuck open, well we discussed those problems. More likely to be dirt. Noisy pumps. Cavitation, and I think earlier on we discussed some reason for this; the high RPM when you've got the valve to the tank stuck open, and you're failing to supercharge the pump, well you'll get that. Excessive oil foaming ....we discussed the foaming problems. Low oil supply...

R; That's a major one.

P; So that would be a high likelihood there.

R; Again, the problem of having a pump being changed, again most causes are running out too often out of oil and cavitating the pump, which is where your damage is coming from.

P; And burning it out as a result of the cavitation.

R; Yes. Air in the pump which again is an O-ring. you're sucking air. again causing cavitation You wear you pump. The same with excessive fluid foaming. Why is your fluid foaming? Most likely you're sucking air on the suction side through a hose or an O-ring, causing oil which again causes heat and again you end up with problems in the pump.

P; OK. High engine speed with cold hydraulic oil. that would create a noisy pump?

R; Yes, your pump will be screaming. Most likely, if its cold like that, you have oil, your oil's OK, but your oil is not going through the system so again you end up with a noisy pump as if I'd run out of oil. Your pump's working , but it's taking too long to go through.

P; I see. And that would be the same as oil viscosity, if you got the wrong kind of oil.

R; Yes, yes. If you were to put the higher viscosity AVS 90 by mistake.

P; But the most likely cause here - if you get a noisy pump - the first thing you'd do is check your oil supply, right?

R; Always the first thing to do. Check your oil supply.

P; And if it was found not to be oil supply, you'd look at the valve on the tank, you'd check that ..

R; Yes..

P; And following that what would you look at?

R; As far as a noisy pump is concerned? Basically that would be it, really.

P; those would be the two to look at?

R; Oh yes, no oil, and you're going to get a noisy pump because of cavitation. Your pump is going to be screaming. That's what you hear.

P; OK. How frequently do you get guys coming in complaining of noisy pumps, I mean how frequently do you get low oil? They probably wouldn't complain!

R; Most operators, if they have a noisy pump, they know it's because they don't have any oil in the pump. Not too often an operator comes in and says "my pump's noisy and my tank is full". If you have a noisy pump and your tank is full, you have to know if it's something else or not.

P; Yes, that's your major cause. OK on to steering. This is the last section we deal with in the hydraulics here. I guess this is mainly concerned with the steering control valve, but there are a couple of symptoms here. Hard steering when turning slowly - do the guys come in complaining of this? What do they complain of when they come in with a steering problem?

R; Again, if you have hard steering, you must be leaking oil from somewhere, because you have a hydraulic leak on the hoist side, or the dump side, which is again low oil, so hard steering.

P; Lack of oil to the actual valve there?

R; Yes. The most common problem, other than not having enough oil, is, after a while, you have more of a problem with the packing inside the cylinder. They'll end up leaking through the packing, or a steering hose. the way they're set up they're low, we'll have more a blown steering hose.

P; that's probably the most common cause of steering problems?

R; yes, when you blow a steering hose, you're mucking, you're mucking down a ramp or whatever, you have a full bucket, and maybe you hit the side of the wall a bit, maybe, then your hoses have more of a tendency of taking a shock and blowing a hose.

P; OK.

R: But most causes of a blown hose is wear. They're (indecipherable), they have a small hose, two hoses ...and the first original ones that we had, like we had to pull out with a tractor. We change them, frequent enough, steering hoses.

P; A frequent enough occurrence.

R; yes it does happen, pressure loss problems, packing problems. They work hard, the steering cylinders. You're always using your steering.

P; OK. So that's a medium, I'd say.

R; Steering control valve, again, maybe two or three valves since I've been here.

P; So it's low frequency.

R; Again, you're always using your steering. Even when you're mucking, even when you're using the hoist, you're using the steering.

P; Right. "No effort required to turn" - loose or worn valve. Unlikely?

R; Unlikely, poor steering return - sticky valve spool, again ...

P; Yes, sticky valve spool, that's again going to be dirt. The "vehicle loads to one side or the other"; unbalance or badly worn valve. Do the guys ever come in complaining of that?

R; No., what you'll end up with is ...you get the same problem, you get two steering cylinders, one leaks more than the other, so if one is pulling more than another... not enough to be classified as a B.O. cylinder it could give you a problem.

P; Ah ..Momentary increase in effort and wheel kick back ...I don't thing these would be problems that the guys would come in complaining about.

R; This set-up here, years ago, when you had steering wheels you could feel that. With a stick... there is very slow response.

(indecipherable)

P; OK I'm going to leave the hydraulics there. I think we covered some good stuff there and so I'm now going to move on to the drivetrain ...and this is the block diagram I drew up to show schematically what the drivetrain was. Firstly I had a couple of questions. There are a couple of gauges that are on the drivetrain, the converter PSI gauge and the converter oil temperature. Now they're actually hooked down to the bottom side of the torque ...Are they on the inlet or the outlet side of the torque converter?

R; Ah .. your temperature gauge, it's on your downstream valve

P; So your outlet here which goes down to the oil cooler right?

R; Yes.

P; I'm going to sketch that in. And the pressure?

R; And the pressure gauge, I think on those, it's right on your transmission cover ...

P; Oh, on the regulator here.

R; There's a pressure switch there.

P; Oh there's a pressure switch in there as well?

R; Yes. What was that ...your convertor PSI gauge?

P; Yes

R; Well that's coming off your main cover.

P; OK., so I'm going to put that in there. Just to give you an idea I'll run your through the diagram so you're familiar with it. OK your engine comes in through your torque converter, driving through two gear trains the charge pump. The charge pump draws from the transmission sump - all of this is your transmission sump - sends it through the line filters into the cover - this is all your cover assembly - through a pressure regulator which regulates the pressure to the clutch packs, then through the release valve, the forward/reverse clutch selector, and then the speed selector there. the forward/reverse assembly comes down to the modulator assembly - the forward and reverse modulators there and each of those contain an accumulator and a pressure setting valve and that drives your clutch packs here, forward and reverse. Similarly, your speed selector drive selects 1st, 2nd, 3rd or 4th. You've got six clutch packs in there, OK. And the output of the transmission goes to forward and rear drive shafts, front and rear differential and then your epicyclic hubs. Now for starters, what are the common types of problems that we're going to observe from the transmission? I mean, one of the things that apparently comes up is leakage at the face seals.

R; The face seals?

P; Yes, well you get leakage at the face seals. Is that fairly frequent?

R; No, not too often. No. The first ones we had, we changed some on 24. Very seldom do we have that problem. Face seals on the brakes eh ...very very seldom.

P; OK.

R; We had problems when they first came in. We had problems with the fittings on the other side of the hub breaking off. The brake hoses break. They're exposed and they rot, and that's were the brake hoses break. Fairly common as far as brake hoses ..

P; What about if one of your clutch packs is playing up? How do you notice that?

R; Slippage. Slippage in the transmission. Also you'd end up with a heat problem. It will show on your gauge there. And your oil will smell. definitely.

P; OK. So from the point of view of a guy driving roboscoop, they're going to notice hot oil in the transmission. (indecipherable) ..and that should be either forward or reverse clutch pack or one of the other. So to diagnose which clutch pack you're looking at, is it usually pretty clear which clutch pack is slipping?

R; Yes, most of the time, if any you check if it's in the forward mode or the reverse mode.

P; If it's still slipping in 1st and 2nd when in forward, you'll know it is your forward clutch pack.

R; Most of the cases it'll be 1st, 2nd and forward involved. Because they're mucking forward and they muck in forward and they muck in first.

P; OK. Right. What we'll do is I'll run through in here, the problems in the drivetrain that I've got listed. OK. Drivetrain. Power transmission. Torque convertor. So number 1 is ....lets go back to low clutch pressure. And if you've got low clutch pressure, you're going to notice slippage, am I right there?

R; First of all your brakes come on.

P; OK, because you've got that pressure switch interlock to your brakes.

R; Most big problems we've had are low oil level. You get leakages there ..hoses and not everyone complains about small leaks, but leaks are leaks. Broken spring in transmission. When was the last time we changed a tranny? Never.

P; What do they mean by that? One of the clutch pack springs?

R; Clutch pressure regulator valve stuck in open position. Faulty charging pump. Infrequent. Possible, this, but not too often. Charge pumps are a possibility, but again, it's not too common. That pump doesn't create pressure either. That pump just creates flow.

P; Well these are the two conditions you have. Normal clutch leakage or excessive clutch leakage. But how do you tell that from up above? If you've got low clutch pressure your brakes are going to come on, you're not going to know whether you've got normal or excessive clutch leakage right?

R; Excessive clutch leakage, you'll get heat. And that'll show on your gauges. It will show as heat.

P; OK. This is what we were talking about before. And this will be worn piston sealings, bleed valve stuck. But either way you'll know that you have a clutch problem. Of that, you're most likely causes are going to be either a clutch pack leaking, or low oil level, I would think.

R; That's right.

P; What about dirt in the transmission system. Where does it tend to clog, if it does, or is it as much as a problem as the hydraulic system?

R; Not normally, no. (indecipherable)

P; OK, so they're much more robust than the hydraulic spool valves. Broken or worn sealing rings ...low convertor charging pump output. See I did a survey of McReedy's work because they were running a couple of ST-8Bs back at the end of 1993 and they had a years operation on those machines. I was looking at the number of repairs they had done there, and they had a problem with clutch packs because Wagner had a design fault

R; Creighton' done three of them.

P: In one year's operation of there machines. I can't tell you how many hours those machines had done. Er what else. Air leaks at pump inlet? - low convertor charging pump output?

R; Yes, absolutely. O-ring problem. Loose connection causing an air lock or a collapsed hose.

P; And do you get that happening?

R; You will get it, but on the transmission part, not that often. We get it more on the hydraulic pump. O-rings going.

P; Again you'd say low frequency.

R; Sometimes, on those B's, you have the return line from the torque to the transmission. That's underneath. And when they're mucking, they'll squeeze and collapse the pipe. That's a problem when muck drops down. He can't see it and drives over it.

P; So under remote that could be quite a possibility.

R; Yes definitely. You get a suction problem. Slow return. So what happens too much oil stays in your torque. Not enough oil goes back to your tranny. Again you end up with overheating, air locks, loss of clutch pressure.

P; OK. I'm with you. Do you see that happening much with the guys operating on line-of-sight remote here?

R; no. On remote? No, but the odd times, we'll have damage of that pipe and it's got a bracket where it's bolted on, and we'll break the bracket off.

P; Would you say that was a high, medium or low frequency likelihood?

R; Medium.

P; Cooler blockages or failures. Do you ever do any of those?

R; Ah, coolers! Yes. Yes coolers we do our fair share. Big problem. Mounting. We'll (indecipherable) up, mountings get loose and you end up with problems. And again leakage and you get poor cooling there for the engine.

P; Yes, that's dirt building up on the cooler.

R; Also dirt. Dirt's a big problem for overheating the coolers. We do our share of coolers.

P; And.. when a cooler actually goes. How do you know a cooler is B.O. If the mounts come undone, the cooler would be all tight and you'd just put it back on. To actually replace a cooler, how do you know ...

R; It leaks, and you lose pressure.

P; How common is that?

R: Oh ..common enough. Hitting walls, you get a damage part of that as well.

P; Is that a medium likelihood, or high frequency event?

R; Oh ...a medium likelihood.

P; Plugged oil coolers ...do you ever get that?

R; Yes ...again that's dirt. Plugged oil coolers. And that low frequency ....Plugged as in oil plugged or plugged as in dirt?

P; Plugged as in dirt.

R; That's common. You have to blow that out.

P; Oh not dirt on the cooler. This is saying dirt in the cooler.... OK dirt accumulating externally on the cooler is a common problem.

R; restricted cooler return line ....

P; You're saying you get that bent with rocks ..So they're saying it will also appear on your pressure.

R; It'll be on your gauge.

P; so not only will you get high temperature, but you'll also get high pressure ... So ..if I could just go over something. For example. You notice that you've got high temperature occurring in your torque convertor. What would be the first thing that you'd look at there?

R; High temperature? Again coolers. Cooler's plugged.

P; That would be the first thing to look at?

R; Yes, I think so.

P; And if it wasn't that, what would follow that?

R; Oil. Oil level.

P; And then more than likely it's probably going to be a clutch pack, but you'd notice that in slippage, anyway. And if you then had high convertor pressure there, from what we're discussing, probably one of the first things you'd look at would be underneath the machine at that return line.

R; The downstream valve, on your torque convertor. That regulates your pressure on the convertor.

P; the downstream valve ...

R; Comes from your cover here, goes through your downstream valve. And your downstream valve goes to your cooler. that's 60, 70 lbs, pressure in your torque. That's what generates your pressure.

P; OK That holds the pressure in there. So if you're getting high pressure, what, you'd check that downstream valve.

R; Yes, the downstream valve's not working right.

P; That's actually built onto the side of the torque convertor?

R; Yes.

P; Overheating problems... well we've looked at that.

R; Worn oil sealing rings ...transmission leakage ... worn oil pump ...low oil level ...That's your most common.

P; Low oil?

R; Definitely. And suction. Like we mentioned about that bottom pipe.

P; So I'd say that was frequent ...

R; The other scoops which were basically the same system we had more problems ...no clutch pressure because of air locks in the systems especially when you ran low on oil. You run low on oil, you get the pressure back up, you can fill your tranny back up and still have no pressure. You have to bleed the system off. You have hoses, on your filters to bleed the system and let the air out, to get your pressure back. We actually blow a hose, or a filter, or a filter housing smashed on the wall and you put it back on and your clutch pressure ...there's a lot less problems.

P; Yes. Noisy convertors?

R; Again, that's very uncommon. I don't think we've changed one here, since we've had them, a convertor. I know for a fact we never changed anything, no.

P; I think we've sort of worked our way through here looking at likely occurrences. I'm just going to go back up here, looking at low charge pump output. you're going to see what ....you're going to see what? Gear changes are very slow in that case? Or are you going to get snagging occurring...? you're not getting as much oil to the control cover as you'd like.

R; Again, that's a problem that we don't usually see. Very seldom do we see a problem. Any problem, it's because somebody either breaks a hose, for some reason, or you've got a leak somewhere, like through an O-ring, and you're getting low on oil pressure. Again ..you should still get torque pressure, unless it got really bad and I left it running like that with low oil for I don't know how long ....

P; OK. And lack of power ....see over here at the overheating section.

R; Low engine RPM at converter stall. Again as long as you have low RPM in a convertor, maybe your O-rings in your convertor are slipping ..you're running into a problem that way.

P; Right.

R; But we don't run into that problem. We don't see that. Very very seldom.

P; OK. So uncommon. OK I think that gives me quite a bit to digest on the transmission first time around. What I'll do now is spend some time writing this up and if there are some gaps ands come back and ask you ...

R; Like transmissions, torque convertors ..very seldom. If anything, it's a hose, or lack of oil.

P; How about differentials or epicyclic hubs?

R; We change the odd one. Differentials. But very uncommon.

P, But you'd hear that with noise, or feel that.

R; Yes. Same as drivelines. We don't change drivelines on these machines.

P; And you'd feel that in vibration too.

R. It was a common thing on the ST-8A's or older machines, we used to change drivelines all the time. Very seldom do we have a problem with drivelines. Like most of our machines now are on 5000 hours, and we don't have that problem.

P; and your hubs are pretty good?

R; Same again with hubs. Planetaries. We don't have that problem. Even axles. Broken axles. We don't have that problem.

P; One other quick question I had for you too, is I know there is a linkage from your torque converter across to your brakes through the starter solenoid circuit to the relay valve here, so if you get low transmission pressure, it'll activate your brakes. I'm just wondering where that line comes from. That's from up here?

(End Tape 2 Side 1).

(Tape 2. Side 2)

P; It's Monday the 24th April, and I'm on afternoon shift and I'm talking to Rick Mayette again. I'm just going to go back over and cover some of the stuff that we covered earlier on, on the hydraulics and the drivetrain. What I've done ..lets just start with the hydraulics here. I wrote up virtually what we had covered in these pretty simple troubleshooting charts. So for example if you have brakes applying during operation you have either loss of pressure to the brakes from the hydraulic system or loss of convertor pressure. And the first thing you do is check the oil level. Check for broken brake hoses, or a jammed treadle valve. The brake stuff is stuff I covered with Mike, and what I haven't got is the likelihoods ...the frequencies of these. So we just work through these and look at what would be, I mean if you are observing these, what would be your major cause. I think the first thing as I mentioned is check oil level, then probably you're going to have a broken brake hose... if you've got brakes coming on during operation. Loss of convertor pressure we'll deal with in the torque convertor a little later on.

R; Also ...it could be electrical. OK either in your brake button, either on your pressure switch, either on your brake solenoid itself, on your park brake solenoid. That would cut off oil flow releasing your brakes and put your brakes back on. You know, it could be electrical, which is very ...like we don't run that often into that kind of problem. But it could happen. That is a problem.

P; But if we took, say, these three ones, it could be either hydraulic, convertor or electrical, what's your most likely cause?

R; What we have here?

P; Yes.

R; Broken brake hoses. They're situated ... where the brake is, they're set-up under the wheel, where the tyres are. They're right on top. They get muck, they get dirt, they get chunks, and they wear there and they break. We do our share of brake hoses.

P; OK. So that gives me an idea. And then second most frequent would be what, electrical or convertor?

R; Ah ... See that again is something that doesn't occur to often. Like as far as generating which one is worse than the other, there's not really ....

P; OK. They're pretty much equally likely to effect ...?

R; That's right.

P; Right. I've also got brakes being slow to release. And the main cause is slow getting pressure off the brakes. And I've said that what you want to look at first is your treadle valve ..restriction in your treadle valve. Is that statement fair?

R; Yes, I think so.

P; Any other things off hand that you can think of which will cause that?

R; No.

P; All right, we'll leave that. Brakes being slow to apply, ah ... slow removal of pressure from the brakes. Again treadle valve?

R; Yes.

P; And noisy brake pump ...well low oil levels ....

R; That's your main cause ..

P; Cold hydraulic oil

R; All the same area. You're getting it from the main tank. that's not your problem area, from your brakes. Where you're going to lose that oil is through your dump hoses or main hoses and that's when you end up losing 40 gallons of oil. Now, as you do that, you start sucking air into the pump and that's exactly what happens. This is not ...the ST-8A's when we used to have a hydraulic leak there and something would drain the drain the tank... then ..your brake pump, it was a really small pump on the ST-8As, and after you fill the tank up you'd have to bleed it. You ran into a problem where you still couldn't get brake fluid because you had an air lock in the system. Well, on the ST-8Bs you've got a main pump right on the torque, you have a different set-up.

P; OK. If you notice that your accumulators are cycling quite fast, and your brakes still appear to be working OK, one of the things that I've said you need to look at are internal leaks at the treadle valve, or externally down past the accumulator.

R; Yes.

P; Is it also possible to have low accumulator pressure?

R; If you have fast cycling of the accumulators?

P; No. If you notice that your accumulator pressure is down low...

R; yes, if you have a problem where your charge valve is not working properly. The charge valve is what generates what's getting to your accumulators.

P; So, if your charge valve is not working will you get low pressure.... low accumulator pressure then?

R; Well you could have a hard time increasing your accumulator pressure. You accumulators might be set all right, but now you're getting a usage of the accumulators from your brakes. OK, you've got your accumulators, as it drops, your charge valve is not charging then up fast enough, and that's where you're stuck. Where instead of having... if you were to turn the machine on, turn the key on, I can put 15 to 20 applications on the brake pedal and still have brakes, while the charge valve wasn't working properly. OK, and I wasn't getting that fluctuation where it goes from 1600 to 2200 lbs where it generates accumulator pressure. It'll stay at 16, and well, I wouldn't get it.

P; Right, I'm with you. OK, the other one I looked at here the face seals leaking on.... Yes, I had a question here. When you refer to face seals, are you looking at the planetary covers?

R; Yes, the sets of seals. There are seals on your planetary that have GX 90 and you have seals in between for your oil cooling ... for your brakes. What happens is that you end up with hydraulic oil into your GX 90, which is into your differential. Your differential fills up, it blows out of the breather, and you're also losing hydraulic tank oil.

P; So ...just out of interest, how are your planetaries cooled? I mean you don't have any separate cooling circuit to the planetary drives?

R; They're not ....these machines are not made for doing any fast travelling. If we were on surface and you're using fourth gear all the time, they would have it set up. For underground, we don't need it. See you have cooling on the brakes. By rights, if you have a cooling brake problem, you can just cap it off... until you fix that problem. You don't really need it.. It's there to cool, but you could eliminate it.

P; OK. That stuff I covered with Mike, so it give some an idea now as to the likelihoods and things that you should check if you observe any of those things. Moving on.... this is the stuff that we covered on Friday here. Sluggish engine response due to a hydraulic problem.... I realise that there are other reasons as to why you'd have loss of engine power as well ....but just from hydraulics alone, a leak at the foot valve or the throttle slave valve there ....and you need to also check the relief valve setting on the treadle valve. But if we look at sluggish engine response, I mean I've got a hydraulic problem here, what else can cause low RPM?

R; Well ....maybe a pump that's relieving all the time ...it's under pressure all the time ... so wanting my engine to rev up, but I'm under load - I have a pump under load let's say. On a JCI set-up where we had valves where we released the pressure for starter purposes - a release on the pumps - otherwise the valves where left on from the accumulators. you get accumulator build-up, you get build up on your pumps, and you come to start it and you say, well, I've got dead batteries or my starters going to much. And what is is you just relieve the pressures on your hydraulics and it takes off on your starter.

P; Right. I'm just thinking here on RPM, you can also have your valve problems...

R; Let's say I have a relief valve stuck, so you know what happens? I go full RPM, I go for full pressure in the hydraulics. I put it to 2200 lbs, OK. As I do that.. if I was to do that on idle without revving it, my engine has a tendency of slowing down, as of stalling. Now if I had a relief valve, in the main control valve, let's say stuck in relief, it would give me low RPM. It would be sluggish on the RPM because my hydraulic systems under pressure ...

P; Right, and so you're actually working it under load.

R; yes. Otherwise you wouldn't be under load, if that relief valve were working properly.

P; OK. I was going to ask you later about stall testing of the engine. I'll move on to that. OK. So then we've moved onto the hoist then, looking at reasons for lack of power in the hoist, for slow hoisting, and I've got two reasons of high likelihood. One is low oil level - you'd check your oil level first - and the second is your port relief valve stuck open, so you're cycling oil through your port relief. That'd give you slow hoisting as well?

R; Yes it would. Also again having checked the stall speed; find out if you've got proper stall speed to start off with.

P; Right, what should your stall speed be?

R; On these ones here? On these, 2150, 2200 roughly.

P; RPM?

R; Yes. Some are a little higher than 2200.

P; Will the engine actually stall out on you if that stage?

R; No... no... In other words, you put your brakes on, put it in second gear, rev it full, that's what it should be reading. That's my ....no that's not my... That's my hydraulic pressure. That's not RPM.

P; Oh that's hydraulic pressure?

R; Yes.

P; OK, that's PSI. OK, so that's what you'd do first. Check that pressure

R; A no load which is full operating should be 2350. See what happens now, let's say I got under load, for whatever reasons. Now what have I got. I've got to put my brakes on and do my load test and I only have 1850, so I'm not getting the proper stall speed. So I'm not getting maximum power under full revs, for whatever reasons it is.

P; Yes, and it may be an engine problem, it may be a convertor problem ....

R; You're revving at 2100 instead of 2400, or whatever the problem could be.

P; Right, although we could check with the RPM gauge to see if you're down from the normal.

R; If I had an RPM gauge, that's why we used to all have the tachometers, OK., now if I was having a problem with the hydraulics, and I could see that my RPM was at 2250 well that's how I'd know that my engine is OK. I've got a problem somewhere else. And if you're used to the machine ...I could actually go outside, and - I have no power, as so I'll go right there as say well, you're engine's not revving high enough. And just by ear ...because after a while you get used to what an engine should be revving at.... or, it's revving too high, it's screaming, it's at 26, 2700. Just because more (indecipherable) doesn't give you more stall speed.

P; Yes, but the other things here, I mean, just to give me an idea as to how frequently these would be the cause...

R; Port relief valve ...

P; Pretty frequent then?

R; Yes it is.

P; So, oil level, port relief then. Worn hydraulic pump you said was low...

R; Yes, very low.

P; Leaking spool in the dump/hoist valve...

R; That again very, very seldom. I don't recall us changing a leaking valve on these machines.

P; OK Leaking/damaged pilot valve?

R; If anything there, is like I say when we had problems in the oil system with dirt or whatever, and it malfunctions the charge valve.

P; OK. Leaking cylinder packing or bypass?

R; Even with a badly leaking cylinder, it doesn't mean that it's going to leak that slowly. It'll leak. As you give it RPM, it's just going to take more oil to do it.

P; If you've got two cylinders ..on is just going to take the load. And again cylinder bypass, the same sort of scenario, I guess.

R; If a cylinder is really bypassing, the other one will just take over.

P; And so you'd get a lot more load on the other cylinder, and you'll end up blowing the seal on that one ...

R; Well, you're heating it up, you're getting too much on it.

P; OK. If hoist is not holding the load, once you've hoisted it up there, I have two main reasons here. One is port relief is leaking, and the second one is cylinder bypass ...

R; Yes.

P; I've got that the most frequent one would be the port relief to check. Causes of slow roll-back ...pretty much the same as we discussed for the hoist up here.

R; Yes.

P; And again, not holding load ..port relief, that's more frequent?.

R; Yes ... port relief valve.... What happens is as soon as you let go of your lever for your roll back, as soon as you let go it should stop, and what it does is it starts rolling back by itself. Going through the port relief ...

P; Ah ... Steering? Slow or sluggish steering response. Again, check your engine stall speed on there, check your oil level, high likelihood of low oil.... leaking or damaged steering hoses are a pretty high likelihood...

R; Yes..

P; OK. Leaking or damage steering valve is low ...

R; low yes.

P; Port relief leaking on your steering?

R; Not very frequent. no. Major problem with the steering is hoses, and the cylinders. Cylinder packing and bypassing or the cylinder itself.

P; Oh OK, that's more of a frequent problem then?

R; Yes. The hoses are number one ...you will get cylinder problems

P; So they'd be the second thing to check ..

R; Yes.

P; Noisy pump ....first you'd check the oil level, whether you've got cold hydraulic fluid if you've just started up, if you've got the right kind of hydraulic fluid, if you have a blocked or damaged suction line...

R; Yes.. yes .

P; That' s pretty common?

R; No, it's not common.

P; OK. Pump in bad order. And if it's noisy at high RPM, you've got a leaking suction line ....Ah, sluggish hoist and dump ...That basically means that you've got a pilot pressure problem..

R; yes ..

P; Or a bad order pump there.. so I'd look at dirt clogging your charge valve, and I've said that's high likelihood, restriction in a sequence valve, that's not as frequent as the charge valve..

R; No ..the charge valve feeds your sequence valve. We have never ...we did it once we diagnosed it as wrong and we went ahead ....it was the charge valve which faulty. the charge valve is what feeds the sequence valve.

P; Yes, as we talked about the other day, the charge valve will collect the dirt first off... Ah leaking or damaged modulator spool in the steering valve, that another possibility?

R; Low, very low..

P; OK, and a bad order pump?

R; Very low.... Biggest problem you're going to get with pumps, major is if you end up with this .

P; No oil and running dry....

R; And if a guy doesn't go and put oil in and say's oh I can get up to here, he's going to blow a pump eventually, or damage the pump. They're pretty tough, these pumps.

P; OK. So that was basically what we covered with the hydraulic system. So you can see the idea. If, behind the instrument panel up there that the guy's looking at, if he's then saying well gee it's really hard to steer when he's teleoperating the thing, he can dial this up and look at these causes. First off check your oil level, check your stall speed and if it's not those you've probably got leaking packing or damaged steering hoses.... So it's onto the transmission. Onto the drivetrain. Again, checking the compiled stats. here ...you've got slippage occurring, traction slippage, when you change gear. So you've probably got a leaking or damaged clutch pack, and it's more likely to be forward, 1st or 2nd.

R; Yes,

P; Anything else could be causing that?

R; Slippage?

P; Yes ...slippage of power when you change gears ...

R; Well, I've never seen it that bad, but, low oil and no oil.... your brakes will come on, you'd have no clutch pressure. So the slippage problem you wouldn't really notice because your brake would come on. You'd have to fix the problem.

P; If you had a leaking clutch pack though, you'd still have pressure to your brakes...

R; But, I think the only time you would probably .....clutch will involve shifting. Let's say it's your 1st clutch pack. As you put it into that clutch pack, it'll cause a slip then. And then it would probably engage and you wouldn't notice it.

P; That's what I'm saying ...when you do change gears that's when you'll notice that it's slipping and that's an indication that you've got a clutch pack that's either faulty or damaged.

R; Yes.

P; OK.. All right. We discussed brakes.... check the oil level. Damaged gravity drain ....if you leak from your gravity drain, that could cause your brakes to come on. Yes ...this is what your guy was complaining about here, is that his brakes were coming on and won't release. And so from the convertor side, I'm looking at low convertor pressure to do that. Convertor temperature high? Low oil level..... Oh sorry, back up here. Brakes won't release. Damaged gravity hose ....that's pretty frequent?

R; Well, not frequent ....but when you get into a problem with this one, you lose your ...you don't have any clutch pressure because you've lost your oil. Or it doesn't drain back fast enough. Or it doesn't drain at all because it's squished ...I've seen a convertor totally squished. So what happens then it all goes to the torque. You have none in the tranny and you lose clutch pressure.

P; OK.... So the main thing to do is check your oil level....

R; That's the main thing, yes, you check the oil level, and if your oil level is low, why is it low? Then you say, OK, I've got a busted hose or whatever, and that's when you might find this...

P; Or a broken pan or whatever ....

R; That's right.

P; Convertor temperature high. Again, low oil level can do that, the same thing. Dirt build up on the cooler ...pretty high frequency?

R; That's very common, yes.

P; OK. Where were we ....we're looking at convertor temperature high. Oil level, dirt build up on the cooler, leaking clutch pack ...leak at the pump ....How about leaks on the transmission cover?

R; That's very uncommon. Never changed a transmission. I don't recall changing a cover on these units.

P; Right. So I've probably covered the majority of reasons there. Loss of convertor pressure? Again oil level ...check oil level. Check the gravity drain pipe there. Anything else can cause you a loss of convertor pressure?

R; No ...if the clutch packs were that bad ...

P; And if the machine is noisy and vibrating a lot ...obviously one cause is a noisy pump, an all the causes that can cause a noisy pump, but we've pretty much covered those before..... But I've also got damaged driveline and damaged differentials, but they're pretty low likelihoods...

R; We don't change drivelines ...not like the other models ..

P; Not at the universal joint, or the sliding spline?

R; very very seldom ...We don't break U joints, on these.

P; OK.... That's basically done the transmission there ... I just wanted to know a little bit more about stall testing the engine, and how you actually would go through a stall test and what you'd be looking for when you did it. If you were going to run a stall test on an engine, how do you go about it?

R; What you do first is you start it up. Leave it in park. Do it in park. Forward gear preferably, but you can do it in another gear. 2nd gear. Put it in 2nd gear. Brakes on. Full RPM. Full RPM, you should run 2150, 2200 RPM.

P; PSI you mean ....pressure?

R; Er no ...Yes PSI yes ...full RPM on your hydraulics yes. And you do the same thing when you do your brake tests. No when you're up to your proper stall speed, you release your brakes, put your foot pedal on for your brakes and do your brakes again.

P; And you have a look at what the engine does ...

R; Well the whole idea is that the machine doesn't move. These here, they've mastered the brake system, with these machines. The machine doesn't move. This machine does not move, when you do the brakes.

P; How about if you were to bring load on with the hydraulic system then? You know. as you say you're in forward ...

R; You can try the same thing with your hydraulic system. What you do is you use your hydraulics for whatever ....so you use your bucket function. Roll back the bucket, relieve it right until it gets to the end, and keep it on for 15 to 20 seconds, and check your oil on your gauge right beside you ..

P; And if you're blowing through a port relief ....well actually you should be through a port relief then when you're right back ...

R; that's right..... The same with your hoist. You can load your hoist up all the way, as far as it will go, and let it relieve, let it go through the relief.

P; So you'd be looking at things like the time ..the time it takes you to lift the hoist as well?

R; Yes. There's a few conditions and that. You might be mucking down below, where your ore is a lot heavier than up here, and an operator is not familiar with the set-up ...but you're lifting this much more weight compared to what you normally lift. And there would be a difference.... This is where they're coming out with these load things, so now you know how much weight you've got on. And if you're having what's on your hoist, let's say you have a cylinder bypass ....the other one's taking over so you will have a slow response, definitely.

P; OK.

(End Tape 2 Side 2).

(Tape 3 Side 1)

P; Now we'll deal with the Deutz engine. And what I have here is the FL 413 fault chart, with a bunch of faults. And again, what we'll do is as we did for the hydraulics. I want you to let me know just how frequently you observe these problems and whether or not you can think of anything else. For example. You start off with the engine being hard to start, and it's given you four reasons for that. Low cranking speed, low compression, insufficient fuel to the engine or insufficient air coming in. So, if your vehicle is hard to start, what would be the avenue that you would explore?

R; Most of the time? The first one.

P; The first one, low cranking speed?

R; Yes. battery problem. What we have a 24 volt system. But it's a 12 - 24 volt system. So what happens, is on our charging system, we always have one battery that gets lower, and that's the one that does the starting ...Instead of having 24 volts, maybe you've only got 22 Volts ...

P; And that 22 volts is enough to make it ...

R; Well it all depends, it all depends. Now when we test it after we've started, you'll get 14 volts on the 12 volt side, and probably 26.5 on the 24 volt side. But when it comes to starting it, what happens there is that we always that one battery on the 12 volt side that has to charge through the other battery ...so it doesn't get as much charging I guess, and that's a common problem with these machines. So we just boost the one battery, and it starts usually.

P; OK. Starter motor problems. Do you ever see that? A defective starter motor?

R; Yes ....I think the most common problem on our system here is sealing problems...

P; Seals on the starter motor getting wet?

R; Getting wet. The back cover for the starter getting wet. It runs on a shaft. And the shaft gets rusted, and then it doesn't want to kick in. And all they do is they take a hammer, they take the cover off and ..tuk ...and then it goes. Or you might get some guy that don't know what they're doing, miners and they'll come along with a scaling bar and hammer the hell out of it ..as far as the cover and that. Just generates more problems for us!

P; So the first thing to check would be your battery ...

R; low battery ..

P; The next one would be your starter motor.

R; Yes ...What you'll hear is that maybe your batteries will give just a big "click", and it doesn't kick in ..

P; And you'll hear your starter motor not turning around ..

R; Yes ..so what you do is pull your cover off, give it a shot, and then your engine goes. That's the most common problems.

P; OK. Low compression ....I gotten here ...valve adjustments or valves sticking or burnt. But you said this is not really the problem with hard starting.

R; No. We don't run into starting problems with the engines with this problem. Or ..OK. fuel. Insufficient fuel, that could be a problem. We're starting now with restrictions in the fuel line, dirty fuel lines. We're starting to get that now. A little bit more common now.

P; I remember that one of the things we say at McReedy all the time was the shut-off solenoid on the fuel ...they had to replace a lot of them. Do you experience that?

R; Not as bad ....I mean after a while ...the solenoid itself, the magnet inside gets weak, and doesn't pull out enough. And then again dirt wise as well. On your linkage to the shut-off. That's medium cause ...

P; Right ..Where abouts on the fuel circuit is that valve actually located?

R; It's right on top of the engine. Right by the injection pump. By the governor.

P; OK. So if that is a problem, it means you've got to pull your injector block out to get to it?

R; Just the hood. It's four bolts.

P; And the coolers as well?

R; Not the coolers ...

P; Oh so you've got access in between the coolers down there?

R; Yes. The pump and that is all in between the coolers. That's another thing when we talk about dirt in your coolers. You have to take that cover off to wash in there ...when you go through the washing process on a service where a guy has a smoking problem or a heating problem, those coolers have to be washed. You've got to take those four bolts off.

P; OK. So number one to check is an electrical problem ...

R; The first one to check is a battery problem because of undercharged battery ...

P; Yes ..but you'd notice that on your charge gauge there .....

R; No ...no The charging system is charging. You're getting 14 volts on your 12 volt side. What happens is it doesn't charge that one battery enough through the 24 volt side. I get a low battery - you might only get 11.7 volts out of the battery ...

P; So you test the voltage across those batteries, is that what you'd do?

R; Yes. We'll go there and put a tester across that battery and say OK 11.7, that's why it's a little bit weak. It should be 12.5 or whatever.

P; Right ....I'm with you. OK. Electrical and then insufficient fuel, probably that shut-off again, a medium likelihood. ..And insufficient air. Well that probably wouldn't stop you from starting, but you'd notice it smoking ?

R; Yes. A big problem, smoking. We have an inner and outer filter. Most times it's always the outer. Change the outer and you can see it, it's dirty. The inner looks new, but we've had times where it looks like it's clean, it looks like it's brand new. You've got gauges. You have them where as you need air, you rev the machine up and your gauges go to green ...

P; Those gauges are actually situated on the filter?

R; On the filter housing ...Your gauge will go red. We had a problem once where we pulled the big filter out and then we looked at the inner filter and, well, we changed the other one, we put a new outer filter. The same problem.... They're turning red. We looked at the gauges, they're turning red. The inner filter looked new, but it was plugged.

P; Right. Insufficient fuel to the engine, well fuel tank empty or ruptured, I guess you wouldn't see that very frequently though? You'd see it empty ...

R; Yes ...That happens ....

P; But ruptured?

R; No. They just bang on the top, the top fittings where the cap goes on where you fill then up ...

P; Right. There's no fuel gauge on those vehicles is there?

R; Yes, there's a gauge in the tanks. There's no fuel gauge in the operator compartment, no.

P; OK. They just check in their tanks. Fuel pressure low due to either air leaks in the circuit or flow obstruction.

R; I guess we're just getting used to the problem of dirty tanks, or maybe restricted hoses. If your hoses are old, they might be collapsed inside the hoses. That type of problem.

P; So you're starting to see those kind of problems now?

R; Especially those lines between your charge pump and injection pump. See now we're getting to a situation where we service a machine every four weeks, which runs into the 250 hours. We don't run into a problem with dirty fuel filters. We're changing them once a month. By rights you could actually probably prolong that, maybe two services. This is the way they want it for their engines. This is what we do. Years ago where we used to run in the stopes and that, you ended up with a lot more problems with filters being plugged.

P; Right. is there a pressure gauge on the fuel? How would you know if your fuel pressure was low or normal?

R; No ...there's no... What you'd notice is you'd come to prime it and you'd have no prime on it. So why haven't I got no prime? Am I sucking air through a hose somewhere? Or have I got fuel? Or is there a restriction in the line?

P; OK. Because it's given us some other options here. Throttle linkage damaged, improperly adjusted ....aneroid valve valve sticking. I don't really know what they mean there ...

R; This is all really low all this. This, I don't know what he means here. You could end up, if you had no pilot pressure. But it would still be starting. But you'd have no throttle.

P; Yes, exactly. No throttle and no other hydraulics. OK...

R; This set up here is infrequent.

P; So that's that ...so normal fuel pressure is infrequent ....and ...

R; Shut-off valve. I mean, that's possible. Very uncommon though. Just by the fuel filters.

P; This is not the same valve as the solenoid valve there?

R; No ...this is fuel shut-off. there is a valve there which shuts your fuel off on your lines coming from the tanks. Near the fuel filters. This is possible, but very unlikely. Where it is, you can't step on it, it's not where somebody can accidentally shut it off.

P; Yes. I think what they were meaning is the solenoid valve near the governor ..

R; that's all sealed under the hood there. that's very uncommon ..

P; All right. Let's go across the page. I think there's about three ..four pages of problems here. OK. Machine lacks power. These are the causes here.

R; Improper engine adjustments. ....Insufficient fuel...

P; Which one of these four here would you look at for starters - engine adjustments, fuel, insufficient combustion air, non-engine related problem?

R; This is very uncommon, non engine related problems. If anything, fuel to the engines. Low fuel. That's probably more common. This one here. Combustion air. Plugged air filters. For the machine to lack power. That would be more of a common one.

P; And so you'd look at your air cleaners for starters and then ..

R; this one here the top one. Improper engine adjustments. Very uncommon. The only thing would be valve adjustments, and we do them every 250 hours. If the machine starts smoking ...we do have the odd machine that smokes. Let's say it probably due for an injector change, or, then again, maybe somebody didn't do the valves the last time, something like that. But we're babying these engines more with the warranty we've got on them... we have 5000 hours on these engines, and we service them every 250 hours. We get no problems, basically.

P; OK. So ..it then talks about exhaust smoke ...looking at different colours ...

R; Black or grey, blue or white ....OK this one here would be the most common right here.

P; Insufficient combustion air?

R; Yes. the filters. That'd be the most common.

P; I just think we'll talk about it smoking, because it's difficult sometimes to tell what type of smoke it is. But what about cylinder skirts leaking and getting oil going into your combustion chamber?

R; Not too often ...The only thing is that we get an oil leak onto the exhaust, and then it smokes. But as far as ....we don't actually have much problem with the O-rings on the plungers, your push rods which will put oil into your cylinders. Not with these ones. Not with these 413's Very very seldom.

P; Do you get leaking oil filters?

R; Are you talking about transmission filters?

P; Well, if it's smoking and your transmission filter is leaking?

R; Yes, that could be a cause.

P; But what about if the lube oil filter was leaking?

R; It leaks, but that's lower. It's right down low and is not going to drop on the exhaust. You're not smoking from there.

P; OK. I think that covers exhaust analysis, cause of smoking in general. Excessive crankcase pressure.

R; Cylinder blow-by, breather restriction, excessive exhaust back pressure. ..

P; How are you going to know when you've got excessive crankcase pressure? Is it going to blow out the breather?

R; Yes. It will be coming out of the dip stick. It'll be smoking through the dip stick. Or through your oil filter. It'll be blowing out of there and smoking there. That's were you find blow by. This new engine right over here. we had no oil pressure. We found out we had no oil pressure. Well when we had that thing running, which was a very short period of time, we had blow by ...smoke coming out of the filter cap really bad. Really really bad.

P; Do you know what the cause of that is?

R; No we don't know what the cause is. It hasn't been sent out yet.

P; But have you got any ideas?

R; Ah ..no oil pressure at all. Now maybe the pipe was off inside on your oil pump. Maybe there's no oil pump on there. I don't really know what it is, but there's definitely damage to that engine.

P; So you'll send it off and have it looked at ..

R; yes.

P; OK. Breather restrictions on the crankcase. Plugged breathers. Do you see that?

R; No. not too often, no. ...Excessive exhaust back pressure, no.

P; You don't get many blockages in your exhaust at all ...

R; No.. no..

P; All right. Low engine oil pressure. It says here that the engine must be at normal operating temperature, but you've got low engine oil pressure. Causes ...oil... low oil level, incorrect oil viscosity or oil dilution, injector pump leaking or charging pump leaking into the oil system. Circulation ...filters clogged.

R; These we've had them three years and we haven't had many problems.

P; Have you had to replace any engines?

R; On these? Yes, we've done one, two, maybe three. We were having a problem in your gear drive which drives your injection pump. There's been wear in there. In fact we did number two and number three about a month ago.

P; So that would be a design fault?

R; Ah ..yes. We talked to Peter of KHD and he said that shouldn't be. He showed me the parts. We're definitely getting wear and that shouldn't happen. And this is also in your timing set-up.

P; And you noticed that in your timing ..?

R; Not the idea of having bad timing, but just the idea of having noise in your gear train, and your gears were worn, and I said I know there's play in there, because your gears are worn. But otherwise. that's a problem that you shouldn't be getting. Like we've done two, I think three up to now. In fact, we changed the whole engine on one, number 12 in fact, down below. And this is all again warranty.

P; Right... That's interesting. Do you ..I mean how frequently would you have to send an engine back to the divisional shops?

R; We haven't with these.

P; I mean, what kind of work do you do here? Do divisional shops recondition engines totally?

R; They rebuild the engines. If we had a major problem ...these are new machine. These are all new machines, and we had a warranty up to 10000 hours, and we haven't had any problems.. Again, number 12, we changed an engine at 1500 hours ....bad gear train for the injection pump. And we did another one on that same machine. So it lasted 3500 hours. For whatever reason. We shouldn't be getting this problem. So then we turn around, we did number 2, and number 3 where we changed the gears. Went in there, pulled it apart because there was a noise and we did that so we didn't end up changing the engine.

P; But low oil level in the sump there ...do you see that?

R; No. We haven't changed a pan in one of these machines yet.

P; But low oil level, just burning oil or losing oil?

R; We do have some where you might end up with low oil either through a hose or leaky filter or an operator doesn't tell us about the filter .. and the filters are actually leaking and you're losing oil. But otherwise.... or through the oil coolers. We do a share of oil cooler changes ...

P; Unscheduled, outside of the regular service?

R; That's right.

P; So if I looked at my oil pressure gauge and it was low. What would be my most likely cause? What would be the course of action that you'd take? What would be the first thing that you'd look at?

R; If my engine oil pressure was low? First of all, is my gauge reading properly? why would I do something unless I really know that this gage is right? I would probably put another gauge on it just to make sure. Just tap into it, with a hose ...

P; Right...

R; Same thing we did here when this engine was blown ...Ah, again oil level . If I have a really bad low oil level, I'm going to have low oil pressure. Then from there I'd go to the filters ...How are my filters?

P; Yes ...but there is a bypass on those filters anyway, so if they get clogged you'll still get oil ...

R; Yes, that's right.

P; You haven't seen worn crankshaft bearings at all?

R; No ..none at all. Oil pump again ....very low, very low on these engines, the 413's.

P; OK. High lube oil consumption. You're going through a lot of it. What have we got. It gives us external leakage, internal leakage ....

R; If anything, you might get the odd external leakage. Through your valve cover gaskets.

P; Through your valve cover gaskets or through the oil filter?

R; Yes, through your oil filter. That's probably the most common. Otherwise ...internal leakage, through the seals, no ...we've never done one.

P; It's more going to be an external leakage problem.... Excessive air cleaner restriction ..how would that cause a high lube oil consumption?

R; Well, if the engine is working, if it was very excessive, in other words it probably ran for a long period of time ...smoking ..

P; Oh I see and it sucks oil through the cylinders ...OK. Onto the last page of engine problems. High engine oil temperature. The first thing here, you've got two cylinder head gauges... temperature gauges. Do you have another oil temperature gauge as well as that on the dash?

R; No.

P; OK. So what we're really looking at here is not really oil temperature but cylinder head temperature and what the likely cause of running a hot engine are.

R; That's right.

P; Now if your engine is overheating, what would you look at for starters? I guess number one thing, you'd look at oil level...

R; Yes, oil level. This is the most common one. This one here. Dirt build up on the cooler. Then again, oil cooler blockage, the oil cooler ...

P; Oil cooler blockage? That's dirt blocking the oil cooler?

R; Yes

P; So that's what, a medium likelihood thing compared to dirt build up on the cooler?

R; Overheating? Most likely your transmission coolers are plugged, that'll give you high temperature on your gauges than your engine oil cooler blockage .....

P; Oh that will actually show on the cylinder head temperature as well?

R; Yes... This is the most common cause of having high temperature on these gauges. Dirt build up on your transmission coolers.

P; Now I noticed when I was going through these schematics here, there's actually a temperature thermostat that controls the oil flow to the blower coupling. ...and is this is regulating the flow of oil to your cooler coupling, so your fan speed is regulated by engine temperature. Do you ever see problems with that thermostat?

R; No ...never. Never run into that problem. Also a sender, as far as temperature senders, there's also one at the housing for the filters here. We put one in right here. And it runs in through your cylinder head senders into your warning system here.

P; So that's looking at oil temperature there, on the filter bank ...Yes, you could run cold up here and not pick up high temperature down the bottom.

R; You also have your sender on your torque, on your downstream valve, as well. That'll be on your gauge for your torque temperature gauge, not on your engine cylinder gauge.

P; Right.. OK. Excessive vibration of the engine, and it gives you internal and external sources here. Just dealing with the internal sources. Broken mounting bolts, broken or loose cooler frames .. you said that was pretty common.

R; Yes... cooler frames, yes.

P; Engine mounts?

R; Engine mounts, yes that's pretty common. ..Worn blower bearing.... that another one we do.

P; Do you see that at all?

R; I think the major thing there is that we don't pre-service it, where you should be changing the buffer, rubber buffers they're called ...so they wear out, and eventually you end up with play in the bearing, because your bearing goes. So we've talked about it ...we should be changing these rubbers, the buffers more often, eliminating the wear on the bearings.

P; I'm with you. So probably the most frequent are broken mounts, and then the blower. But you'd be able to pick up a loose blower by listening to the blower ....

R; Oh yes you'll hear it ...

P; OK. improper engine adjustments, your valves. You said that was not as much as a problem with the services that you're doing. OK.

(End Tape 3 Side 1)

(Tape 3 Side 2)

P; OK It is Thursday 22nd April and I'm talking to Rick Mayette about the electrics, and troubleshooting the electrics on the ST-8B. If we start here and look at the problems that are listed. Low charging or no charge at all. First of ...what's the most likely problem that we're looking at here?

R; Too low or no charge at all?

P; Yes, not charging. It says bad order alternator, bad order battery ...

R; defective battery will only be after you have a problem ...

P; So you'd check your battery first.

R; Yes, yes.

P; So you'd check your battery first. If your battery voltage wasn't up to spec., you'd know that you had a battery problem ...

R; That's right.

P; These are lead acid batteries in there?

R; Yes.

P; So you've got to look at your water level there in case they've dried out a little bit. How frequently do you get defective alternators?

R; Ah ..maybe medium ....and before you end up with this problem, you probably end up with more or less power problems, to the alternator, down the line, master switch... it all relates back through the charging system.

P; OK. Your master switch is on your charging.....

R; Your master switch is on your..... If you're not getting proper charging from your alternator to the batteries, it because your master switches are not .. You're having problems with the master switches so you're not getting proper charging in the batteries, and you've got a bad battery because of the master switches. That's fairly common.

P; OK. But those master switches are located where? Are they actually on the dash?

R; That's right. Right as you sit down, right above the tranny compartment.

P; OK. So you switch those off to isolate the electrical circuit if you do any work on the electrical circuit ....

R; That's your shut-off, your main shut-off. You've got your key, those are your main shut-off. One is for your 24 volt side, the other one is for your 12 volt side. And you turn them both on, then you turn your key on.

P; Right. Is that standard practice to turn those off when you come off a scoop?

R; Oh definitely. Yes, definitely.

P; OK. I guess ...what's the most common type of electrical fault that you deal with? Probably damaged wiring ...

R; Yes. Most times wiring close to the alternator. At the alternator itself, because it's exposed. And then your connections. They have the quick couple.

P; Yes, I've got those on the ele..rical diagrams. Electrical sockets ..

R; Sockets ..we're starting to get problems in there. There's one in the dash. They get loose, and they have a problem inside. We've had to do a few changes were we've spliced them and eliminated them.

P; OK. If your charging voltage is too high. Do you ever see that?

R; Yes. That happens. Not very frequently though. More of a problem low ...not enough charging.

P; If it was charging too high, what would you look at? What is your troubleshooting reason there?

R; The alternator itself. The regulator in the alternator.

P; So to do that you actually replace the whole alternator itself?

R; Yes, It's built in.

P; OK. Because the other one they give here is incorrect pulley used on generator, if it's too tight or something like that ..

R; No. We don't see that.

P; Ah ...The battery going throug: an excessive amount of water - charge rate too high ...also hot conditions, I guess. Or a leak in the battery

R; There're at a fairly good spot. There're right at the top of the machine. Charging rate too high, that would be the most common possibility.... but like I say we don't run into it too often. We change alternators because they're not charging... we're not getting too high a charge.

P; Yes, low is more common.

R; Yes.

P; If you've got low alternator output, what's your troubleshooting rational?

R; Low alternator?

P; An alternator problem, the brushes ...

R; Yes, you're running into wear of the alternator brushes.

P; You have to replace the alternator?

R; Yes, you replace the alternator. You will end up with - if anything low - belt slippage. Pulled belts, or worn belts which will give you more of a low output.

P; Right, so the thing to do there is to test your belts ..

R; Yes. Make sure your belts are good. Go with the wires down the line, and maybe there' s only a stator wire holding it so you're not getting enough charge through the wire.

P; OK. If we can just go back up here. If your starter motor is not working at all ...battery discharged.

R; Battery discharged ...that's it. One of the batteries we have a problem with in these scoops, one of the batteries doesn't get the full amount of charge. Especially on the 12 volt side, because it charges through the 24 volt battery side first, and the 12 volt battery gets less charge so you end up with a leaked battery, and that's where you have starting problems.

P; Right ...and the other ones are the water problems which we talked about the other day, when we talked about rusted starter motors, and you have to take the cover off and give it a bit of a nudge.

R; Yes ...yes. Ah ...defective solenoid. That's not too common, but it does happen

P; That's the starter solenoid? The 24 volt starter solenoid?

R; When they say solenoid, that's part of the solenoid in the dash you're talking about. I don't thing you're talking ...

P; I though they were referring to ....here ...

R; It says here, defective cranking motor.

P; Here I thought that what they were referring to is that there is a solenoid that clicks the starter cog into place.

R; That's the one on the starter itself ...it's built right in.

P; So what happens when the motor is actually up and running then? Your starter is still connected?

R; No ... there is a starter. But there's s a point set-up inside with a shaft that kicks in. It's a solenoid basically, but it's built into the starter.

P; That's what I thought they were referring to there.

R; Defective solenoid ...they may be talking about that, but then again when you're talking.... now you're talking defective cranking motor.

P; Exactly, so you replace your starter motor.

R; We do have solenoids besides that in the electrical switching box, which goes when you're cranking over like on the 24 volt side, to crank it, it opens that solenoid up to give you 24 volts

P; OK, so that could also be ...

R; It's a 12 volt system, OK. You're running a 12 volt starter button, which kicks in the solenoid, and it throws in the 24 volts through that solenoid. There's a solenoid for the starting, plus there's a solenoid for the preheating, which runs off your preheat button.

P; And they're two separate solenoids ...

R; Yes.

P; OK. No lights, or lights are dim. Check your batteries. Loose connections or poor ground ..Same thing, that's a connection problem again

R; Yes..

P; Electrical gauges defective ...

R; Sensor defective ..Bad connection or connector plug. a gauge is not normally. Temperature gauge. As far a sensors, we have more problems with sensors because you're getting the heat right off the engine ..

P; Because it runs out of calibration or burns out ...

R; Yes.... but as far as gauges are concerned, not too often.

P; Sounds likely to check your connections. I think I remember Paul looking at an electrical problem on a scooptram one day and it was actually one line that supplies power to the gauges ..No. 6 line or No. 7.

R; It was your main power line, and it was in your box, on the top of the scoop, and he had power when he tested, he had power, but he didn't have enough power through the connection.

P; OK. It was the connector plug again?

R; It was the connector plug. Once he hooked it on then he had enough power. See what we normally do is you have a 12 volt side and a 24 volt side. Now when you check your 12 volt side and you're getting 12 volts plus, 12.25 or 12.5, and, on the same thing when you're on the 24 volt side, what am I getting? I should be getting ...like on the 12 volt side you're going to be charging 13.5. on the 24 volt side you're going to be getting 26.5. If I test it at the alternator, and I'm only getting 22.5, I'm not even getting my 24 volts to start with? So where is the problem? Now it could be all the way down the line. It could be master switches, it could be the cross-over solenoids, it could be quite a few problems. Or again it could be alternator again.

P; OK. What have we got here ...ignition on, no gauges or lights. Check battery, check connections from battery to ammeter.... Why are they talking about ammeters? There's no ammeter in the circuit!

R; It says ignition on. No gauges or lights working. Again you've got two master switches. The 24 volt side ..now it could be the other master switch not running. Then you could turn the key on and still get no power.

P; OK So it could be a faulty master switch. How frequently does that happen?

R; They get a lot of heat ...we had better ones when they originally came, now I think we have an 850 output out of them ...850 instead of a 450 or a 550, and we have lots of problems now. We always have problems. Scoop won't start. Scoop won't start. And all the time it was losing voltage through the master switch.

P; No electrical gauges or lights working - we've just gone through that.

R; Loose connection between ammeter and switch ...bad light switch. Then again you've got wiring in general. You have plugs.. eh ...rubber harness plugs, so that when you open the machine they have different sections where you can actually take the whole harness plugs ...where you ended up by cutting them before. Muck falls down, into the hoses, pulled on the hoses, pulls on the plugs in the midships and pulls then all inside the boom area...

P; That's a fairly common ....

R; Yes. Yes ..the front lights.

P; OK. That's handy to know. OK. You've got all your electrical gauges but you've got no lights... and that would be a cause there. You've got rocks and muck falling down pulling the connecting plugs...

R; Yes.. here with your all your lights, you have breakers ...we've had some problems with those breakers. They're fairly good, but you've got lots of power going through, lots of heat. They'll click off and that's what shuts off your power going to your light switch. It's your light breakers..

P; That's run through that fairly well. I just want to pull out the schematics because I want to locate these solenoids ...

R; With these solenoids there's a box in the back behind the engine. You have your breakers, your breakers, these are 15 amp and 25 amps. What you have are your main breakers your 60 amp and 80 amps ..

P; And if that goes ....

R; You reset them. You just push that button and reset them. There's your preheat ...

P; Ah ...there's one solenoid ...

R; Yes ...and there's your starter solenoid.

P; OK. Also shown on this diagram here is this parking brake interlock, but, is that the true place? I think that that goes to your relay valve which is just past your solenoid on the brake circuit.

R; Yes. I'm trying to figure out which one this is here. Isn't that just the park brake solenoid itself?

P; Yes ..so your park brake solenoid is basically hooked to that relay valve in the brake circuit?

R; Yes

P; So these are your two master switches here ..right ..one and two?

R; Yes.

P; <u>But I was talking to Paul the other day and he was saying that they actually had switched the position of this master switch</u> ...

R; Yes ...yes. We had a problem with batteries blowing.

P; yes, I scribbled that out, and pulled that across here, and now it's in this circuit here.. because that's on your 12 volt circuit there, and this is on your 24

R; The old ..when they first came out, to get the 24 volts, they had what you called a parallel switch with this box ....and now they actually hook up the batteries and just have a solenoid in between. So when you push your starter button, it opens a solenoid and it automatically gives you 24 volts.

P; OK. That's on the newer ...the B's. That probably going to give me enough to chew on for a while, but another thing I wanted to ask you was ...how many years have you been working for Inco?

R. <u>I'll be going on to my 25th year</u> ....

Appendix 5:

Expert System Demonstration Prototype

Expert System Demonstration Prototype

Filename; ST8B.knw
Author; P.F.Knights.
Description; Expert system for diagnosing loss of steering faults
Last Revised; June 15 1994.

```
Object
@name = fault
@attribute = condition.excessive_noise, condition.no_steering, condition.oil_overheating,
        condition.pulls_to_one_side, condition.slow_or_erratic_steering
endObject

Object
@name = hydraulic
@attribute = circuit.dump_hoist, circuit.hydraulic_throttle, circuit.SAHR_brakes,
        circuit.steering, circuit.@string
endObject

Object
@name = lhd
@attribute = identification.unit_804, identification.unit_805, identification.unit_806
endObject

Object
@name = ST8B
@subObject = hydraulic
@attribute = problem.drivetrain, problem.electrical, problem.engine,
        problem.hydraulic
endObject

Procedure
@name = diagrams
@do =
 MACRO ( "diagrams_*" )
 FREERULE ( $Rule, "diagrams_*" )
endProcedure

Procedure
@name = notes
@do =
 MACRO ( "notes_*" )
 FREERULE ( $Rule, "notes_*" )
```

```
endProcedure

Procedure
@name = welcome
@do =
 PAINT ( "welcome.bmp", "Click Remove to begin a consultation session" )
 ASK ( "Select the LHD unit which is malfunctioning", lhd.identification.unit_804 )
 APPLYRULE ( "ST8B.problem.*" )
endProcedure

Question
@name = Select_hydraulic_subcircuit
@userlevel = 1
@do =  ASK ( "Which one or more of the following subcircuits are malfunctioning?",
hydraulic.circuit.steering )
endQuestion

Question
@name = Subsystem_choice
@userlevel = 1
@do =  ASK ( "Select the subsystem which is malfunctioning;", ST8B.problem.engine )
endQuestion

Exclusive
@name = exclusive_lhd_unit_number
@state = unit_804, unit_805, unit_806
endExclusive

Exclusive
@name = problem_type
@state = engine, drivetrain, hydraulic,
      electrical
endExclusive

Exclusive
@name = select_steering_fault_condition
@state = no_steering, slow_or_erratic_steering, pulls_to_one_side,
      oil_overheating, excessive_noise
endExclusive

Multichoice
@name = select_faulty_hydraulic_circuits
@state = dump_hoist, steering, SAHR_brakes,
      hydraulic_throttle
endMultichoice
```

```
Rule
@name = diagrams_steering
@priority = 2
IF  hydraulic.circuit.@string is "steering"
THEN RUN_CONTINUE ( "steering.knw" )
endRule

Rule
@name = hydraulic_brakes
@priority = 2
IF  hydraulic.circuit.steering is FALSE
AND  hydraulic.circuit.dump_hoist is FALSE
AND  hydraulic.circuit.SAHR_brakes is TRUE
THEN hydraulic.circuit.@string = "brake"
THEN TEXT ( "A problem has been identified in the SAHR brake circuit." )
THEN DISPLAY ( "hydraul", "start" )
THEN HALT ( )
endRule

Rule
@name = hydraulic_dump_hoist
@priority = 2
IF  hydraulic.circuit.steering is FALSE
AND  hydraulic.circuit.dump_hoist is TRUE
AND  hydraulic.circuit.SAHR_brakes is FALSE
THEN hydraulic.circuit.@string = "dump-hoist"
THEN TEXT ( "A problem has been identified in the dump-hoist circuit." )
THEN DISPLAY ( "hydraul", "start" )
THEN HALT ( )
endRule

Rule
@name = hydraulic_general
@priority = 2
IF  hydraulic.circuit.SAHR_brakes is TRUE
AND  hydraulic.circuit.dump_hoist is TRUE
OR  hydraulic.circuit.SAHR_brakes is TRUE
AND  hydraulic.circuit.steering is TRUE
THEN hydraulic.circuit.@string = "hydraulic"
THEN TEXT ( "A general problem has been identified with all hydraulic circuits." )
THEN DISPLAY ( "hydraul", "no_flow" )
THEN HALT ( )
endRule
```

```
Rule
@name = hydraulic_pump
@priority = 2
IF   hydraulic.circuit.steering is TRUE
AND  hydraulic.circuit.dump_hoist is TRUE
AND  hydraulic.circuit.SAHR_brakes is FALSE
THEN hydraulic.circuit.@string = "steering & dump-hoist"
THEN TEXT ( "A problem has been identified in the steering and dump-hoist circuits." )
THEN DISPLAY ( "hydraul", "noisy_pump" )
THEN HALT ( )
endRule

Rule
@name = hydraulic_steering
@priority = 2
IF   hydraulic.circuit.steering is TRUE
AND  hydraulic.circuit.dump_hoist is FALSE
AND  hydraulic.circuit.SAHR_brakes is FALSE
THEN hydraulic.circuit.@string is "steering"
THEN ASK ( "Which of the following best describes the behaviour of the steering system?",
fault.condition.no_steering )
THEN MACRO ( "steering_*" )
endRule

Rule
@name = hydraulic_throttle
@priority = 2
IF   hydraulic.circuit.hydraulic_throttle is TRUE
AND  hydraulic.circuit.steering is FALSE
AND  hydraulic.circuit.SAHR_brakes is FALSE
AND  hydraulic.circuit.dump_hoist is FALSE
THEN hydraulic.circuit.@string = "hydraulic throttle"
THEN TEXT ( "A problem has been identified in the hydraulic throttle circuit." )
THEN DISPLAY ( "hydraul", "start" )
THEN HALT ( )
endRule

Rule
@name = notes_unit804
@priority = 2
IF   lhd.identification.unit_804 is TRUE
THEN ACTIVATE ( "c:\os2\apps\epm c:\comdale\unit804.log" )
endRule
```

```
Rule
@name = notes_unit805
@priority = 2
IF  lhd.identification.unit_805 is TRUE
THEN ACTIVATE ( "c:\os2\apps\epm c:\comdale\unit805.log" )
endRule

Rule
@name = notes_unit806
@priority = 2
IF  lhd.identification.unit_806 is TRUE
THEN ACTIVATE ( "c:\os2\apps\epm c:\comdale\unit806.log" )
endRule

Rule
@name = ST8B_drivetrain
IF  ST8B.problem.drivetrain
THEN TEXT ( "The drivetrain fault detection module is currently under development",
"drivetrain" )
THEN HALT ( )
endRule

Rule
@name = ST8B_electical
IF  ST8B.problem.electrical
THEN TEXT ( "The electrical fault detection module is currently under development",
"electrical" )
THEN HALT ( )
endRule

Rule
@name = ST8B_engine
IF  ST8B.problem.engine
THEN TEXT ( "The engine fault detection module is currently under development", "engine" )
THEN HALT ( )
endRule

Rule
@name = ST8B_hydraulic
IF  ST8B.problem.hydraulic
THEN MACRO ( "hydraulic_*" )
endRule
```

```
Rule
@name = steering_nosteer
IF   fault.condition.no_steering is TRUE
THEN LOAD ( "nosteer.knw" )
THEN RUN_CONTINUE ( "nosteer.knw" )
THEN UNLOAD ( "nosteer.knw" )
THEN HALT ( )
endRule

Facets
@triplet = fault.condition.excessive_noise
@exclusive = select_steering_fault_condition
endFacets

Facets
@triplet = fault.condition.no_steering
@exclusive = select_steering_fault_condition
endFacets

Facets
@triplet = fault.condition.oil_overheating
@exclusive = select_steering_fault_condition
endFacets

Facets
@triplet = fault.condition.pulls_to_one_side
@exclusive = select_steering_fault_condition
endFacets

Facets
@triplet = fault.condition.slow_or_erratic_steering
@exclusive = select_steering_fault_condition
endFacets

Facets
@triplet = hydraulic.circuit.dump_hoist
@multichoice = select_faulty_hydraulic_circuits
@question = Select_hydraulic_subcircuit
endFacets

Facets
@triplet = hydraulic.circuit.hydraulic_throttle
@multichoice = select_faulty_hydraulic_circuits
@question = Select_hydraulic_subcircuit
endFacets
```

Facets
@triplet = hydraulic.circuit.SAHR_brakes
@multichoice = select_faulty_hydraulic_circuits
@question = Select_hydraulic_subcircuit
endFacets

Facets
@triplet = hydraulic.circuit.steering
@multichoice = select_faulty_hydraulic_circuits
@question = Select_hydraulic_subcircuit
endFacets

Facets
@triplet = lhd.identification.unit_804
@exclusive = exclusive_lhd_unit_number
endFacets

Facets
@triplet = lhd.identification.unit_805
@exclusive = exclusive_lhd_unit_number
endFacets

Facets
@triplet = lhd.identification.unit_806
@exclusive = exclusive_lhd_unit_number
endFacets

Facets
@triplet = ST8B.problem.drivetrain
@exclusive = problem_type
@question = Subsystem_choice
endFacets

Facets
@triplet = ST8B.problem.electrical
@exclusive = problem_type
@question = Subsystem_choice
endFacets

Facets
@triplet = ST8B.problem.engine
@exclusive = problem_type
@question = Subsystem_choice
endFacets

```
Facets
@triplet = ST8B.problem.hydraulic
@exclusive = problem_type
@question = Subsystem_choice
endFacets

!*** LoadStrategy must go at the end of the Knowledge Base ***!
LoadStrategy
@name = "st8b2.stg"
EndLoadStrategy
```

```
Filename;      nosteer.knw
Author;        P.F.Knights.
Description;   Expert system for diagnosing loss of steering faults
Called by;     ST8B.knw
Last Revised;  June 20 1994.

Class
@name = other
@object = failure
endClass

Class
@name = unit
@object = unit1, unit2, unit3
endClass

Object
@name = failure
@class = other
@attribute = cause.found, cause.@string, hypothesis.@string,
        threshold.@integer
endObject

Object
@name = unit1
@class = unit
@attribute = fail_freq.@integer, status.suspect
endObject

Object
@name = unit2
@class = unit
@attribute = fail_freq.@integer, status.suspect
endObject

Object
@name = unit3
@class = unit
@attribute = fail_freq.@integer, status.suspect
endObject

Procedure
@name = initial_procedure
@do =
 failure.cause.found is FALSE
```

```
 failure.hypothesis.@string is "none"
 failure.threshold.@integer is 100
 IMPORT ( "failfreq.dat", 0, 100 )
endProcedure

Procedure
@name = notes
@do =
 ACTIVATE ( "c:\os2\epm unit804.log" )
endProcedure

Fuzzy
@name = unit1_conf
@source =  unit1.fail_freq.@integer
@range = 3
@value = 0.000000, 50.000000, 100.000000
@rank = 0.000000, 100.000000, 100.000000
endFuzzy

Fuzzy
@name = unit2_conf
@source =  unit2.fail_freq.@integer
@range = 3
@value = 0.000000, 50.000000, 100.000000
@rank = 0.000000, 100.000000, 100.000000
endFuzzy

Fuzzy
@name = unit3_conf
@source =  unit3.fail_freq.@integer
@range = 3
@value = 0.000000, 50.000000, 100.000000
@rank = 0.000000, 100.000000, 100.000000
endFuzzy

Rule
@name = CYCLE
IF   ( failure.cause.found is FALSE )
OR   UNKNOWN ( failure.cause.found )
AND  failure.threshold.@integer > 10
THEN failure.threshold.@integer = failure.threshold.@integer - 10
THEN ASNTHRESHOLD ( failure.threshold.@integer )
THEN FREERULE ( $Rule, "test*" )
THEN MACRO ( "test*" )
THEN FREERULE ( $Rule, "free_cycle_rule" )
```

```
THEN GOTO ( "free_cycle_rule" )
endRule

Rule
@name = end_rule
IF   failure.cause.found is TRUE
THEN failure.cause.@string is failure.hypothesis.@string
THEN TEXT ( "Thankyou for using the Expert System" )
endRule

Rule
@name = free_cycle_rule
IF   failure.cause.found is FALSE
OR   UNKNOWN ( failure.cause.found )
THEN FREERULE ( $Rule, "cycle" )
endRule

Rule
@name = start
IF   TRUE
THEN RUN_PROCEDURE ( "initial_procedure" )
THEN GOTO ( "cycle" )
endRule

Rule
@name = test_unit1
IF   unit1.status.suspect is TRUE
THEN failure.hypothesis.@string is "unit1"
THEN DISPLAY ( "nosteer", "unit1" )
THEN ASK ( "Was the failure cause due to a fault in unit1 ?", failure.cause.found )
THEN unit1.status.suspect is FALSE
endRule

Rule
@name = test_unit2
IF   unit2.status.suspect is TRUE
THEN failure.hypothesis.@string is "unit2"
THEN DISPLAY ( "nosteer", "unit2" )
THEN ASK ( "Was the failure cause due to a fault in unit2 ?", failure.cause.found )
THEN unit2.status.suspect is FALSE
endRule

Rule
@name = test_unit3
IF   unit3.status.suspect is TRUE
```

```
THEN failure.hypothesis.@string is "unit3"
THEN DISPLAY ( "nosteer", "unit3" )
THEN ASK ( "Was the failure cause due to a fault in unit3 ?", failure.cause.found )
THEN unit3.status.suspect is FALSE
endRule

Facets
@triplet = unit1.status.suspect
@fuzzy = unit1_conf
endFacets

Facets
@triplet = unit2.status.suspect
@fuzzy = unit2_conf
endFacets

Facets
@triplet = unit3.status.suspect
@fuzzy = unit3_conf
endFacets

Ruleset
@name = test_rules
@rule = test_unit3
endRuleset

!*** LoadStrategy must go at the end of the Knowledge Base ***!
LoadStrategy
@name = "nosteer.stg"
EndLoadStrategy
```

Filename; nosteer.doc
Author; P.F.Knights.
Description; Expert system for loss of steering faults
Called by; ST8B.knw
Last Revised; June 20 1994.

\bt\
\nt[unit7]\
\h2.Unit7 - Steering Cylinders & Return Line to MSV\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@sS!

\c5\\jt[unit7].No Steering Movement\
\c1\\ep[testunit7].testunit.bmp\
\jt[unit6].No pressure delivery from MSV \ \c9\ Bind in linkage
\c9\ Broken piston rod
\c9\ Return line plugged
\c9\ External leak

\ep[exit].btnnext.bmp\ \ep[pic_unit7].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit6]\
\h2.Unit6 - Main Steering Valve & Return Line to Reservoir\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@sS!

\c5\\jt[unit7].No pressure delivery to cyl.s\
\c1\\ep[testunit6].testunit.bmp\
No pressure from \jt[unit4].Sequence Valve\ \c9\ Main RV stuck open
or \jt[unit5].Pilot Circuit \ \c9\ Compensator spool sticking
\c9\ Main spool sticking
\c9\ Valve orifice plugged
\c9\ External leak

\ep[exit].btnnext.bmp\ \ep[pic_unit6].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit5]\
\h2.Unit5 - Pilot Control Valve & Pilot Line\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@s$!

\c5\\jt[unit6].No pilot pressure to MSV \
\c1\\ep[testunit5].testunit.bmp\
\jt[unit4].No pressure from seq. valve\ \c9\ Defective spool movement
\c9\ Valve orifice plugged
\c9\ Pilot line plugged
\c9\ External leak

\ep[exit].btnnext.bmp\ \ep[pic_unit5].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit4]\
\h2.Unit4 - Pilot Sequence Valve & Line to MSV\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@s$!

\c5\\jt[unit6].No pressure delivery to MSV \
\c1\\ep[testunit4].testunit.bmp\
\jt[unit3].No pressure delivery from pump\ \c9\ Valve spool stuck closed
\c9\ External leak

\ep[exit].btnnext.bmp\ \ep[pic_unit4].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit3]\
\h2.Unit3 - Tandem Pump & Line to Sequence Valve\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@s$!

\c5\\jt[unit4].No pressure delivery\
\c1\\ep[testunit3].testunit.bmp\
\jt[unit2].No fluid delivery from suction line\ \c9\ Broken shaft or coupling
\c9\ external leak

\ep[exit].btnnext.bmp\ \ep[pic_unit3].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit2]\

\h2.Unit2 - Suction Filter & Suction Line to Pump\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@s$!

\c5\\jt[unit3].No fluid delivery\
\c1\\ep[testunit2].testunit.bmp\
\jt[unit1].No oil delivery from tank \ \c9\ Plugged strainer screens
\c9\ Suction line plugged

\ep[exit].btnnext.bmp\ \ep[pic_unit2].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[unit1]\
\h2.Unit1 - Reservoir & Hydraulic Fluid\

System Fault Condition;\c4\no movement
Current hypothesis;\c4\!$failure.hypothesis.@s$!

\c5\\jt[unit2].No fluid delivery\
\c1\\ep[testunit1].testunit.bmp\
External failure cause \c9\ Low oil level

\ep[exit].btnnext.bmp\ \ep[pic_unit1].btnschem.bmp\ \ep[pic_block].btnblock.bmp\
\ep[log].btnlog.bmp\

\bt\
\nt[testunit7]\
TEXT ("Check MSV outlet delivery pressure")

\bt\
\nt[testunit6]\
TEXT ("Feel MSV for excess heat casued by internal leakage")

\bt\
\nt[testunit5]\
TEXT ("Insert pressure gauge in pilot circuit. Check pilot pressure")

\bt\
\nt[testunit4]\
TEXT ("Insert pressure gauge before MSV. Check for delivery pressure.")

\bt\
\nt[testunit3]\

```
TEXT ("Insert pressure gauge after tandem pump. Check delivery pressure.")

\bt\
\nt[testunit2]\
TEXT ("Check for clogged strainers. Lint indicates worn piston packing and metallic chips
indicates scored cylinders or worn pump components.")

\bt\
\nt[testunit1]\
TEXT ("Check oil level. Check for cracks. Check for clean oil.")

\bt\
\nt[pic_unit1]\
PAINT ("steer_08.bmp")

\bt\
\nt[pic_unit2]\
PAINT ("steer_02.bmp")

\bt\
\nt[pic_unit3]\
PAINT ("steer_03.bmp")

\bt\
\nt[pic_unit4]\
PAINT ("steer_04.bmp")

\bt\
\nt[pic_unit5]\
PAINT ("steer_06.bmp")

\bt\
\nt[pic_unit6]\
PAINT ("steer_05.bmp")

\bt\
\nt[pic_unit7]\
PAINT ("steer_07.bmp")

\bt\
\nt[pic_block]\
PAINT ("fn_steer.bmp","Steering System Functional Block Diagram")

\bt\
\nt[log]\
```

```
RUN_PROCEDURE ("note")

\bt\
\nt[exit]\
_EXIT
```