PUMP-PRO—A CENTRIFUGAL PUMP DIAGNOSTIC EXPERT SYSTEM

by

Thomas J. Fritsch
Consulting Engineer, Consulting Group
Stone & Webster Engineering Corporation
Boston, Massachusetts

Thomas J. Fritsch has 25 years experience in the engineering industry. He joined Stone & Webster Engineering Corporation (SWEC) in 1979, as a Consulting Engineer on rotating equipment. He is responsible for consulting within the company and with clients on all aspects of mechanical rotating equipment, including pumps, compressors and turbines, and the systems in which they are employed. Prior to joining SWEC, Mr. Fritsch was Manager of Engineering for the Engineered Pump Division of Worthington Pump Corporation and Ingersoll Rand Company. He has over 20 years experience in design, development, sales, marketing and engineering management primarily related to centrifugal and reciprocating pumps, but also including reciprocating, centrifugal, screw and lobe-type compressors.

Mr. Fritsch received a Bachelor's degree in Mechanical Engineering in 1958 from Drexel University. He is a member of ASME and the ASME Power Pump Test Code Committee. He is a past member of the Hydraulic Institute. He has a number of professional publications and presentations and is a new member of the International Pump Symposium Advisory Committee.

ABSTRACT

Expert systems are a part of that developing branch of computer science known as Artificial Intelligence. Artificial Intelligence, how it relates to the other branches of computer science and where expert systems fit into that order are briefly discussed. Typical industrial applications and approaches to the software and hardware requirements for developing expert systems are also discussed. It gives a detailed description of PUMP-PRO and why and for whom it was developed. Several of the roadblocks encountered in its development are covered and finally experiences of some of its users are related.

INTRODUCTION

"Artificial Intelligence (AI) is usually thought of as a computer program which produces a result normally thought to require human intelligence"[1]. To differentiate between the conventional uses of computers and artificial intelligence, the two tables below list some of the major uses of each to date.

The following brief descriptions show the differences and the increased complexity between conventional and artificial intelligence uses of the computer.

• Word processing is that use of a computer that allows the user to place words in proper positions with respect to each other, and with some programs, to ensure that all of the words are spelled properly.

• Natural language processing is of a higher order in that it looks at words as symbols and their meaning by themselves and in relation to each other.

• Data processing allows the user to handle large bits of data and keep them in some order, so various processes can be done with the data.

• Pattern recognition looks at the shapes of objects and their spatial position with respect to each other. It has obvious potential as an inspection tool and is being developed in industry for that purpose at this time.

• "Expert systems consist of a body of knowledge and a mechanism for interpreting this knowledge. The body of knowledge is divided into facts about the problems and heuristics or rules that control the use of knowledge to solve problems in a particular domain"[1].

EXPERT SYSTEMS

In its simplest terms, an expert system can be represented by the Figure 1.

The user is anyone with access to the proper computer that will operate the program and who has a need for the knowledge contained therein.

The inference engine is the software which controls the reasoning operations of the expert system. This is the part of the program which deals with making assertions, hypotheses, and

Figure 1. Use of an Expert System.
conclusions. It is through the inference mechanism that the reasoning strategy (or method of solution) is controlled [3].

The knowledge base is that part of the program where the domain knowledge is stored in the form of facts and heuristics which are expert “rules of thumb” that are usually empirical in nature, based on experience or intuition, with no physical justification or scientific proof [2].

An expert system (Figure 2) is developed with the close interaction of the expert that has the knowledge and the knowledge engineer (which is another name for a computer engineer who has the expertise to either develop the required system software or to use available commercial systems that will make a suitable marriage with the type of expert information to be presented to the user).

An example of a typical rule that would be used in an expert system is shown in Figure 3.

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| EXPERTS | KNOWLEDGE ENGINEER | RULE COMPILER | KNOWLEDGE BASE |
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**Figure 2. Expert System Development.**

**CONDITION**

**ACTION**

**IF:** A IS TRUE  
**THEN:** TAKE ACTION X

AND

**B IS TRUE**

AND

**C IS TRUE**

**Figure 3. Typical Expert System Rule.**

The rule tells the computer that if A is true and B is true and C is true, the computer can take action X. It follows then that if any of the facts are not true or their status is unknown, the computer cannot take action X.

There are two basic forms of computer-based reasoning, these being forward chaining and backward chaining. In both methods, the program acquires information either in the form of a question to the user, or by means of accessing other programs and data bases.

In backward chaining systems, the program has a built-in method for making an initial hypothesis as to what the solution is. That is, it assumes one possible solution to be true. The procedure then attempts to prove that the assumption is correct, by asking the user (or using its own inference capabilities) to confirm all of the prerequisite conditions for this particular solution. If the solution is disproved, through the non-existence of the prerequisite symptom, for example, then the program chooses a different possible solution, and proceeds to prove this one in the same manner as the previous solution. Because this approach is based on assuming that the goal is known, backward-chaining systems are also known as “goal-driven systems.”

In a forward-chaining system, the program has no a-priori knowledge of the possible solutions. It uses the acquired information to prune the tree of possibilities, as it progresses through the solution procedure. Information is gathered, until the list of possible causes of problems has been narrowed down as far as possible. This method of reasoning (or inference) is sometimes referred to as “data driven” because of the use of data obtained from the user to make further hypotheses or assumptions. The reasoning progresses from an initial state (at which the program has no knowledge of the solution), through intermediate states (in which the program’s knowledge of the solution), to the final state (when the programs has reached its goal) [2].

A detailed explanation of a forward chaining program is presented in APPENDIX A. It includes figures, so that the working of the rules can be followed with ease.

**TYPICAL INDUSTRIAL APPLICATIONS**

Most of the industrial applications of expert systems have been for internal use, such as the Schumberger Dipmeter Advisor, which looks for oil-bearing geologic structures from seismic data, or the AMOCO ELAS system which analyzes oil-well boring logs. DEC has developed a VAX scheduling and checking program (XCON). They are also currently developing other systems to enhance their current operations.

In the power industry General Electric is developing an expert system for nuclear reactor operations, funded by the Electric Power Research Institute. Westinghouse is currently using a system to monitor and diagnose faults in generators and to advise operators of appropriate actions. This approach avoids the transfer of responsibility from the operator to the computer [2].

The space shuttle program has developed on-board expert systems to enable the crew to monitor, diagnose and fix problems with some of the critical on-board systems. The aviation industry has also been developing expert systems, one of which assists the pilot of a fighter aircraft in flight by monitoring systems and warns him of possible failures when he does not have time to focus on them because his attention is occupied with other matters.

**APPROACHES TO EXPERT SYSTEMS**

Many expert systems applications are developed for specialized AI computers, such as LISP machines. The most sophisticated inference mechanisms are generally geared toward workstation class computers, which have built-in LISP interpretation and execution. These machines generally provide a complete AI environment for system development. Other computers are also being used for AI applications, including IBM mainframes, DEC VAX computers, Apollo and SUN computers, as well as microcomputers.

When developing engineering applications systems, the identification of the intended group of end users, and their familiarity with and accessibility to different computers are major considerations. In some applications, it is feasible to invest in a stand alone AI machine, if the application is intended for a single use at a single location. If the product is intended for distribution to a
multi user group, then the hardware cannot be so limiting.

The writer's company has a large number of micro-
computers throughout its offices and field sites. Much of
the engineering work is done on these computers and it
is obvious that the work is done on these computers
and it is obvious that this provides an existing hardware
vehicle for product delivery. We have found the same
to be true of the majority of our clients regardless of the
industry field that they are in.

Another consideration in the selection of micro
computer based expert systems is that some of the
experts have little or no experience with computers[2].

This was true of the writer when he initially became involved
with the development of the PUMP-PRO system. It has been
found that access to a personal computer affords an environment
in which people are most willing to participate in the expert
system development process. The in-house development of the
MAIDS software program and the availability of other commer-
cial packages has further encouraged the use of microcomputer
based expert system development.

The writer's company has also installed a VAX-based
inference mechanism, and has transferred some of the
PC-based systems to the VAX computer where it may
be accessed from any terminal or a PC with a modem
[2].

PUMP-PRO—A CENTRIFUGAL PUMP DIAGNOSTIC
PROGRAM

Centrifugal pumps are one of the most commonly used pieces
of equipment in power plants, refineries, petrochemical and
chemical plants and many large industrial facilities. Many of these
pumps are in systems that are critical to the operation of the plant
or at least significant segments of it. When one of these pumps fail, it is necessary that the problem be diagnosed and fixed as
quickly as possible. Frequently the plant personnel do not have
the expertise to do this. Typically they do one or more of the
following:

- Try one fix after another until they hit or stumble onto the
  right one.
- Call for help from their own headquarters engineering staff.
- Call in an outside consultant to help them.

All of these take time, which is usually in short supply, and
eventually the program is fixed, but at the cost of expensive
down time.

PUMP-PRO is a centrifugal pump diagnostic program which
fills the need for expert help at the finger tips of the people at the
plant. It provides expertise for use at the operating plant level, it
operates on an IBM-PC or PC compatible computer with at least
512 KB memory and dual 360 KB disk drives. It is backed by in-
house expertise in centrifugal pumps. The program was co-
developed and the writer now provides the back up for its field
use.

The program, PUMP-PRO, uses an inference engine called
MAIDS (Microcomputer Artificial Intelligence Diagnostic Ser-
vice). It is a forward chaining, rule based system with a total of
460 rules. It functions in the same way that humans do in solving
many problems. It proceeds from symptoms to causes and then
to remedies for the causes.

First it reviews the following symptoms:
1. Is pump capacity zero/inadequate/adequate?
2. Is pump discharge pressure low?
3. Is pump losing prime after starting?
4. Is pump driver overloading?
5. Is pump/driver vibration excessive?
6. Are bearings overheating?
7. Are bearing wearing rapidly?
8. Is pump starting properly?
9. Is pump power consumption excessive?
10. Is packing leaking excessively?
11. Is packing life short?
12. Is pump overheating?
13. Is pump excessively noisy?
15. Is check valve noisy when starting/stoping the pump?
16. Is pipe movement excessive when starting/stoping
pump?
17. Are internal gaskets leaking?
18. Is pump cavitating excessively?
19. Is pump seized?
20. Is pump not performing well, but I can't define symptoms?

The user then answers the following question regarding the
history of the pump(s) in question.

Is the pump history start-up, overhaul or running? The answer
to this history question influences the causes and their sequence
that are then brought up one at a time for the symptoms
previously selected.

It is not practical to list herein all of the causes for the above 21
symptoms. The number of causes varies from one, in the case of
No. 16, to 22 for No. 1 - the case of a pump not delivering enough
liquid.

The program now brings up, one at a time, each of the possible
causes for the symptoms selected. The user reviews the causes
one at a time, and again selects those that apply or are thought to
apply to his particular problem. Each of the symptoms and cause
questions requires that the user give a Yes or No answer before
proceeding to the next question.

At the completion of the cause selection process the program
then brings up, again one at a time, the remedies for those causes
that were selected.

The text in the program is written so that an experienced and
competent mechanic or millwright can understand it. To that
depth, there is a wealth of information included in the cause
questions as well as the remedy responses to enable the user to
better understand the subject and make intelligent decisions. In
addition, there are seven separate tutorial files which present
expanded explanations of the following subjects:

1. Understanding NPSH Available and Required
2. Finding the NPSH Available and Required for Your Pump
3. Finding the Suction Lift for Your Pump
4. Understanding Specific Speed
5. Understanding the Pump Affinity Laws
6. Reducing System Head and Increasing Pump Total Head
7. Field Performance Testing

Each of these subjects is covered in greater detail, because they
must be understood in order to solve many pump problems.

An example of the program at work for the symptom "Is the
pump/driver vibration excessive?" is presented in APPENDIX B.
All elements of the program are shown, including one of the
tutorial files "Understanding the Affinity Laws."

ROADBLOCKS TO THE DEVELOPMENT
OF EXPERT SYSTEMS

Experiences to date in the development and use of PUMP-
PRO have led to several observations regarding the difficulties,
problems and roadblocks that can be experienced with this type
of expert system.

- The first is software selection. The initial selection for PUMP-
  PRO was a commercially available program that turned out to be
  limiting in that only one symptom (cause and remedy) could be
  followed at a time. Also, once started, a chain had to be followed

- The second is expert system selection. The concern is the
  success of the expert system in the field. This is a matter of
  experience and judgment of the expert system designer. It is
  important to choose the right expert system for the job.

- The third is user acceptance. The user must be convinced
  of the benefits of using the expert system. This is a matter of
  education and training.

- The fourth is maintenance and support. The expert system
  must be maintained and supported. This is a matter of
  availability and cost.

- The fifth is the cost. The cost of the expert system must be
  considered. This is a matter of budget and justification.

- The sixth is the user interface. The user interface must be
  user-friendly. This is a matter of design and testing.

- The seventh is the expert system's knowledge base. The
  expert system must have a good knowledge base. This is a
  matter of the expert system designer and the user.

- The eighth is the expert system's performance. The expert
  system must perform as expected. This is a matter of optimiza-
  tion and testing.

- The ninth is the expert system's support. The expert system
  must be supported. This is a matter of availability and cost.

- The tenth is the user's satisfaction. The user must be satisfied
  with the expert system. This is a matter of training and
  education.

- The eleventh is the expert system's documentation. The
  expert system must be well-documented. This is a matter of
  design and testing.

- The twelfth is the expert system's portability. The expert
  system must be portable. This is a matter of design and
  implementation.
to a conclusion before another could be started by resuming the program. This was too time consuming and constraining. It did serve a useful purpose in that it helped to focus thinking in terms of how to structure the system.

The decision was made that no commercial software was then available for the PC computer, with the versatility required; it was then that Dr. Martin R. Rooney developed the MAIDS™ (Micro Computer Artificial Intelligence Diagnostic Service), which is the software system used to develop PUMP-PRO.

• It was defined that the program would be focused toward experienced mechanics and millwrights, and careful attention was paid that the expected audience did not get information over or under its capabilities.

• The structure and content of the cause questions, the remedies and finally the tutorial sections required careful thought, so that the user would have sufficient knowledge of the subject to make a worthwhile selection of answers. It was during this process that the decision to include tutorials on certain subjects was made. It was impractical to include all the information deemed necessary in the questions so separate "tutorial subjects" were selected that were found to require more extensive treatment. Separate tutorial files were created so that the user could access them at appropriate points where the question or remedy required the knowledge or understanding.

• Since PUMP-PRO was one of the first expert systems with usefulness outside a single company, it was decided to go for extensive distribution in a wide variety of industries. The goal was to quickly get the program into the hands of operating plant personnel, where the decisions are made regarding what is wrong and how it is going to be fixed. Accordingly, the program was made available at no cost to qualified clients, in return for a promise that they would try and use it on real applications and provide feedback on its good and bad features, and most particularly, whether it successfully helped them to solve real problems.

Distribution of the program began in July 1985 and approximately 350 copies are now in use in power plants, refineries, chemical plants and industrial plants. A roster of each recipient has been kept and about one third of the mail back cards that were included with the program packet have been received. The users are being surveyed to determine whether the program is being used, and with what frequency and success. It is now evident that reporting results is going to be difficult and time consuming, to monitor the use of a program that is distributed in the manner that PUMP-PRO was distributed.

EXPERIENCE TO DATE

A contract with a large chemical company to modify the program has been received and filled with the following four enhancement features:

• The ability to back up and review an/or reselect the answer to previous questions.

• The ability to store a problem at any point in its execution and return to it later without re-running the entire program.

• Addition of the client's own plant and headquarters personnel to the program, so their users will call them prior to contacting outside sources for assistance.

• The ability to print out a hardcopy of a complete problem with all of the selected symptoms with the answers given by the user, causes, remedies and tutorials.

Fifty copies of this enhanced program have been delivered to this client for installation in many plants in this country and overseas.

Another client, an electric utility that owns and operates nuclear power plants, was having problems with one of their residual heat removal (RHR) pump in their boiling water reactor (BWR) unit. They tried to use PUMP-PRO to help them solve the problem, which involved not being able to meet Tech Spec requirements, because the pump was not making its required flow and head requirements. The engineer working on the problem reported that the program was not giving the right answers. After he described the symptoms, he was told that the program was correct and something must have been wrong in the inspection of the pump. The engineer agreed to send all of their records for analysis, including the system diagrams, the test results and the data on the pumps. After reviewing the data, a suggested course of action was presented that involved re-inspecting the pump. This was accomplished by paying careful attention to the inlets to the impeller vanes. An impeller had been replaced and the new one did not have the vanes sharpened on the inlet as the original one did. This substantially increased the NPSH required by the pump and caused the head to break off when they tried to reach their Tech Spec operating point, because of excessive cavitation in the pump.

Another electric utility, which also owns and operates several nuclear power plants, had a similar problem with one of their service water pumps, not meeting the Tech Spec requirements during the in-service testing. They used the program, and it led them to suspect the suction side of the system. In this case, they involved a consulting firm in the resolution and solution of the problem. All of the options have been identified and recommendations for the solution are currently being examined.

It is evident that PUMP-PRO is not going to be able to lead every user to a solution to every problem; what it can do is provide options and give the user some directed guidance toward the solution of his problem.

CONCLUSIONS

Over 350 copies of PUMP-PRO have been distributed to date and are in power plants, refineries, chemical plants and industrial plants. It is evident that it is possible to construct expert systems to aid in trouble-shooting components such as pumps, valves, heat exchangers, compressors and the like. It should then be possible to combine these component programs with other system parameters and build expert systems that will be able to diagnose entire fluid system problems.

The technology to develop expert systems is available and expanding at a rapid rate. Expert systems have been developed, they are in use and they work.

APPENDICES

APPENDIX A

The following is a description of a simple forward chaining system. In each of the illustrations the notations are as follows:
1. Items 1A through 1J are facts.
2. Items 2A through 2D, 3A through 3E, 4A through 4D, and 5A through 5C are rules that can only be activated when the inputted facts are true.
3. Items 6A through 6C are the conclusions that we are trying to reach.

Step 1 is the first input step and shows that facts 1A, C, F, G, H, and I are eventually going to be shown to be true (Figure A-1).

Step 2 shows that the user has inputted the facts 1A, C, F, and G are true and the rule 2C is the only one that can trigger at this time because each rule requires two true inputs to take action (Figure A-2).

Step 3 shows that the user has also found, possibly after some investigation, that facts 1H and I are also true, causing 2D to now trigger. When it does, the input from rules 2C and 2D cause rule 3E also to trigger (Figure A-3).

Step 4 shows the input from rule 3E inputs into rules 4C and D. However, these rules also require two true fact inputs for them to
trigger and for the program to go forward to a conclusion. If no other facts can be shown to be true then the program is stymied and cannot reach a conclusion (Figure A-4).

Step 5 shows that the user has again done some investigation and now finds that fact 1d is true. This allows rule 3D to trigger, since it now has two true inputs and allows rule 4D also to fire, for the same reason (Figure A-5).

Step 6 shows the input from rule 3D into rules 4B and C and the input from rule 4D into rule 5C (Figure A-6).

Step 7 shows that rule 4C can now trigger inputting into the rules 5B and C (Figure A-7).

Step 8 shows that rule 5C is now satisfied and can now trigger to the conclusion 6C, completing the chain (Figure A-8).

In this manner, a system is slowly developed using both expert and knowledge engineer to configure the facts, rules and conclusions into a workable system that is useful to some one who himself is neither an expert nor a knowledge engineer.

Figure A-1. Forward Chaining, Step 1, Input.

Figure A-2. Forward Chaining, Step 2, Input and Assertions.

Figure A-3. Forward Chaining, Step 3, Input and Assertions.

Figure A-4. Forward Chaining, Step 4, Assertions.

Figure A-5. Forward Chaining, Step 5, Assertions.

Figure A-6. Forward Chaining, Step 6, Assertions.

Figure A-7. Forward Chaining, Step 7, Assertions.
APPENDIX B

The following are examples of the hardcopy of a typical field problem. It includes all of the screens for a problem of excessive vibration in a pump. To show the completeness of the cause and remedies screens, all of the cause questions were answered so that all of the remedies would appear for the user. This would not normally happen in a real problem. In addition, the tutorial file "Understanding the Pump Affinity Laws" was also included, so the reader can see the scope of these files.

Figure A-8. Forward Chaining, Step 8, Goal.
danger that the cavitation of itself can cause damage to the pump in addition to the potential because of the high vibration levels. Now times three effects are more than additive. The vibrations are usually of a high frequency and are broad based and random.

**QUESTION**

**CAUSATION OF HIGH VIBRATION**

Answer given was 'YES'

*Does the pump possibly have a bent or bowed shaft? This is a special case of imbalance because the head or bow moves the center of gravity away from the shaft centerline causing the unbalance.*

**QUESTION**

**15 SHAFT BEND**

Answer given was 'YES'

*Most resonance problems are solved by adding stiffening or ease to the system. It is usually easier to try and do this on a trial and error basis since this may aggravate the situation and cause structural damage. Instrumentation is the key. Just to avoid the excessive solution of the problem. If you think you have a resonance problem, please call*

T.J. (Tom) Fritch
Stone & Webster Engineering Corporation
P.O. Box 2325
Boston, Massachusetts 02107
Telephone (617) 599-5416

**NOTE**

It is difficult to give rules of thumb for things like runout because of the great variation in size and configuration of centrifugal pumps. Usually the manufacturer gives limits for his particular pump in the instruction book. Be aware that any imbalance coupled with a bent or bowed shaft aggravates the situation so you have to look at both when trying to determine the source of the problem. Be careful when trying to remove vibration at the time the pump was installed or occurred while running; that will help you find the source of the problem rather than exasperate it further, caused by uneven heating or cool down and the vibration here also is aggravated by unbalance in the pipe, causing the high vibrations.

*Be very careful when trying to straighten a shaft; it is somewhat of an art requiring a large picture of mechanical principles. Do not try it if you have not done it before or you will probably crash the shaft and have to wait for a replacement or be forced into trying to make one on your own.***

**NOTE**

If you think that one or more of your pumps are being forced to run at or near shut off, you have two choices other than changing the system so they don’t run in parallel. If you think the head capacity curve on one or more pumps are being hung up parallel to each other, you might take a very quick look. Do not do this until you understand the Pump Affinity Laws. Once familiar with the affinity laws, contact:

T.J. (Tom) Fritch
Stone & Webster Engineering Corporation
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Telephone (617) 599-5416

Please take the time to discuss it so that you do not make a mistake. The affinity laws are very simple to use if you make sure the cause of excessive runout with commensurate high vibrations, you also have two choices other than to change the parallel system arrangement which most times is not acceptable. Examine the pump head capacity curve(s) and the system curves and check the vibration while operating. As with the previous example, this will allow you to see the possible causes and remedies for excess vibration which can be dangerous.

**NOTE**

*If you think there is misalignment between your pump and driver, it is a good idea to try and get some idea of the running hot alignment by checking it immediately after start-up. This is very often true where the misalignment is the result of inadequate or deteriorating support. At the end of the program, you should record the program once more and compare it with the initial hot alignment. This will allow you to review the possible causes and remedies for excess vibration which can be dangerous.*

**NOTE**

*The unbalance is in either the pump or driver rotor or both. To correct this, since most pumps do not have in-place balancing capability, the rotors must be removed and replaced with a balancing capability. It is good practice to run the driver with the coupling disconnected and check the vibration level. This will give a good clue whether it is the pump or the driver that is out of balance. Be sure when the balance is done to check for loose parts and extra shaft runout. Also, try and determine if the unbalance is caused by poor balancing at manufacture, or occurred somewhere during operation. This will aid in preventing the recurrences of the problem.*

**REFERENCES**
