PUMP-PRO—A CENTRIFUGAL PUMP DIAGNOSTIC EXPERT SYSTEM

by

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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.

Conventional	*Artificial Intelligence*
Word processing	Natural language processing
Data Processing	Pattern recognition
payroll	Symbolic mathematics
inventory	Theorem proving
purchase orders	Expert systems
Graphics	
Scientific	
mathematics	
engineering	

• 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 processings can be done with the data.

• Pattern recognition looks at the shapes of objects and their spacial 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 propeer 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

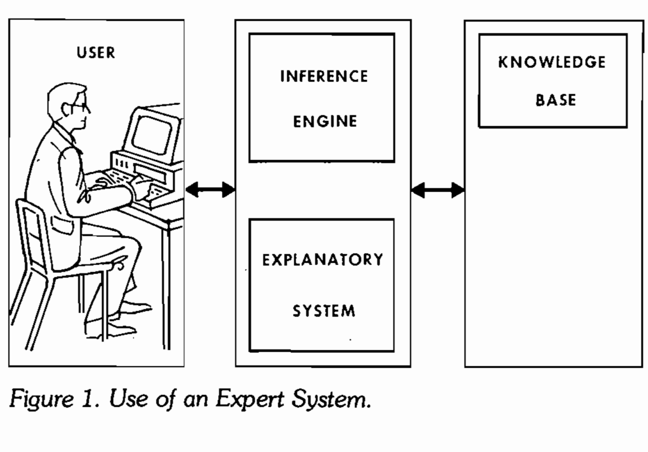

Figure 1. Use of an Expert System.

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.

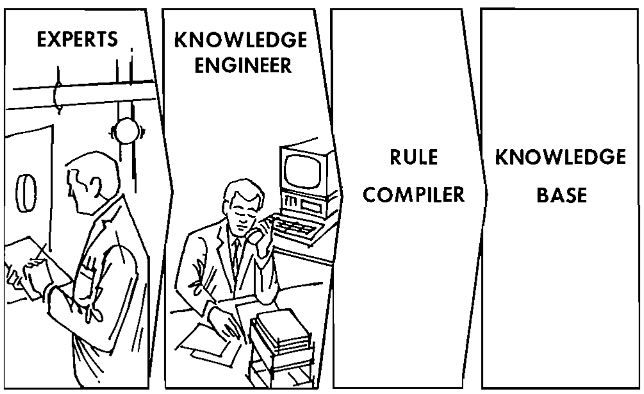

Figure 2. Expert System Development.

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 geological structures from seismic date, or the AMOCO ELAS sytem 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 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 user 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 microcomputers 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 commercial 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 Service). 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?
14. Is mechanical seal leaking?
15. Is mechanical seal life short?
16. Is check valve noisy when starting/stopping the pump?
17. Is pipe movement excessive when starting/stopping pump?
18. Are internal gaskets leaking?
19. Is pump cavitating excessively?
20. Is pump seized?
21. 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 symptom 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 end, 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 to a conclusion before another could be started by rerunning 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 versatiity 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 user 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 is it 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 reinspecting 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 inputed 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 inputed 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 investigtion, that facts 1H and I are also true, causing 2D to now trigger. When it does, the input from rules 2C and D 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 1J 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.

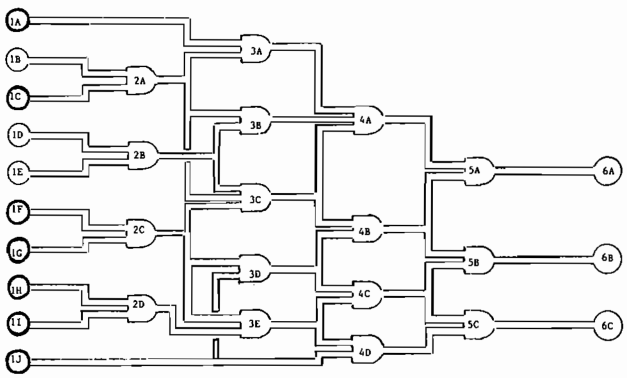

Figure A-1. Forward Chaining, Step 1, Input.

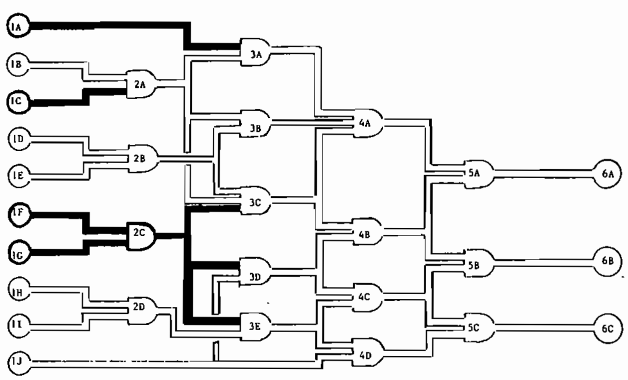

Figure A-2. Forward Chaining, Step 2, Input and Assertions.

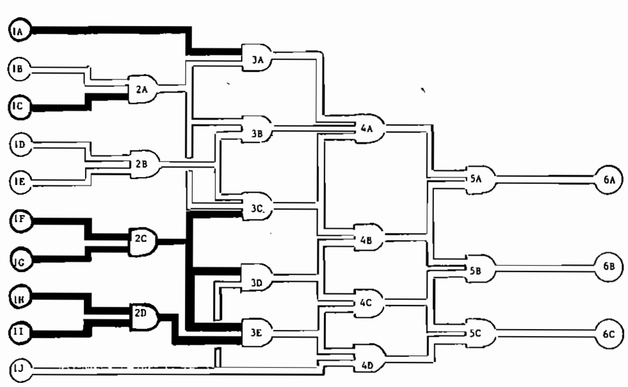

Figure A-3. Forward Chaining, Step 3, Input and Assertions.

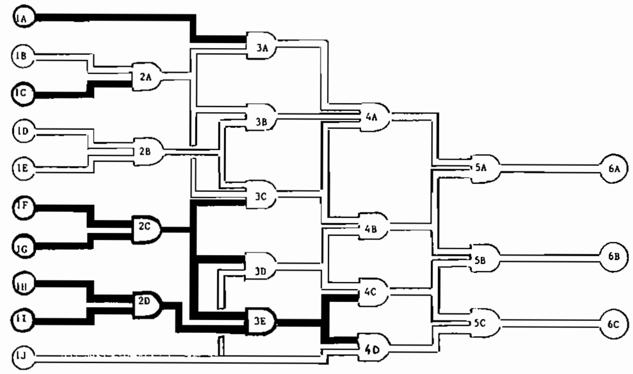

Figure A-4. Forward Chaining, Step 4, Assertions.

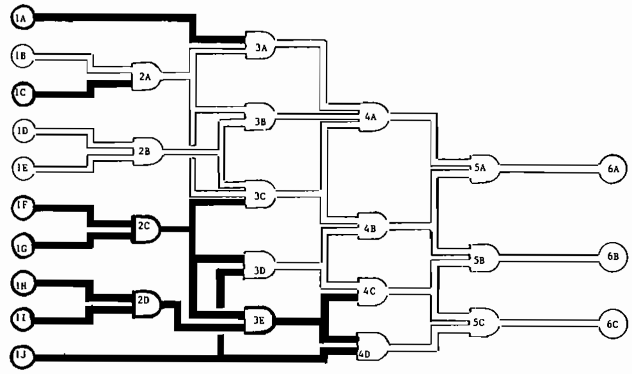

Figure A-5. Forward Chaining, Step 5, Assertions.

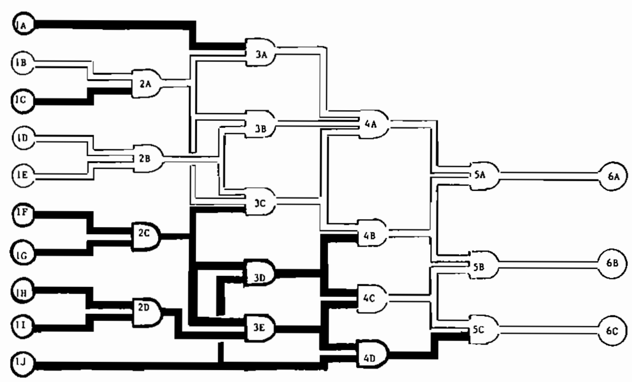

Figure A-6. Forward Chaining, Step 6, Assertions.

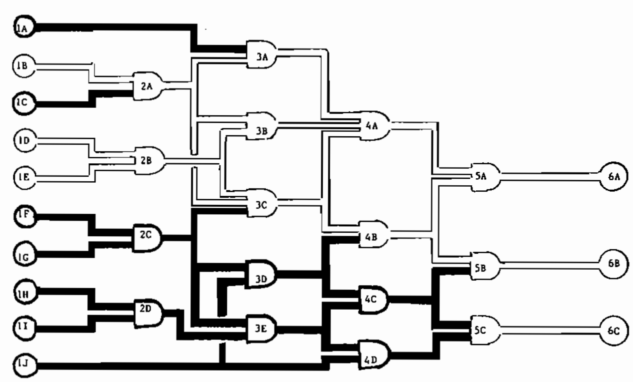

Figure A-7. Forward Chaining, Step 7, Assertions.

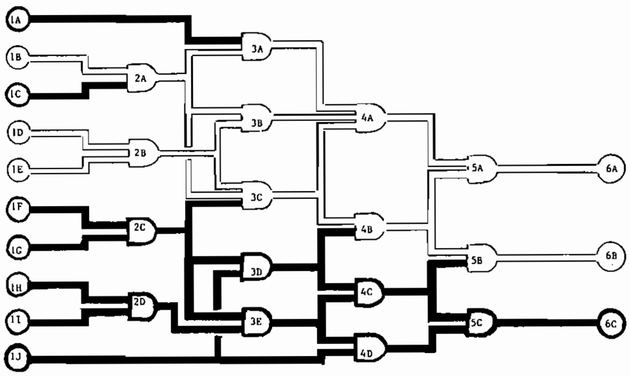

Figure A-8. Forward Chaining, Step 8, Goal.

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.

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===========================================================================
Pump-Pro II,  Centrifugal Pump Diagnosis Program           Page: 1
(C) 1985 Stone & Webster Engineering Corp.                 Date:03-05-1986
 H A R D C O P Y  O F   D I A G N O S I S                  Time:10:45:04
===========================================================================
***TEXT***

                       D I S C L A I M E R

While all efforts have been made to assure both completeness and accuracy
of the material contained in this system; Stone & Webster Engineering
Corporation assumes no responsibility nor liability for the advice provided
through this system.  You are expressly warned that the intent of this
system is to function as ADVISOR; it cannot and should not take the place
of a responsible informed technician, mechanic, millwright, or engineer.
***TEXT***
                    Welcome to PUMP-PRO, the Pump Diagnosis Aid

 The first few questions asked will be used to determine the general
nature of your pump problem.  Once the major symptoms have been established,
the system will begin to ask more specific questions until a cause(s) have
been determined; and then, the system will give specific remedies.  Where
necessary, tutorials will be displayed so you may understand the concepts
covered.  If you have questions regarding the PROGRAM (not the advice)
please call T.J. (Tom) Fritsch, Stone & Webster Engineering Corp., 245/10
Summer St., Boston, MA 02107, telephone: 617-589-5416.
------
      Notation: the / character is to be read as "or"
                the & character is to be read as "and"
------
PUMP-PRO is a trademark of Stone & Webster Engineering Corporation
Copyright 1985 & 1986, by Stone & Webster Engineering Corporation
Authors: M.F.Rooney; T.J.Fritsch; G.A.Finn
***QUESTION***
Which of the following describe: the PUMP CAPACITY
 1 . PUMP CAPACITY IS ZERO
 2 . PUMP CAPACITY IS INADEQUATE
 3 . PUMP CAPACITY IS ADEQUATE
Choice selected was  3
***QUESTION***
IS PUMP DISCHARGE PRESSURE LOW ?
Answer given was 'NO'
***QUESTION***
IS PUMP LOOSING PRIME AFTER STARTING ?
Answer given was 'NO'
***QUESTION***
IS PUMP DRIVER OVERLOADING ?
Answer given was 'NO'
***QUESTION***
IS PUMP / DRIVER VIBRATION EXCESSIVE ?
Answer given was 'YES'
***QUESTION***
ARE BEARINGS OVERHEATING ?
Answer given was 'NO'
***QUESTION***
ARE BEARINGS WEARING RAPIDLY ?
Answer given was 'NO'
***QUESTION***
IS PUMP FAILING TO START ?
Answer given was 'NO'
***QUESTION***
IS PUMP POWER CONSUMPTION EXCESSIVE ?
Answer given was 'NO'
***QUESTION***
IS PACKING LEAKING EXCESSIVELY ?
Answer given was 'NO'
***QUESTION***
IS PACKING LIFE SHORT ?
Answer given was 'NO'
***QUESTION***
IS PUMP OVERHEATING ?
Answer given was 'NO'
***QUESTION***
IS PUMP EXCESSIVELY NOISY ?
Answer given was 'NO'
***QUESTION***
IS MECHANICAL SEAL LEAKING ?
Answer given was 'NO'
***QUESTION***
IS MECHANICAL SEAL LIFE SHORT ?
Answer given was 'NO'
***QUESTION***
IS CHECK VALVE NOISY WHEN STARTING / STOPPING THE PUMP ?
Answer given was 'NO'
***QUESTION***
IS PIPE MOVEMENT EXCESSIVE WHEN STARTING / STOPPING THE PUMP ?
Answer given was 'NO'
***QUESTION***
ARE INTERNAL GASKETS LEAKING ?
Answer given was 'NO'
***QUESTION***
IS PUMP CAVITATING EXCESSIVELY ?
Answer given was 'NO'
***QUESTION***
IS PUMP SEIZED ?
Answer given was 'NO'
***QUESTION***
IS PUMP NOT PERFORMING WELL BUT ITS SYMPTOMS AREN ' T DEFINED ?
Answer given was 'NO'
***TEXT***
    Now that you have selected the appropriate symptoms for your particular
pump problem, Pump-Pro III will present possible causes for you to review
and select from.  You can select as many as you consider appropriate.
When all of the causes have been presented and you have completed your
selection; Pump-Pro III will present remedial action for each selected
cause.  Where necessary to amplify the causes or increase your understanding
of the cause or remedy, instruction will be given or tutorial subjects
will be presented.
***TEXT***
The history of a pump is often useful in diagnosis of a pump problem.
For this program, three possible histories are used: a pump that is starting
up for the first time; a pump that has just been overhauled; and a pump
that was running and is now giving a problem.
***QUESTION***
Which of the following describe: the PUMP HISTORY
 1 . PUMP HISTORY IS START-UP
 2 . PUMP HISTORY IS OVERHAUL
 3 . PUMP HISTORY IS RUNNING
Choice selected was  3
***TEXT***
Before you start through the questions that will attempt to lead you to
the cause of your excessive vibration, and help you fix it, you will want
to review the following list of the primary and most common causes of
vibration problems:
1. Rotor unbalance in the pump and/or driver rotor causes vibration that
   can be excessive and sometimes destructive.  It usually shows up at a
   frequency the same as the running speed and can be detected on a variable
   speed equipment because its frequency changes with the speed.
2. Misalignment between the pump and its driver is another major cause of
   pump vibration. It can either be caused by improper alignment procedures
   at the time of installation or by such things as differential thermal
   growth, excessive pipe loads due to dead weight, pressure and temperature
   effects, improper pipe supports and the like, when the pump is operating.
   It usually shows up at a frequency of twice running speed, but can show up
   at running speed frequency where it can be confused with unbalance.
3. Resonance in the pump, driver, baseplate, piping, motor stand can cause
   high vibrations especially when one of the vibratory mode frequencies
   coincides with the running speed of the pump.  This is not an easy cause to
   detect without some expertise and vibration diagnostic instrumentation.
4. Operation of a pump at flow rates significantly lower or higher than
   the design or best efficiency point (BEP) of a centrifugal pump can often
   cause high vibrations.  These are caused by the less than ideal flow
   conditions that result in turbulent and uneven flow within the pump.  The
   degree of vibration depends on several factors; the size of the pump, the
   flow rate, the head developed, the horsepower, and the type of pump and its
   mounting.  It either excites some resonant frequency or shows up at the
   impeller vane passing frequency.
5. Cavitation within the pump, no matter what the cause, can result in high
   vibrations, usually at the higher frequencies in a wide band random
   fashion.
***TEXT***
Unbalance in the pump and/or driver rotor is probably the most common
cause of excessive vibrations.  It can be caused by an improper, or
inadequate balancing of the rotor at manufacture, or during an overhaul, or
by some event during operation such as loss of part of or damage to the
rotor, uneven wear, or foreign material build-up.  It shows up as a vibration
at the running speed frequency and follows the running speed on a variable
speed installation.  The amplitude almost always increases with speed.
***QUESTION***
IS ROTOR BALANCED ?
Answer given was 'NO'
***TEXT***
Misalignment between the pump and it driver is also a major cause of
vibration.  Many times it is caused by improper alignment at the time of
installation either because the millwrights aren't certain of the technique
or the original thermal offsets were not correct.  Even though the alignment
was originally done correctly, the running alignment could be off because
of excessive pipe loading, thermal growth, pressure growth, movement
in the baseplate, and shifting in the rotor position.
  The usual frequency that you pick up misalignment is at twice running
speed, although it also shows up at running speed and sometimes at both
frequencies.
***QUESTION***
ARE PUMP / DRIVER MISALIGNED ?
Answer given was 'YES'
***TEXT***
   On a horizontally mounted pump and driver, structural resonances usually
occur in the baseplate and its pump and/or motor pedestals.  On a vertical
pump, the resonances usually occur in the pump discharge head and motor
stand and the structural members that support the pump.  Less common, but
still possible, causes are resonances in the pump or driver rotor, the
piping, or the foundation itself.  It is usually excited by the running
speed or one of its harmonics.
***QUESTION***
IS THERE A POSSIBLE RESONANCE IN YOUR PUMP / DRIVER SYSTEM ?
Answer given was 'YES'
***TEXT***
A centrifugal pump is designed to run best at one capacity at a given speed.
At flows lower or higher than the best efficiency point (BEP), the vibration
level will increase, sometimes to excessive levels.  The degree to which
this occurs depends on several factors; how far to the left or right of
the BEP the pump is operating, the size of the pump, the flow rate, the
total head developed, the horsepower, speed, type of pump, and the driver
mounting.
Two of the more common times when this occurs are related to pumps installed
in parallel with headered suction and discharge lines.  First,
when pumps are operating at low flow rates and one pump has a slightly
higher or lower head characteristic curve, there is the danger that it or
the other pumps will be forced close to or at shutoff, or zero flow with
commensurate vibration levels.  The second involves multiple pumps in a
common system where one or more pumps are shut down and the remaining ones
run out in flow beyond their BEP, the degree depending on the respective
shapes of the pump and system characteristic curves.
  The resulting high vibrations are usually at some resonant mode that is
excited by the flow disturbance.
***QUESTION***
ARE PUMP FLOW RATES EXCESSIVELY HIGH / LOW ?
Answer given was 'YES'
***TEXT***
Cavitation, regardless of how it is initiated, if it is severe, can cause
high vibration levels in a pump and driver system.  There is the added
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danger that the cavitation of itself can cause damage to the pump in addition to the potential because of the high vibration levels. Many times these effects are more than additive. The vibrations are usually of a high frequency and are broad band and random.
QUESTION
IS CAVITATION THE CAUSE OF HIGH VIBRATION ?
Answer given was 'YES'
TEXT
Does the pump possibly have a bent or bowed shaft? This is a special case of unbalance because the bend or bow moves the center of gravity away from the shaft centerline causing the unbalance.
QUESTION
IS SHAFT BENT ?
Answer given was 'YES'
TEXT
Most resonance problems are solved by adding stiffening or mass to the system. It is usually unwise to try and do this on a trial and error basis since this may aggrevate the situation and cause structural damage. Instrumentation is avaiable to allow quick diagnosis and solution of the problem. If you think you have a resonance problem, please call

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TEXT
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. Remember that any unbalance coupled with a bent or bowed shaft aggravates the situation so you have to look at both when trying to solve the problem. Also, try and determine whether the bend was there at the time the pump was installed or occurred while running; that will help you find and fix the root problem. A bowed shaft is most times caused by uneven heating or cool down and the vibration here also is aggravated by unbalance in the rotor.
Be very careful when trying to straighten a shaft, it is somewhat of an art usually requiring a mixture of mechanical pressure and heat. Don't try it if you haven't done it before or you will probably scrap the shaft and have to wait for a replacement or be forced into trying to make one on your own.
TEXT
If you think that one or more of your pumps are being forced to run at or near shutoff, 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 strong but still parallels the otber pump curves, you might take a a very small cut. Don't do this until you understand the Pump Affinity laws. Once familiar with the affinity laws, contact:

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Please take the time to discuss it so that you do not make a mistake and overcut the impeller (it cannot be stretched). If the cause is 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 curve and see if some excess head can be trimmed from the impellers to reduce the runout. If not, then friction must be added to the system with either a control valve or some other device such as an orifice. Each system must be examined to understand the layout and the operating modes so the proper fix can be made.
QUESTION
ARE AFFINITY LAWS UNDERSTOOD ?
Answer given was 'NO'
TEXT
The primary cause of cavitation in centrifugal pumps is operation where the NPSH Available is less than tbe NPSH Required. This is usually the result of inadequate or deteriorating suction conditions for the pump. At the end of the program, you should rerun the program once more and select the sypmptom "Is the pump cavitating execssively? - 1. Yes". This will allow you to review the possible causes and remedies for excess cavitation which may be causing the high vibrations.
TEXT
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 shutdown; this isn't a true indication because of the temperature decay and the lack of pressure in the pump casing and discharge piping, but it is the best indicator you have without some sort of continuous monitor, which incidently is available. In most cases you should use the reverse dial indicator method which will give a good check on the parallel and angular misalignment. Since this method is more time consuming than other methods, you should be sure it is necessary by weighing such factors as pump size, speed, and type of coupling. For instance, you can usually be less stringent when aligning an 1800 RPM ANSI chemical pump and a 25 HP motor with a Sureflex coupling than with a 3600 RPM boiler feed pump with agear type coupling and a 1000 HP motor or steam turbine. In the first case, a straight edge will probably be satisfactory while a reverse dial indicator method is called for in the latter case; however, if you must err, do it on the side of the closed tolerance method.
TEXT
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 shipped to a facility with 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 balancing is done to check for loose parts and excess shaft runout. Also, try and determine if the unbalance is caused by poor balancing at manufacture, or overhaul, or occurred somehow during operation. This will aid in preventing the reoccurrence of the problem.

TEXT
"The Pump Affinity Laws"
As you would expect, centrifugal pumps like other mechanical equipment follow certain laws. If you know what the laws are, you can predict what the equipment, in this case the pump, is going to do. The hydraulic performance of centrifugal pumps as well as fans and compressors follow rules known as the Affinity Laws.

For a given pump; the flow, total head, and power vary with changes in speed as follows:
1. The flow varies directly as the speed ratio. Double the speed and the flow doubles, halve the speed and the flow halves.
2. The total head developed by the pump varies as the square of the speed ratio. Double the speed and the total head is four times as much, halve the speed and the total head is one-quarter as much. Remember this is the total head developed by the pump, NOT the discharge head.
3. Since the power required is the product of the flow and the total head, it follows that the power varies as the cube of the speed ratio. Double the speed and the power increases by a factor of eight; halve the speed and the power is one-eighth as much.

With these rules it is possible to step the performance curve of a centrifugal pump to any desired speed from any other speed. Here is how to do it--- Make three columns, one flow, one total head, and the final power; the units will usually be gallons per minute (GPM), feet, and horsepower. Using an existing pump performance curve at a given speed, do the following: Starting at shutoff or zero flow, tabulate five or six convenient flows and the total head and power at those flows. Calculate the speed ratio, its square and cube, and factor up or down consistent with the ratio the tabulated values of flow total head and power. With these new values, draw new curves of flow vs. total head and flow vs. power.

If the speed change is not too great, say less than 20%, then you can use the efficiencies from the original curve on the new curve.

The same Affinity Laws apply to the impeller diameter as they do to the pump speed, that is;
1. The flow varies directly as ratio of the impeller diameters. Theoretically, this means if I cut the diameter in half, the flow is reduce to one half. In practice this does not work because no impeller is designed to have half of its diameter removed and still perform satisfactorily. So to be on the safe side, let's work within the limits that we won't consider cutting any impeller more than 10% of the original maximum diameter and that we won't cut any impeller without discussing it with the pump manufacturer or contact:

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With those limitations set, let's continue: If we cut the impeller to 90% of the original, the flow is reduced to 90% of the original.
2. The total head varies as the square of the ratio of the impeller diameter. If we trim an impeller to 90% of its original diameter, then the total head Developed will be 81% of the original head.
3. The power required will vary as the cube of the impeller diameter ratio. Again, if the impeller diameter is 90% of the original, then the power will be 73% of the original power.

You can use a similar method to that used with a speed change and draw new performance curves at various impeller diameters. Using the existing performance curve, first checking to determine what the maximum impeller diameter is and staying within 10% of that, tabulate five or six flows, total heads and power readings. Calculate the direct, square and cube of the impeller diameter ratio and multiply the above tabulated values by these factors. Using these new figures, construct a new curve of flow vs. total head and flow vs. power.

If you have any questions or wish to discuss it further, please call:

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