Heat Exchanger Expert System Logic

R. Cormier
Radio Frequency and Microwave Subsystems Section

This article describes the reduction of the operation and fault diagnostics of a DSN heat exchanger to a rule base by the application of propositional calculus to a set of logic statements. The value of this approach lies in the ease of converting the logic and subsequently implementing it on a computer as an “expert system.” The rule base was written in Process Intelligent Control (PICON) software.

I. Introduction

The application of formal systems analysis and propositional calculus has great value in the design of an “expert system” rule base, where the need is to model knowledge. Propositional calculus is a formal logic system from which conclusions are deduced independent of the structure of the propositions. The conclusions follow uniquely from the truth or falsity of the propositions. Once a knowledge base has been converted to propositions, assuming it has been done correctly, the process of deduction cannot lead to contradictions or to invalid conclusions. One of the consequences is that, given an appropriate model, every deduction is a tautology. A description of formal systems and propositional calculus can be found in [1]. The breadboard heat exchanger expert system is described in [2].

The controls and operation were first described in terms of hardware for all conditions of service. For example, the heat exchanger has dual pumps which are fully redundant. The failure of one pump does not affect the capability of the heat exchanger to cool the transmitter, except for the reliability factor. Two fans are provided, but these are only partially redundant. Under certain conditions, both fans are required. In addition, a number of other failures can be tolerated provided the heat exchanger is operated locally. The Pumps Alternating command can be bypassed with a local switch, in which case both pumps may be operated simultaneously. All of these conditions were described and incorporated in the rule base, as the expert system needed the capability to distinguish between and not be confused by these alternatives.

II. Operational Logic Statements

The word description of the heat exchanger operation was then converted to logic statements or schemata. The symbols used for the elements are defined in Table 1. The operand symbols are defined in the Appendix.
For simplicity, the limits in the summations have been omitted, but are equal to those of Eq. (A-3). After considerable algebra, the functions in Eq. (A-6) reduce to

\[ f_{11} = \frac{(N_s - |\xi|) \cos \left[ \frac{\pi \xi}{N_s} \right]}{\sin \left( \frac{\pi}{2N_s} \right)^2} \quad 0 \leq |\xi| \leq N_s \quad (A-9) \]

\[ f_{12} = \frac{\sin \left( \frac{\pi |\xi|}{N_s} \right)}{\sin \left( \frac{\pi}{N_s} \right)} \quad 0 \leq |\xi| \leq N_s \quad (A-10) \]

\[ f_{21} = (N_s - |\xi|)^2 \quad 0 \leq |\xi| \leq N_s \quad (A-11) \]

\[ f_{22} = \left[ \frac{\sin \left( \frac{\pi |\xi|}{N_s} \right)}{\sin \left( \frac{\pi}{N_s} \right)} \right]^2 \quad 0 \leq |\xi| \leq N_s \quad (A-12) \]

After collecting the terms in Eqs. (A-9)–(A-12) and using Eq. (A-6), the correlation function shown in the main text is obtained.
The heat exchanger is operational whenever it is providing cooling for the transmitter. Coolant must be flowing and heat must be removed from the coolants. This implies that at least one pump and at least one fan are operating, with the second fan available if required for additional heat transfer. The fan operation depends on the coolant temperature at the output of the core. The two conditions are (a) for a coolant temperature $< 120^\circ F$; and (b) for a coolant temperature $> 110^\circ F$.

Let

- $a$ denote condition a is true,
- $b$ denote condition b is true,
- $\bar{a}$ denote condition a is false,
- $\bar{b}$ denote condition b is false.

Given this notation, it can be stated that the heat exchanger is operational when

$$v \lor w : \bar{a} \rightarrow xy : \bar{b} \rightarrow .x\bar{y} \lor \bar{x}y : ab \rightarrow .x \lor y$$

The use of dots in the above statement indicates grouping as referenced in the appendix. This states that (1) for the heat exchanger to be operational, at least one pump ($v$ or $w$) is on; and (2) if the coolant temperature is not less than $120^\circ F$, then two fans ($x$ and $y$) are operating, if the coolant temperature is not greater than $110^\circ F$, then at least one fan is on but not both, and if the coolant temperature is between $110^\circ F$ and $120^\circ F$, then either fan 1 is on or fan 2 is on or both. The advantage of schemata can be appreciated when it is desired to check the consequences of a statement like the one above. The heat exchanger is not operational when the negative of the above is made by the use of DeMorgan's law:

$$\bar{a} \lor \bar{b} . x \lor \bar{y} : v . \bar{b} \lor x v y . x : y : v \lor a b \lor y$$

This states that for the heat exchanger to be not operational, both pumps ($v$ and $w$) are off or the coolant temperature is not less than $120^\circ F$, and either fan 1 ($x$) is off or fan 2 ($y$) is off; or the coolant temperature is not greater than $110^\circ F$ and either fan 1 is off or fan 2 is on, or vice versa; or the coolant temperature is between $110^\circ F$ and $120^\circ F$ and both fans are off.

In the process of taking the inverse, the “if-then” statements of the original schema were eliminated and only conjunctions and alternations remained. This form is known as the “alternative normal form.” Using this form, it is simple to remove inconsistencies. If the schema was found to be valid, i.e., true under all conditions of its terms, then this would mean that the original schema before inversion was inconsistent. This is a useful check, and errors were found and eliminated by this method. Although the above may be logically true, from a practical point of view the heat exchanger would not be considered not operational if both fans were on with a coolant temperature of less than $110^\circ F$. In this case, the failure does not degrade the cooling capacity of the heat exchanger. This is an example of the necessity of analyzing each schema and its inverse. It is not always obvious what the consequences are, even for rather simple definitions.

Several assumptions and simplifications were made. It was assumed that the heat exchanger is commanded on either from the transmitter or from the local panel and that prime power is available. It was also assumed that with one pump operating, 20 gpm of coolant with a pressure differential of 125 psi is being supplied. Similarly, it was assumed that the operation of the fans moves a quantity of air adequate to maintain the coolant exhaust temperature at the transmitter output at less than $70^\circ C$. Obviously, however, these conditions are not always necessarily true; they are also addressed in Section III.

The heat exchanger is controlled from a three-position switch located on a panel on the heat exchanger. In the Local position ($c_2$), power is applied; in the Off position ($c_0$), no power is applied; and in the Remote position ($c_1$), power is applied if the transmitter control power ($p_1$) is on. With respect to the REMOTE/OFF/LOCAL switch $S_2$, and again using the notation of the appendix, the heat exchanger is operational when

$$c_1 p_1 V c_1 \rightarrow v \lor w . x \lor y$$

Associated with the pumps are time delay relays TDR1 and TDR2 and pressure switches $S_4$ and $S_5$. When the heat exchanger is turned on, the time delay relays inhibit the pressure switches during the time required for the motors to reach operating speed. If a pump does not deliver operating coolant pressure by the time the time delay relay has timed out, that pump will be turned off and the other backup pump will be turned on. This provides redundancy in case of a pump failure. The time delays of relays TDR1 and TDR2 are designated $t_1$ and $t_2$, and the functions of pressure switches $S_4$ and $S_5$ are designated $s_4$ and $s_5$.

In addition, there are two alternating relays for the pumps and the fans $K_9$ and $K_{14}$, respectively. To simplify which pump and which fan are being turned on at any given time, the times are designated $t_1$ for pump 1 and fan 1, and $t_2$ for pump 2 and fan 2. After $t_2$, the time starts at $t_1$ again.

The hardware conditions for the operation of pump 1 are as follows:

1. The control circuit breaker ($b_4$) is closed.
(2) The main circuit breaker \( (b_T) \) is closed.
(3) The pump 1 circuit breaker \( (b_1) \) is closed.
(4) The pump 1 contactor \( (k_1) \) is closed.
(5) The tank low-level switch \( (s_1) \) is closed.
(6) The 480-Vac three-phase power \( (p_2) \) is available.
(7) The pump 1 thermal overload \( (o_1) \) is closed.

Similarly, for pump 2:
(1) The control circuit breaker \( (b_6) \) is closed.
(2) The main circuit breaker \( (b_7) \) is closed.
(3) The pump 2 circuit breaker \( (b_2) \) is closed.
(4) The pump 2 contactor \( (k_2) \) is closed.
(5) The tank low-level switch \( (s_3) \) is closed.
(6) The 480-Vac three-phase power \( (p_2) \) is available.
(7) The pump 2 thermal overload \( (o_2) \) is closed.

The control switch is in either the Local or the Remote position. If it is in Remote, the 28-Vdc control power \( (p_1) \) is on from the transmitter and the tank low-pressure cutoff switch \( (s_1) \) is closed. In addition, either the alternating relay is in Pump 1 position (and when pump 1 was turned on, it reached a pressure of 60 psig before the pump 1 time delay relay closed) or pump 2 was turned on (and the alternating relay for pump 2 timed out before the pressure reached 60 psig or the pressure dropped while pump 2 was operating). This can be written in a condensed form using the dot notation in the appendix (with multiple dots representing a greater break) as follows:

For pump 1:
\[
\begin{align*}
&c_1 V c_r s_1 p_1 \cdot c_r s_1 p_1 \cdot b_6 b_7 p_2 b_1 k_1 s_3 o_1 :
\end{align*}
\]

Similarly, with appropriate change of components, pump 2 operation is:
\[
\begin{align*}
&c_1 V c_r s_1 p_1 \cdot c_r s_1 p_1 \cdot b_6 b_7 p_2 b_2 k_2 s_3 o_2 :
\end{align*}
\]

There are conditions when both pumps may be operating together. This involves either the use of the critical command \( (c_c) \) or the closure of the alternating relay disable switch \( (s_{10}) \). For pump 1 and pump 2 both operating,

The hardware conditions for the operation of the fans are similar but not identical to those for the pumps. The appropriate circuit breakers, relays, overloads, switches, and voltages are required. The difference is that the fans are not fully redundant and do not back each other up. In addition, the coolant level, the alternating bypass switch, and the pressure cutoff switches are not in the fan circuit. A temperature switch monitors the coolant, and when the coolant temperature is greater than 110°F at the output to the coil, the second fan is commanded on.

The hardware conditions for the operation of fan 1 are:
(1) The control circuit breaker \( (b_6) \) is closed.
(2) The main circuit breaker \( (b_T) \) is closed.
(3) The fan 1 circuit breaker \( (b_3) \) is closed.
(4) The fan 1 contactor \( (k_3) \) is closed.
(5) The 480-Vac three-phase power \( (p_2) \) is available.
(6) The fan 1 thermal overload \( (o_3) \) is closed.

Similarly, for fan 2:
(1) The control circuit breaker \( (b_6) \) is closed.
(2) The main circuit breaker \( (b_T) \) is closed.
(3) The fan 2 circuit breaker \( (b_4) \) is closed.
(4) The fan 2 contactor \( (k_4) \) is closed.
(5) The 480-Vac three-phase power \( (p_2) \) is available.
(6) The fan 2 thermal overload \( (o_4) \) is closed.

For fan 1:
\[
\begin{align*}
&t_2 V t_1 k_{15} \cdot c_r s_1 p_1 \cdot b_7 b_6 p_2 k_3 o_3 :
\end{align*}
\]

For fan 2:
\[
\begin{align*}
&t_1 V t_2 k_{15} \cdot c_r s_1 p_1 \cdot b_7 b_4 b_6 p_2 k_4 o_4 :
\end{align*}
\]

At this point, schemata have been written to describe the operation of the pumps and the fans. These are true when the antecedent and the consequent are both true or both false. The
schema is false when the antecedent and the consequent are not both true or false. Since the operation of the pumps or fans is monitored independent of the hardware used for the antecedent, a false schema indicates a problem with either the sensor or the data collection. If the biconditional is broken into two conditionals and each is tested independently, the conditionals may provide different information. This is the case with the pumps, and this procedure can be used as a diagnostic.

Part of knowing the operational status lies in keeping track of the various time durations. How long has the expert system been monitoring? How long has the heat exchanger been on? How many times has the heat exchanger been turned on and off? Other clocks were added as required. Time clock parameters are the following:

\[ t_1 = \text{elapsed time since PICON has been on line monitoring} \]

\[ t_r = \text{continuous accumulated time since the heat exchanger was turned on} \]

\[ t_t = \text{continuous accumulated time duration since the transmitter was turned on} \]

\[ t_c = \text{number of times the heat exchanger has been turned on} \]

III. Heat Exchanger Diagnostics Description

The next task was to list all components (least replaceable units) and failure modes. It was then necessary to identify the symptoms and the response of the sensors to each. After describing the various possible failures, the propositional logic statements were written using the available sensors. For this purpose, the phrase "heat exchanger on" was taken to mean that one pump and one fan were operating. A sensor was available for the coolant flow, but the sensor for the air flow proved to be so noisy as to be unusable. The fan rotation sensor was inoperative due to burned-out lamps. Consequently, no direct means of monitoring air flow was available, so the fan motor prime power loading was used instead for the rules. A sensor for the position of the local control switch S2 was not available, although such a sensor would have simplified the rules.

The heat exchanger is required to provide liquid cooling for the transmitter. In order to do this, it must deliver at least 20 gpm with a pressure differential of at least 125 psid. The coolant temperature is not to exceed 70°C. The head of the transmitter load from the output of the heat exchanger is 125 ft. Coolant purity is to be maintained with a resistivity of not less than 2 megohms per centimeter. These are the most critical requirements. Failure to meet these requirements may be due either to parts failure in the heat exchanger or to failures in the transmitter or prime power; this project was limited in scope to the heat exchanger. External failures were identified whenever possible, but no procedures were developed to isolate such faults.

The diagnostics began with the heat exchanger off: In the Off state, is the heat exchanger available for operation? It is not possible to answer this on the basis of sufficient conditions, but it is possible to conclude some necessary conditions for the heat exchanger to be turned on. The "H.E. not available" rule defines the conditions that prevent the heat exchanger from being turned on. Fault localization depends on sensors. It is always possible that a sensor has failed and the equipment is nevertheless operational. Unfortunately, it is not easy to isolate sensor failures from equipment failures; only through gross sensor error or sensor redundancy can some sensor failures be isolated. This area has not been thoroughly analyzed, and rules have not been developed except for a few obvious ones.

The "H.E. not available" rule was then broken up into various rules that identified faults either to a component or, if that was not possible, to an area. For example, if a circuit breaker has tripped, the possibilities are endless. Reasonable and probable considerations must be used in the deductive process. The tripped circuit breaker could be the result of sabotage, but this is neither reasonable nor probable. The following basic assumptions were made:

1. Wiring has a negligible probability of failure.
2. Multiple failures of independent components involving the joint probability of two failures occurring simultaneously are negligible.
3. Problems that cannot be isolated to a component will require a technician to troubleshoot the fault with the use of test equipment and procedures.

For the category "H.E. not available," the choice of sensors was an adequate compromise. With the sensors available, it was not possible to identify the failure of a fuse in the control circuit. Sensors should be relocated in the future to identify this potential failure.

The next category is "H.E. available." In this category, warnings are included. In general, if the heat exchanger is capable of providing cooling for full power operation with no failures, no reporting is desired. If the heat exchanger is capable of providing cooling even though failures or potential failures exist, then that information is reported. The basic schema was deduced as an exclusive-OR of these two conditions, namely, "H.E. not available" and "no failures."
Some faults are detected only with the heat exchanger on. If the heat exchanger is not capable of cooling the transmitter as required, the condition is called "H.E. not working." Note that the conditions "H.E. not working" and "H.E. not available" differ only in that the heat exchanger must be commanded to operate to detect "H.E. not working" conditions. In the "H.E. not available" category are faults which are detected whether the heat exchanger is commanded on or off.

An interlock fault is indicated when a switch sensor located in the transmitter indicates a fault. A corresponding analog sensor provides the actual value for each interlock. Since these are independent of each other, small differences in calibration can be expected. The heat exchanger may be operating correctly and an interlock fault may indicate a problem in the transmitter.

When an interlock is activated, the transmitter beam power is turned off, reducing the heat load immediately and decreasing the coolant temperature drastically. The values of flow rate and temperature just before the activation of an interlock comprise very useful diagnostic information.

The failure of the pumps or the fans to cycle properly is an indication of equipment failure. Each time the heat exchanger is turned off and then turned on, the pumps and fans are alternately switched. A failure to switch indicates a failure that, if not repaired, will lead to a heat exchanger failure. In addition, the reliability factor is degraded by the loss of redundancy.

IV. Diagnostics Logic Statements

The next step in the task was to convert the diagnostic description to maintenance logic that is understood by a computer. One simplification made was that any fan failure is a heat exchanger failure.

A. "H.E. Not Available" Rules

In terms of hardware sensors:

(1) If both pump thermal overloads (sensors d6,100 and d6,200) are open, or

(2) If both pump circuit breakers (sensors d3,80 and d3,100) are open, or

(3) If one pump circuit breaker and the other pump thermal overload are open, or

(4) If either fan circuit breaker (sensors d3,200 and d3,400) is open, or

(5) If either fan thermal overload (sensors d6,400 and d6,800) is open, or

(6) If the control circuit breaker (sensor d3,1) is open, or

(7) If the main circuit breaker (d3,8000) is open, or

(8) If the phase-sensitive relay (sensor d3,400) is open, or

(9) If the 120-Vac control power (sensor d6,8000) is not present, or

(10) If low reservoir level switch (d6,10) is open, or

(11) If low nitrogen pressure switch (d6,20) is open,

then the sensors indicate that if the heat exchanger were to be asked to operate, it would not be available to cool the transmitter. Indeed, if it did turn on, then the sensors or the data link have failed. This is written as:

$$
\begin{align*}
\overline{d}_{3,1} & \lor \overline{d}_{3,40} \lor \overline{d}_{5,10} \lor \overline{d}_{6,20} \lor \overline{d}_{3,80} \lor \overline{d}_{6,200} \lor \\
\overline{d}_{3,100} & \lor \overline{d}_{6,100} \lor \overline{d}_{6,800} \lor \overline{d}_{3,400} \lor \overline{d}_{3,100} \lor \overline{d}_{3,200} \lor \\
\overline{d}_{3,400} & \lor \overline{d}_{6,100} \lor \overline{d}_{6,200} \lor \overline{d}_{3,8000} \lor \overline{d}_{6,8000}.
\end{align*}
$$

Sensors indicate that the heat exchanger is not available

where \(d_{ij}\) indicates a normal value from the sensor \(D_{ij}\) and \(\overline{d}_{ij}\) indicates a fault value from the sensor \(\overline{D}_{ij}\).

When the rule "H.E. not available" is activated, the following sensor information is useful in localizing faults:

$$
\overline{d}_{3,80} \overline{d}_{6,200} \overline{d}_{3,100} \overline{d}_{6,100} \overline{d}_{3,80} \overline{d}_{3,100} \overline{d}_{6,100} \overline{d}_{6,200} \overline{d}_{6,100} \overline{d}_{6,200}.
$$

Sensors indicate that both pumps are not operational due to either tripped circuit breakers or tripped overloads.

This can be divided further:

(1) \(d_{3,80} \overline{d}_{3,100} \overline{d}_{6,100} \overline{d}_{6,200} \rightarrow \) Sensors indicate a short in pump 1.

(2) \(\overline{d}_{3,80} d_{3,100} d_{6,100} d_{6,200} \rightarrow \) Sensors indicate a short circuit in primary wiring to pump 1.

(3) \(d_{3,80} \overline{d}_{3,100} \overline{d}_{6,100} \overline{d}_{6,200} \rightarrow \) Sensors indicate a short in pump 2.

(4) \(d_{3,80} \overline{d}_{3,100} d_{6,100} d_{6,200} \rightarrow \) Sensors indicate a short circuit in primary wiring to pump 2.

(5) \(d_{6,10} \overline{d}_{1,1} \rightarrow \) Low reservoir level sensor indicates the heat exchanger is not available. Add coolant and check for leaks. (Note that an analog sensor always has a value because for a signal of zero a current of 4 mA is the output. A sensor failure or data link failure is detected by not receiving the 4 mA.)
(6) \( \bar{d}_{6,10} a_{1,1} \) \( \rightarrow \) Low reservoir level signal is not available.

(7) \( \bar{d}_{6,20} a_{1,2000} \) \( \rightarrow \) Low nitrogen pressure indicates the heat exchanger is not available. Add nitrogen.

(8) \( \bar{d}_{6,20} a_{1,2000} \) \( \rightarrow \) Low-pressure cutoff switch signal is not available.

The next set of diagnostics involves control power:

(1) \( \bar{d}_{3,1} \rightarrow \bar{d}_{6,800} \)

(2) \( \bar{d}_{3,1} \lor \bar{d}_{6,800} \lor \bar{d}_{3,3400} \lor \bar{d}_{3,40} \) \( \rightarrow \) Sensors indicate a heat exchanger control short circuit.

(3) \( \bar{a}_{3,40} \lor \bar{d}_{6,800} \lor \bar{d}_{3,1} \) \( \rightarrow \) Sensors indicate a heat exchanger three-phase power fault.

(4) \( \bar{d}_{3,200} \lor \bar{d}_{3,400} \lor \bar{d}_{6,400} \lor \bar{d}_{6,800} \) \( \rightarrow \) Sensors indicate a short in fan 1.

(5) \( \bar{d}_{3,200} \lor \bar{d}_{3,400} \lor \bar{d}_{6,400} \lor \bar{d}_{6,800} \) \( \rightarrow \) Sensors indicate a short circuit in primary wiring to fan 1.

(6) \( \bar{d}_{3,200} \lor \bar{d}_{3,400} \lor \bar{d}_{6,400} \lor \bar{d}_{6,800} \) \( \rightarrow \) Sensors indicate a short circuit in primary wiring to fan 2.

B. "H.E. Available" Rules

The heat exchanger may be in need of maintenance and still be capable of cooling the transmitter. This condition is called "H.E. available." The following schema can be deduced from the "H.E. not available" rule:

(1) \( \{a_{1,800} - a_{1,2000}\} < 125 \text{ psig} \) \( \rightarrow \bar{a}_{1,800} \)

(2) \( \bar{a}_{1,20} \lor \bar{a}_{1,800} \lor (a_{1,20} > 2 \text{ gpm}) \lor \bar{d}_{6,4} \) \( \rightarrow \) The heat exchanger output flow is less than 20 gpm with a pressure of less than 125 psid as indicated by coolant flow sensors. Replace operating main pump.

(3) \( \bar{d}_{6,4} \lor \bar{d}_{6,10} \lor \bar{d}_{6,20} \) \( \rightarrow \) Relay K7 defective or heat exchanger control switch S2 in the off position. The heat exchanger may be operated locally until K7 is replaced.

(4) \( \bar{a}_{2,4} \lor \bar{a}_{2,8} \lor \bar{d}_{6,10} \lor \bar{d}_{6,20} \lor \bar{d}_{6,4} \) \( \rightarrow \) Fans are not operating properly. Both fans are off.

(5) \( \bar{a}_{1,40} \lor \bar{a}_{1,20} \lor \bar{a}_{2,4} \lor \bar{a}_{2,8} \lor \bar{a}_{2,8} \lor \bar{a}_{2,4} \lor \bar{a}_{2,8} \) \( \rightarrow \) Warning! Coolant temperature greater than 110°F and both fans are not on.

(6) \( \bar{a}_{6,1} \lor \bar{a}_{1,20} \) \( \rightarrow \) There is no flow in the purity loop. Replace the submicrometer filter (item 34 of the piping diagram).

(7) \( \bar{a}_{1,4} \lor \bar{a}_{1,20} \lor (t_r > 10 \text{ min}) \) \( \rightarrow \) Replace the purity cartridge (item 24 of the piping diagram).

(8) \( \bar{a}_{1,2} \lor \bar{a}_{1,4} \lor \bar{a}_{1,20} \lor (t_r > 1 \text{ hr}) \) \( \rightarrow \) Main coolant loop is being contaminated. Localize the cause of contamination. Replace defective component.

(9) \( a_{1,20} < 2 \text{ gpm} \) \( \lor \bar{d}_{3,1} \lor \bar{d}_{3,800} \lor \bar{d}_{6,2} \lor \bar{d}_{6,4} \lor \bar{d}_{6,10} \lor \bar{d}_{3,80} \lor \bar{d}_{6,10} \lor \bar{d}_{6,20} \lor \bar{d}_{6,800} \) \( \rightarrow \) Sensors indicate a heat exchanger control open circuit.

The transmitter and heat exchanger are usually operated with the heat exchanger controlled by the transmitter. It is also possible to operate the heat exchanger from local controls. This condition is detected only when the transmitter is off and the heat exchanger is on. If both systems are on, there is no way to tell that the heat exchanger is being operated locally:

\( a_{1,20} \lor \bar{d}_{6,4} \) \( \rightarrow \) Heat exchanger under local control.

An interlock fault is indicated when a switch sensor located in the transmitter indicates a fault. A corresponding analog sensor provides the actual value for each interlock. Since these are independent of each other, small differences in calibration can be expected. The heat exchanger may be operating cor-
rectly and an interlock fault may indicate a problem in the transmitter:

\[
\begin{align*}
& a_{1,20} a_{1,800} \cdot d_{5,1} V d_{5,2} V d_{5,4} V d_{5,8} V d_{5,10} V \\
& d_{5,20} V d_{5,40} V d_{5,80} : \quad \text{Interlock monitoring problem, not a heat exchanger problem.}
\end{align*}
\]

The following sensor information is useful in isolating interlock faults:

1. \( a_{1,20} a_{1,800} \cdot d_{5,1} V d_{5,2} V d_{5,4} V d_{5,8} V d_{5,10} V \\
   d_{5,20} V d_{5,40} V d_{5,80} \) \quad \text{Sensors indicate the cause of the interlock is the heat exchanger.}

2. \( d_{5,1} V d_{5,4} V d_{5,10} V d_{5,40} \) \quad \text{Flow interlock:}
   - Magnet flow
   - Body flow
   - Collector flow
   - RF load flow

3. \( d_{5,2} V d_{5,8} V d_{5,20} V d_{5,80} \) \quad \text{Temperature interlock:}
   - Magnet temperature
   - Body temperature
   - Collector temperature
   - RF load temperature

The values of flow and temperature would be given where the dashed lines appear. These values provide valuable information to a maintenance technician.

A condition for the cycling is that a different pump and a different fan be turned on each time the heat exchanger is turned on. Turn-on counter \( t_c \) is incremented each time the heat exchanger is turned on.

**Pumps cycling:**

1. \( d_{3,10} d_{3,20} \) \quad \text{Pump 1 is on.}
2. \( d_{3,10} d_{3,20} \) \quad \text{Pump 2 is on.}
3. \( d_{3,10} d_{3,20} (t_c) \cdot d_{3,10} d_{3,20} (t_c + 1) : \quad \text{Pumps are cycling properly.}
4. \( d_{3,10} d_{3,20} (t_c) \cdot d_{3,10} d_{3,20} (t_c + 1) : \quad \text{Pumps are cycling properly.}
5. \( d_{3,10} d_{3,20} (t_c) : d_{3,10} d_{3,20} (t_c + 1) : \quad \text{Pumps are not cycling properly.}

**Fans cycling:**

1. \( d_{3,10} d_{3,20} \) \quad \text{Fan 1 is on.}
2. \( d_{3,10} d_{3,20} \) \quad \text{Fan 2 is on.}
3. \( d_{3,10} d_{3,20} (t_c) \cdot d_{3,10} d_{3,20} (t_c + 1) : \quad \text{Fans are cycling properly.}
4. \( d_{3,10} d_{3,20} (t_c) \cdot d_{3,10} d_{3,20} (t_c + 1) : \quad \text{Fans are cycling properly.}
5. \( d_{3,10} (t_c) : d_{3,10} (t_c + 1) : \quad \text{Fans are not cycling properly.}

This is not an exhaustive set of rules. Additional rules should be added by maintenance personnel as experience is obtained with actual failures and repairs. Ideally, each failure should be analyzed and new rules developed to improve the capability of the expert system.

**V. Other Diagnostics**

Analysis of heat exchanger efficiency and trends such as reservoir level changes can be implemented. This type of information alerts maintenance personnel to possible future problems. Preventive or scheduled maintenance can correct a potential problem before an actual failure occurs.

A decreasing reservoir level indicates a leak which, if not corrected, will lead to an equipment failure. Actually, detecting the tank level is somewhat complicated. The reservoir level changes when the pumps are turned on due to the expansion of the piping caused by the increased pressure at the output of the pumps. Another factor is the expansion of metals due to temperature. These complications can be taken into account in one of two ways: the variation of each measured parameter can be found and appropriate corrections made, or the measurement can be made only at times when conditions are identical. For example, the tank level will be measured only when the pumps are off and the temperature is within defined limits.

The heat exchanger efficiency was a different problem. Deteriorating efficiency indicates future problems. Originally, it was intended to calculate the U-factors in the following manner [3]:

\[
q = UA \Delta T_m
\]

where

\[
U = \text{overall heat-transfer coefficient}
\]
\( A \) = surface area for heat transfer consistent with the definition of U

\( \Delta T_m \) = suitable mean temperature difference across the heat exchanger

However, this method proved to be impractical for a number of reasons. Some of the parameters needed are difficult to measure (e.g., mass air flow); some of the sensors proved to be unreliable; some of the sensors were not available (e.g., sensors to measure specific heat of the coolant); and the heat is dissipated in other places outside the heat exchanger core. (The dissipation of heat in the long piping lines between the heat exchanger and the transmitter depends on the elements, such as rain, snow, ambient temperature, and wind.) Actually, the choice of U-factors was a bad one. A better choice would have been the Effectiveness-NTU method, defined as

\[
\text{effectiveness} = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}}
\]

This method has the advantage that the inlet and outlet air temperature do not have to be measured. The disadvantage of this method is the difficulty in obtaining the mass flow rate of air across the coil.

However, the problem can be reduced to a much simpler one. The heat taken out of the coolant by the coil can be measured without difficulty, and the efficiency of the heat transferred is a function of the difference in temperature between the coolant temperature at the outlet of the coil and the air ambient temperature. The heat exchanger can be calibrated and a table of values stored for comparison. Corrections can be made for the specific heat of the coolant, air humidity, and barometric pressure. Allowing for data errors, a value of the efficiency can be used to estimate long-term degradation in cooling efficiency. The failure to measure U-factors appears to be a case of insufficient investigation of the problem during the design stage. As described above, however, a simple alternative exists that could provide the information needed by maintenance personnel.

VI. Conclusions

Based on the work carried out, the following conclusions were made:

1. The use of propositional logic is well suited to the development of expert maintenance systems.
2. The development of expert maintenance systems must involve on-site maintenance personnel.
3. The expert system must include not only past experience but present and future experience as well.
4. The initial effort need not be exhaustive, but rather should form a shell that can be expanded with new rules and new procedures. In this way it will be easily accepted by users and can be developed to reach its full potential.

References


<table>
<thead>
<tr>
<th>Sensor number</th>
<th>Description</th>
<th>Definition</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-01*0001</td>
<td>Reservoir level transducer</td>
<td>&gt;1.5 ft → a_{1,1}</td>
<td></td>
</tr>
<tr>
<td>A-01*0002</td>
<td>Resistivity inlet purity</td>
<td>&gt;2 megohms/cm² → a_{1,2}</td>
<td></td>
</tr>
<tr>
<td>A-01*0004</td>
<td>Resistivity outlet purity</td>
<td>&gt;5 megohms/cm² → a_{1,4}</td>
<td></td>
</tr>
<tr>
<td>A-01*0008</td>
<td>HE core flow</td>
<td>a_{1,8}</td>
<td></td>
</tr>
<tr>
<td>A-01*0010</td>
<td>HE bypass flow</td>
<td>&gt;20 gpm → a_{1,10}</td>
<td></td>
</tr>
<tr>
<td>A-01*0020</td>
<td>HE total flow</td>
<td>&lt;112°F → a_{1,40}</td>
<td></td>
</tr>
<tr>
<td>A-01*0080</td>
<td>HE core outlet temperature</td>
<td>a_{1,80}</td>
<td></td>
</tr>
<tr>
<td>A-01*0100</td>
<td>HE assy inlet temperature</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-01*0200</td>
<td>Ambient air temperature</td>
<td>a_{1,200}</td>
<td>not usable; too noisy</td>
</tr>
<tr>
<td>A-01*0400</td>
<td>Core air flow pressure delta</td>
<td>a_{1,800}</td>
<td></td>
</tr>
<tr>
<td>A-01*0800</td>
<td>Pump outlet pressure</td>
<td>a_{1,1000}</td>
<td></td>
</tr>
<tr>
<td>A-01*1000</td>
<td>Core outlet pressure</td>
<td>&gt;15 psig → a_{1,2000}</td>
<td></td>
</tr>
<tr>
<td>A-01*4000</td>
<td>Pump inlet temperature</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-01*8000</td>
<td>Heater outlet temperature</td>
<td>not part of DSN HE</td>
<td></td>
</tr>
<tr>
<td>A-02*0001</td>
<td>Pump 1 motor load</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-02*0002</td>
<td>Pump 2 motor load</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-02*0004</td>
<td>Fan #1 motor load</td>
<td>&gt;1200 watts → a_{2,4}</td>
<td></td>
</tr>
<tr>
<td>A-02*0008</td>
<td>Fan #2 motor load</td>
<td>&gt;1200 watts → a_{2,8}</td>
<td></td>
</tr>
<tr>
<td>A-02*0010</td>
<td>Fan #1 speed</td>
<td>not reliable</td>
<td></td>
</tr>
<tr>
<td>A-02*0020</td>
<td>Fan #2 speed</td>
<td>not reliable</td>
<td></td>
</tr>
<tr>
<td>A-02*0040</td>
<td>3-way valve position</td>
<td>not working</td>
<td></td>
</tr>
<tr>
<td>A-02*0080</td>
<td>Spare</td>
<td>not attended</td>
<td></td>
</tr>
<tr>
<td>A-02*0100</td>
<td>HE assy outlet temperature</td>
<td>&lt;15 psid → a_{2,400}</td>
<td></td>
</tr>
<tr>
<td>A-02*0200</td>
<td>Heater load</td>
<td>not part of DSN HE</td>
<td></td>
</tr>
<tr>
<td>A-02*0400</td>
<td>Differential pressure across main line filter</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-03*0001</td>
<td>Auxiliary contacts on CB6</td>
<td>d_{3,1}</td>
<td>b_{6}</td>
</tr>
<tr>
<td>D-03*0002</td>
<td>Auxiliary contacts on K5</td>
<td>d_{3,4}</td>
<td>k_{1}</td>
</tr>
<tr>
<td>D-03*0004</td>
<td>Auxiliary contacts on K1</td>
<td>d_{3,8}</td>
<td>k_{2}</td>
</tr>
<tr>
<td>D-03*0008</td>
<td>Auxiliary contacts on K2</td>
<td>d_{3,10}</td>
<td>k_{3}</td>
</tr>
<tr>
<td>D-03*0010</td>
<td>Auxiliary contacts on K3</td>
<td>d_{3,20}</td>
<td>k_{4}</td>
</tr>
<tr>
<td>D-03*0020</td>
<td>Auxiliary contacts on K4</td>
<td>d_{3,40}</td>
<td>p_{2}</td>
</tr>
<tr>
<td>D-03*0040</td>
<td>Auxiliary contacts on K6</td>
<td>d_{3,80}</td>
<td>b_{1}</td>
</tr>
<tr>
<td>D-03*0080</td>
<td>Auxiliary contacts on CB1</td>
<td>d_{3,100}</td>
<td>b_{2}</td>
</tr>
<tr>
<td>D-03*0100</td>
<td>Auxiliary contacts on CB2</td>
<td>d_{3,200}</td>
<td>b_{3}</td>
</tr>
<tr>
<td>D-03*0200</td>
<td>Auxiliary contacts on CB3</td>
<td>d_{3,400}</td>
<td>b_{4}</td>
</tr>
<tr>
<td>D-03*0400</td>
<td>Auxiliary contacts on CB4</td>
<td>not used</td>
<td>c_{c}</td>
</tr>
<tr>
<td>D-03*0800</td>
<td>Auxiliary contacts on CB5</td>
<td>not working on test HE</td>
<td></td>
</tr>
<tr>
<td>D-03*1000</td>
<td>Auxiliary contacts on K8</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-03*2000</td>
<td>Limit SW #1, plenum door</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-03*4000</td>
<td>Limit SW #2, plenum door</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-03*8000</td>
<td>Auxiliary contacts on CB7</td>
<td>d_{3,8000}</td>
<td></td>
</tr>
<tr>
<td>A-04*0001</td>
<td>Magnet flow</td>
<td>&gt;1.5 gpm → a_{4,1}</td>
<td></td>
</tr>
<tr>
<td>A-04*0002</td>
<td>Magnet temperature</td>
<td>&lt;70°C → a_{4,2}</td>
<td></td>
</tr>
<tr>
<td>A-04*0004</td>
<td>Body flow</td>
<td>&gt;1.2 gpm → a_{4,2}</td>
<td></td>
</tr>
<tr>
<td>A-04*0008</td>
<td>Body temperature</td>
<td>&lt;70°C → a_{4,4}</td>
<td></td>
</tr>
<tr>
<td>A-04*0010</td>
<td>Collector flow</td>
<td>&gt;18 gpm → a_{4,10}</td>
<td></td>
</tr>
<tr>
<td>A-04*0020</td>
<td>Collector temperature</td>
<td>&lt;70°C → a_{4,20}</td>
<td></td>
</tr>
<tr>
<td>A-04*0040</td>
<td>RF load flow</td>
<td>&gt;6 gpm → a_{4,40}</td>
<td></td>
</tr>
<tr>
<td>A-04*0080</td>
<td>RF load temperature</td>
<td>&lt;70°C → a_{4,80}</td>
<td></td>
</tr>
<tr>
<td>A-04*0100</td>
<td>Magnet voltage</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-04*0200</td>
<td>Magnet current</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>Sensor number</td>
<td>Description</td>
<td>Definition</td>
<td>Statement</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------</td>
<td>---------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>A-04*0400</td>
<td>Spare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-04*0800</td>
<td>Body current</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-04*1000</td>
<td>RF load power</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-04*2000</td>
<td>Spare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-04*4000</td>
<td>Beam voltage</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>A-04*8000</td>
<td>Beam current</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-05*0001</td>
<td>Low magnet flow interlock</td>
<td>d5,1</td>
<td></td>
</tr>
<tr>
<td>D-05*0002</td>
<td>High magnet temperature interlock</td>
<td>d5,2</td>
<td></td>
</tr>
<tr>
<td>D-05*0008</td>
<td>High body temperature interlock</td>
<td>d5,8</td>
<td></td>
</tr>
<tr>
<td>D-05*0010</td>
<td>Low collector flow interlock</td>
<td>d5,10</td>
<td></td>
</tr>
<tr>
<td>D-05*0020</td>
<td>High collector temperature interlock</td>
<td>d5,20</td>
<td></td>
</tr>
<tr>
<td>D-05*0040</td>
<td>Low RF load flow interlock</td>
<td>d5,40</td>
<td></td>
</tr>
<tr>
<td>D-05*0080</td>
<td>High RF load temperature interlock</td>
<td>d5,80</td>
<td></td>
</tr>
<tr>
<td>D-05*0100</td>
<td>RF load and RF power range</td>
<td>not used</td>
<td></td>
</tr>
<tr>
<td>D-06*0001</td>
<td>Purity loop flow switch</td>
<td>d6,1</td>
<td>k_7</td>
</tr>
<tr>
<td>D-06*0002</td>
<td>Auxiliary contacts on K7</td>
<td>d6,2</td>
<td>k_7</td>
</tr>
<tr>
<td>D-06*0004</td>
<td>Monitor control power across connector pins A and B</td>
<td>d6,4</td>
<td>P_1</td>
</tr>
<tr>
<td>D-06*0008</td>
<td>Auxiliary contacts on S8</td>
<td>d6,8</td>
<td>s_3</td>
</tr>
<tr>
<td>D-06*0020</td>
<td>Low reservoir level switch</td>
<td>d6,10</td>
<td>s_1</td>
</tr>
<tr>
<td>D-06*0040</td>
<td>Monitor control power across connector pins A and B</td>
<td>d6,20</td>
<td></td>
</tr>
<tr>
<td>D-06*0080</td>
<td>PM1 resistivity meter status</td>
<td>d6,40</td>
<td></td>
</tr>
<tr>
<td>D-06*0100</td>
<td>PM2 resistivity meter status</td>
<td>d6,80</td>
<td></td>
</tr>
<tr>
<td>D-06*0200</td>
<td>OL1 K1 thermal O/L status</td>
<td>d6,100</td>
<td>o_1</td>
</tr>
<tr>
<td>D-06*0400</td>
<td>OL2 K2 thermal O/L status</td>
<td>d6,200</td>
<td>o_2</td>
</tr>
<tr>
<td>D-06*0800</td>
<td>OL4 K4 thermal O/L status</td>
<td>d6,400</td>
<td>o_3</td>
</tr>
<tr>
<td>D-06*1000</td>
<td>OL5 K5 thermal O/L status</td>
<td>d6,800</td>
<td>o_4</td>
</tr>
<tr>
<td>D-06*2000</td>
<td>S4 pressure switch status</td>
<td>not working in test HE</td>
<td>s_4</td>
</tr>
<tr>
<td>D-06*4000</td>
<td>S5 pressure switch status</td>
<td>not working in test HE</td>
<td>s_5</td>
</tr>
<tr>
<td>D-06*8000</td>
<td>120-Vac control power status</td>
<td>d6,8000</td>
<td>k_15</td>
</tr>
<tr>
<td></td>
<td>S2 panel control switch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Remote</td>
<td>c_r</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>c_0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>c_l</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TDR1 pump 1 time delay relay</td>
<td>t_1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TDR2 pump 2 time delay relay</td>
<td>t_2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S_10 pump alternating disable switch</td>
<td>s_10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K9 pump alternating relay</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pump 1</td>
<td>t_1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pump 2</td>
<td>t_2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K14 fan alternating relay</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fan 1</td>
<td>t_1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fan 2</td>
<td>t_2</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1. Heat exchanger flow diagram
Fig. 2. Heat exchanger electrical schematic
Appendix
Logic Symbol Definitions

The symbols used in the description of the operation of the assemblies of the transmitter were taken from [4]. They are described below.

Negation. A bar above a letter represents negation of the statement that this letter represents. For example, \( \overline{p} \) means "not-p" or \(-p\). The meaning of negation is summed up in "the negation of a true statement is false; the negation of a false statement is true."

Conjunction. The conjunction of two statements such as \( p \) and \( q \) is represented as \( pq \). The meaning of conjunction is taken to mean "a conjunction of statements all of which are true is true, and a conjunction of statements not all of which are true is false."

Alternation. The alternation of two statements such as \( p \) or \( q \) is represented as \( p \lor q \). The meaning of alternation is given by this rule: "An alternation is true if at least one of the components is true and otherwise false."

Conditional. A statement of the form "if \( p \) then \( q \)" is represented as \( p \rightarrow q \) and is called a conditional. The \("p\) component is called the antecedent and the \("q\) component is called the consequent. Note that the antecedent is not to be interpreted to be the cause of the consequent. If the antecedent is false, the conditional is taken as true regardless of whether the consequent is true or false. The relation is "if \( p \) then \( q \)" and "if \( q \) then \( p \)." It is represented as \( p \leftrightarrow q \) and is called biconditional.

Grouping. The dot convention is used in place of brackets. The insertion of a dot indicates a greater break at the point where it is inserted. For example, \( pq \lor r \) is understood to mean "\((pq) \lor r \)". If the intent is \( (pq \lor r) \), the representation is \( p \cdot q \lor r \), indicating the break between "\( p \) and \( q \)." Greater emphasis is indicated by the use of multiple dots such \("\cdot\)\), \("\cdot\cdot\)\), etc.

Consistency and validity. A schema is called consistent if it comes out true under some interpretation of its letters. A schema is valid if it is true under every interpretation of its letters.