# A Method for Diagnosing Time Dependent Faults using Model-Based Reasoning Systems

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## Abstract

This paper explores techniques to apply model-based reasoning to equipment and systems which exhibit dynamic behavior (that which changes as a function of time). The model-based system of interest is KATE-C (Knowledge based Autonomous Test Engineer) which is a C++ based system designed to perform monitoring and diagnosis of Space Shuttle electro-mechanical systems. Methods of model-based monitoring and diagnosis are well known and have been thoroughly explored by others[1] A short example is given which illustrates the principle of model-based reasoning and reveals some limitations of static, non-time-dependent simulation. This example is then extended to demonstrate representation of time-dependent behavior and testing of fault hypotheses in that environment.

## Model-Based Reasoning Overview

Model-Based Reasoning is a technique which compares simulated measurement values with actual readings from the physical system and attempts to diagnose component failures when a significant discrepancy exists (see figure 1).
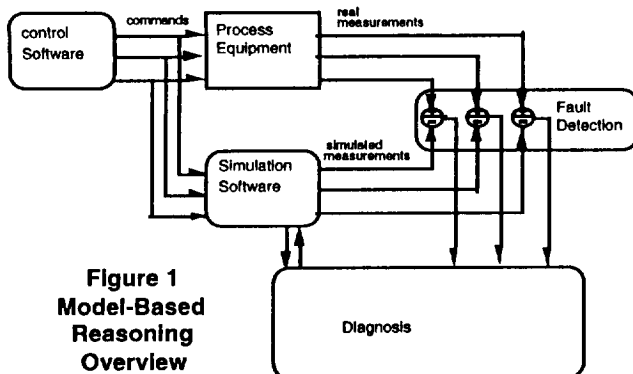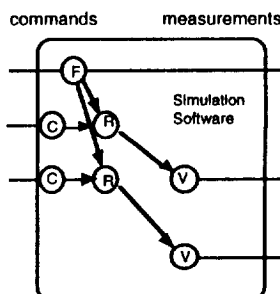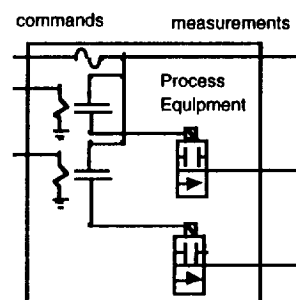


**Figure 1
Model-Based
Reasoning
Overview**

To be practical for monitoring and diagnosis, the simulation should occur in real-time in parallel with operation of the process equipment. Inputs to the process equipment are sent to the simulator. The simulator computes expected values for each of the components in the equipment including measurements.

When measurements predicted by the simulator disagree significantly with those observed in the process equipment, an anomaly has occurred. Anomalous behavior may indicate that some component of the process equipment has failed.

Diagnosis is accomplished by generating fault hypotheses for various components and substituting these values in the simulator. The simulation is then re-calculated taking the failure into account. If the simulator now predicts measurements that agree with those observed, the fault hypothesis is reported as a plausible explanation for the anomalous behavior.

To illustrate how this works, consider the system shown in figure 2.



**Knowledge Base Example
Figure 2**

This figure shows details inside the "process equipment" box and the "simulation software" box from Figure 1. Two solenoid valves are shown in the "process box" along with two relays which actuate the valves and a single fuse which provides power to the solenoids. In the "simulation box" is a knowledge base which represents this equipment. F represents the fuse, R the relays, C the relay coils, and V the solenoid valves. The arrows represent the calculation of the simulation. Commands from the outside are directed to the relay coils and the fuse. The fuse outputs to the relays; and they in turn, output power to the solenoids. Measurements of the valve positions are reported to the outside world.

To further illustrate the technique, this knowledge-base may be represented by a spreadsheet.

Figure 3a shows **formulas** in a Microsoft Excel Spreadsheet which simulates the equipment shown in Figure 2. When power is on or =TRUE, then the fuse is

also =TRUE. When the fuse is =TRUE then the relays and valves may be turned on or off with command_1 and command_2.

| COMMANDS: | | | |
|---|---|---|---|
| POWER | FUSE | RELAY 1 | VALVE 1 |
| =TRUE | =POWER | =IF(FUSE,COMMAND_1,FALSE) | =RELAY_1 |
| | | | |
| COMMAND 1 | COIL 1 | | |
| =TRUE | =COMMAND_1 | | |
| | | | |
| COMMAND 2 | COIL 2 | RELAY 2 | VALVE 2 |
| =TRUE | =COMMAND_2 | =IF(FUSE,COMMAND_2,FALSE) | =RELAY_2 |

Figure 3a (spreadsheet formulas)

Figures 3b and 3c show the **values** calculated by the spreadsheet. Changing the value of any of the commands causes the spreadsheet to be recalculated.

| COMMANDS: | | | |
|---|---|---|---|
| POWER | FUSE | RELAY 1 | VALVE 1 |
| TRUE | TRUE | TRUE | TRUE |
| | | | |
| COMMAND 1 | COIL 1 | | |
| TRUE | TRUE | | |
| | | | |
| COMMAND 2 | COIL 2 | RELAY 2 | VALVE 2 |
| TRUE | TRUE | TRUE | TRUE |

Figure 3b spreadsheet values (command_1 =TRUE)

For example, Setting command_1 =FALSE causes coil_1, relay_1 and valve_1 to be =FALSE.

| COMMANDS: | | | |
|---|---|---|---|
| POWER | FUSE | RELAY 1 | VALVE 1 |
| TRUE | TRUE | FALSE | FALSE |
| | | | |
| COMMAND 1 | COIL 1 | | |
| FALSE | FALSE | | |
| | | | |
| COMMAND 2 | COIL 2 | RELAY 2 | VALVE 2 |
| TRUE | TRUE | TRUE | TRUE |

Figure 3c spreadsheet values (command_1 =FALSE)

Diagnosis can be demonstrated by setting one of the component values in the spreadsheet to a hypothetical failed value. Figure 3d shows failure of the fuse. The cell representing the fuse is set =FALSE. As a result, both relays and valves are turned off.

| COMMANDS: | FAILED!! | | |
|---|---|---|---|
| POWER | FUSE | RELAY 1 | VALVE 1 |
| TRUE | FALSE | FALSE | FALSE |
| | | | |
| COMMAND 1 | COIL 1 | | |
| TRUE | TRUE | | |
| | | | |
| COMMAND 2 | COIL 2 | RELAY 2 | VALVE 2 |
| TRUE | TRUE | FALSE | FALSE |

Figure 3d Diagnosis: (FUSE =FAILED)

Externally, the failed system is configured the same as Figure 3b - both commands and power are on. If measurements of the valves in 3b read closed, this would represent an anomaly. The anomaly is resolved by the hypothetical failure inserted in 3d since the simulated measurements for the two valves agree with actual measurements resulting from a blown fuse.

## Adding a Time Dimension to Model-based Simulation

In the past, KATE-C knowledge bases have represented time by means of components with state.



Figure 4 Latching Relay
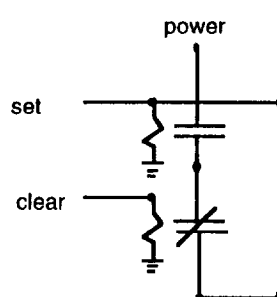
A component with state is one in which its present value depends on its previous condition or state. Consider figure 4, a latching relay. The relay stays on once the set command has been issued and until the clear command is activated.

The spreadsheet for the latching relay is shown in figure 5. The spreadsheet simulating the relay contains a *circular reference*; i.e. the formula for RELAY_3 refers to its old value. This works well and simulates the latching mechanism faithfully.

| Command: | RELAY 3 |
|---|---|
| SET | =AND(NOT(CLEAR),OR(SET,RELAY_3)) |
| =TRUE | |
| CLEAR | |
| =FALSE | |

Figure 5 - Spreadsheet Formulas for Latch

Unfortunately there is no way to tell solely from the inputs what the condition of this relay should be. The history of the set and clear commands must be known as well as the initial value of the relay.

Another type of problem that has been represented by objects with state is a tank. The tank simulation references the previous value for its contents and the rate of flow filling the tank in order to compute the new level in the tank. In order to simulate a hypothetical failure, it is necessary to restore the model state of all components at the time of failure, insert a fault, re-simulate to TIME=NOW, and determine if the fault hypothesis is valid throughout the intervening time period.

### Freon Cooling Loop

A current KATE-C application is an intelligent monitoring and diagnostic system for the Shuttle's Environmental Control and Life Support System (ECLSS). KATE encounters time-dependent anomalies which arise during the normal operation of ECLSS. For example, one of the ECLSS subsystems is a Freon cooling loop (figure 6) where excess heat from various avionic systems is transferred to the freon cooling loop and dissipated in one or more heat sinks.
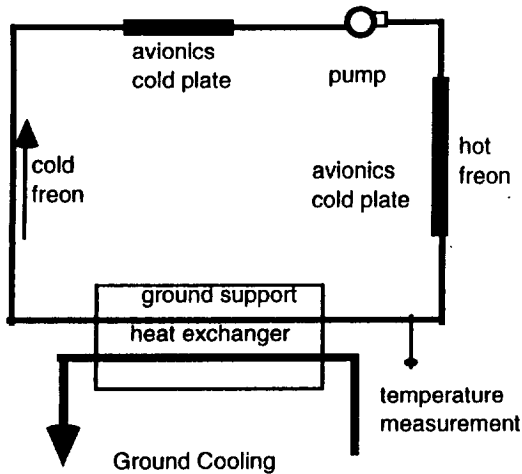
**Orbiter Freon Cooling Loop**

**Figure 6**

A anomaly arises when unanticipated changes in Freon temperature occur. Changes in heat which is added or subtracted from the circulating freon do not show up until minutes after a component failure when hotter or colder freon than expected reaches a measurement further around the loop.

For example, when the Orbiter's Ground Support Heat Exchanger loses ground cooling, the hotter temperatures take anywhere from 30 seconds to three minutes to start showing up at remote measurement points. The problem is to represent this type of dynamic effect in a way that will allow us to diagnose such a fault as though its gradual, time-dependent measurement anomalies had happened instantly.

## Alternatives to Objects With State

An alternative representation of time in such situations may be useful for model-based diagnosis and monitoring systems. One such representation is illustrated with the help of an example called the Bucket Brigade Problem. In this scenario, buckets of sand travel on a conveyor belt from left to right. At the beginning of the line, buckets pass under two hoppers which deliver sand at a controlled rate. The moving buckets are thus partially filled with sand. A load sensor under the conveyor measures the weight of the buckets at the end of the belt. This problem is time dependent because an unanticipated change (fault) in delivery rate from one of the hoppers will not be detected until some time later when the bucket passes over the load sensor.
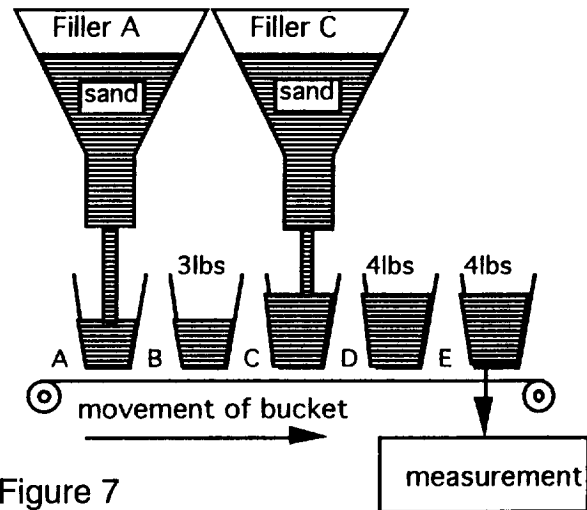


**Figure 7**

## The Bucket Brigade Problem

In order to solve this problem, a knowledge base is used which represents bucket weights and sand delivery at several discrete intervals of time. By representing several time intervals to KATE-C simultaneously, it is possible to determine the time and nature of a fault as long as it occurs within the limits of time represented in the Knowledge Base.

| TIME | Bucket | | Station | | | | Fill Rate | fill rate |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | | at A | at C |
| T= NOW | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-1 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-2 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-3 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-4 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-5 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-6 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-7 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-8 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-9 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-10 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-11 | 3 | 3 | 4 | 4 | * | | 3 | 1 |
| T-12 | 3 | 3 | 4 | * | * | | 3 | 1 |
| T-13 | 3 | 3 | * | * | * | | 3 | * |
| T-14 | 3 | * | * | * | * | | 3 | * |

Figure 8 - Bucket Brigade Spreadsheet(* = unknown value)

Sand in A for time=NOW is determined by the fill rate at A for T=NOW. Sand at B NOW is determined by the fill rate at A at T-1. Sand in C is A:T-2 +C:NOW. and so forth. Here are the formulas for the first 2 rows of Bucket data:

| \ | N | O | P | Q | R | S | T | U | V |
|---|---|---|---|---|---|---|---|---|---|
| 2 | TIME | | Bucket | Station | | | | fill rate | fill rate |
| 3 | | A | B | C | D | E | | at A | at C |
| 4 | T= NOW | =U4 | =U5 | =U6+V4 | =U7+V5 | =U8+V6 | | 3 | 1 |
| 5 | T-1 | =U5 | =U6 | =U7+V5 | =U8+V6 | =U9+V7 | | 3 | 1 |

Figrure 9 - Bucket Formulas

To get an idea of how this model works consider Figure 8. With fill rates at A and C steady for the last 14 time

periods, the weight in Bucket E will be a constant 4 pounds.

If the delivery rate of sand at A fails to 0 pounds at T-5 as shown in figure 10, the measurement at E will begin to register 1 pound instead of 4 at T-1. This simultaneous representation of model values and time in the knowledge base enables a fault hypothesis with a specified time (A, 0 pounds, T-5) to be correctly diagnosed.

| TIME | A | Bucket B | Station C | D | E | | Fill Rate at A | fill rate at C |
|---|---|---|---|---|---|---|---|---|
| T=NOW | 0 | 0 | 1 | 1 | 1 | | 0 | 1 |
| T-1 | 0 | 0 | 1 | 1 | 1 | | 0 | 1 |
| T-2 | 0 | 0 | 1 | 1 | 4 | | 0 | 1 |
| T-3 | 0 | 0 | 1 | 4 | 4 | | 0 | 1 |
| T-4 | 0 | 0 | 4 | 4 | 4 | | 0 | 1 |
| T-5 | 0 | 3 | 4 | 4 | 4 | | 0 | 1 |
| T-6 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-7 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-8 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-9 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-10 | 3 | 3 | 4 | 4 | 4 | | 3 | 1 |
| T-11 | 3 | 3 | 4 | 4 | * | | 3 | 1 |
| T-12 | 3 | 3 | 4 | * | * | | 3 | * |
| T-13 | 3 | 3 | * | * | * | | 3 | * |
| T-14 | 3 | * | * | * | * | | 3 | * |

Figure 10 - Fill rate at A failed to 0 at T-5
(* = unknown value)

## A Loop of Buckets

The bucket problem is somewhat trivial. To demonstrate that this technique can be extended to a problem such as the freon loop consider the following modification to our bucket apparatus:
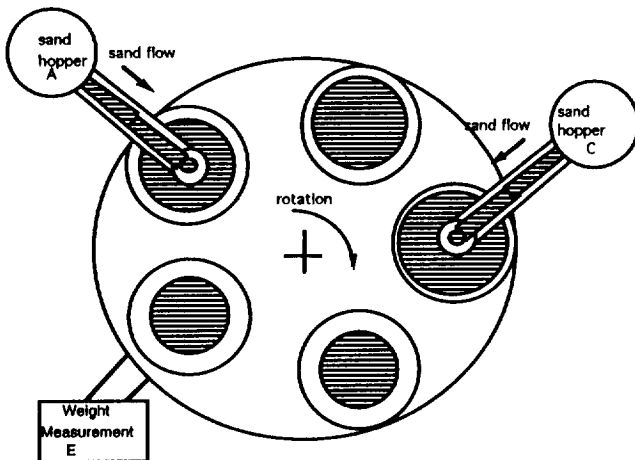


Figure 11 - A turntable of buckets - plan view

Instead of falling off the end of the conveyor belt and dumping its load of sand, suppose that the bucket at E is recycled to A without emptying its load. We can represent the load at A by reference to the load at E at time T-1. Figure 12 represents the formulas for the first two rows of the spreadsheet:

| \ | N | O | P | Q | R | S | T | U | V |
|---|---|---|---|---|---|---|---|---|---|
| 2 | TIME | | Bucket | Station | | | | fill rate | fill rate |
| 3 | | A | B | C | D | E | | at A | at C |
| 4 | T=NOW | =U4+S5 | =U5+S6 | =U6+V4+S7 | =U7+V5+S8 | =U8+V6+S9 | | 3 | 1 |
| 5 | T-1 | =U5+S6 | =U6+S7 | =U7+V5+S8 | =U8+V6+S9 | =U9+V7+S10 | | 3 | 1 |

Figrure 12 - Bucket Loop Formulas

If the sand is delivered at the same rate as before at A and C, the weight in the buckets will accumulate over time as shown in the following table:

| TIME | A | Bucket B | Station C | D | E | | fill rate at A | fill rate at C |
|---|---|---|---|---|---|---|---|---|
| T=NOW | 12 | 12 | 12 | 12 | 12 | | 3 | 1 |
| T-1 | 12 | 11 | 12 | 12 | 9 | | 3 | 1 |
| T-2 | 11 | 11 | 12 | 9 | 9 | | 3 | 1 |
| T-3 | 11 | 11 | 9 | 9 | 8 | | 3 | 1 |
| T-4 | 11 | 8 | 9 | 8 | 8 | | 3 | 1 |
| T-5 | 8 | 8 | 8 | 8 | 8 | | 3 | 1 |
| T-6 | 8 | 7 | 8 | 8 | 5 | | 3 | 1 |
| T-7 | 7 | 7 | 8 | 5 | 5 | | 3 | 1 |
| T-8 | 7 | 7 | 5 | 5 | 4 | | 3 | 1 |
| T-9 | 7 | 4 | 5 | 4 | 4 | | 3 | 1 |
| T-10 | 4 | 4 | 4 | 4 | 4 | | 3 | 1 |
| T-11 | 4 | 3 | 4 | 4 | 1 | | 3 | 1 |
| T-12 | 3 | 3 | 4 | 1 | 1 | | 3 | 1 |
| T-13 | 3 | 3 | 1 | 1 | 0 | | 3 | 1 |
| T-14 | 3 | 0 | 1 | 0 | 0 | | 3 | 1 |
| T-15 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 |

Figure 13 - Bucket Loop Results

Because the sand is delivered to the buckets at two different rates and because both delivery points are at one side of the table, weight in the buckets increases as time passes, but the measurement history has a somewhat choppy appearance. The profile of the measurement history at E is as follows:
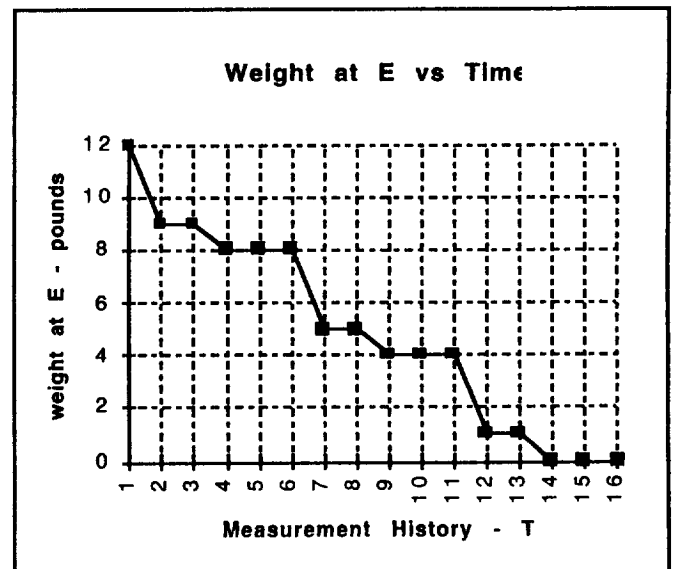


Figure 14 - Measurement history at E

If the sand delivery at A fails to 0 pounds at time T-7, the following pattern emerges in the spreadsheet:

| TIME | | Bucket | Station | | | | fill rate | fill rate |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | | at A | at C |
| T= NOW | 6 | 6 | 6 | 9 | 9 | | 0 | 1 |
| T-1 | 6 | 5 | 9 | 9 | 6 | | 0 | 1 |
| T-2 | 5 | 8 | 9 | 6 | 6 | | 0 | 1 |
| T-3 | 8 | 8 | 6 | 6 | 5 | | 0 | 1 |
| T-4 | 8 | 5 | 6 | 5 | 8 | | 0 | 1 |
| T-5 | 5 | 5 | 5 | 8 | 8 | | 0 | 1 |
| T-6 | 5 | 4 | 8 | 8 | 5 | | 0 | 1 |
| T-7 | 4 | 7 | 8 | 5 | 5 | | 0 | 1 |
| T-8 | 7 | 7 | 5 | 5 | 4 | | 3 | 1 |
| T-9 | 7 | 4 | 5 | 4 | 4 | | 3 | 1 |
| T-10 | 4 | 4 | 4 | 4 | 4 | | 3 | 1 |
| T-11 | 4 | 3 | 4 | 4 | 1 | | 3 | 1 |
| T-12 | 3 | 3 | 4 | 1 | 1 | | 3 | 1 |
| T-13 | 3 | 3 | 1 | 1 | 0 | | 3 | 1 |
| T-14 | 3 | 0 | 1 | 0 | 0 | | 3 | 1 |
| T-15 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 |

Figure 15 - Bucket Loop Results with failure of A at T-7

The measurement history with a failed delivery at A is unusual because of the unique features of the system. Such a fault would be difficult to diagnose intuitively. Reference to the model gives the engineer the advantage of being able to recognize the effects of various faults more quickly and decisively. The profile of the measurement history at E with the failure at A is as follows:
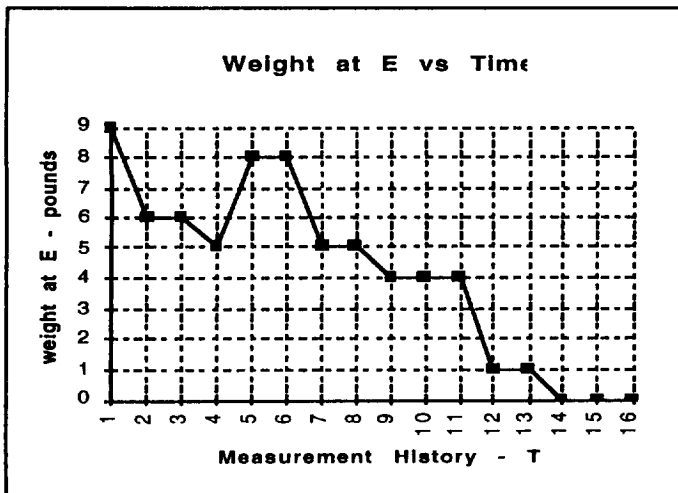


Figure 16 - Measurement history after failure at A, T-7, 0 lbs.

The method used here to track successive revolutions of the turntable in may be easily extended to calculate temperatures in the Shuttle Freon Cooling Loop. The circulating freon can be divided into discrete segments in the math model as follows:
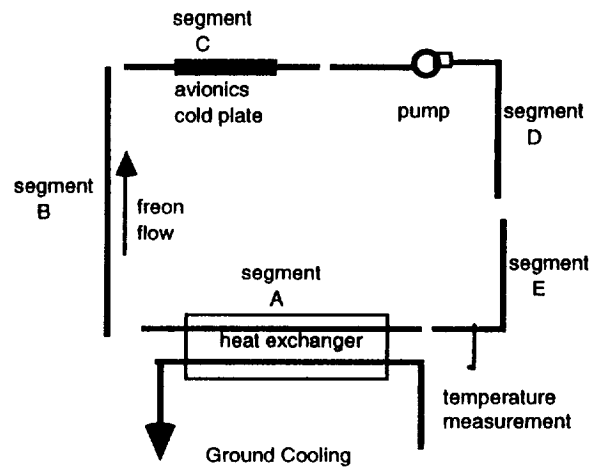


Figure 17 - Freon Loop divided into Segments

In Figure 12, the weight in bucket A was defined as follows: =U4+S5. This is simply the weight delivered by hopper A plus the weight in bucket station E at time T-1. To calculate temperatures for the circulating freon, assume that the incoming freon to segment A of the loop is the temperature of segment E modified by the ground coolant temperature and the heat exchange coefficient of the heat exchanger.

For time NOW, This could be expressed as =CoefA*(U4-S5)+S5 where **CoefA** is the heat exchanger coefficient, **U4** is the temperature of the ground coolant and **S5** is the temperature of fluid segment E at time T-1. The temperature of segment B would simply be =CoefA*(U5-S6)+S6. The temperature of segment C would be =CoefC*(V4-(CoefA*(U6-S7)+S7))+CoefA*(U6-S7)+S7 where **CoefC** is the heat exchange coefficient of the avionics cold plate, **V4** is the temperature of the avionics cold plate, and **S6** and **S7** are the temperatures of segment E at time T-2 and T-3 respectively.

## Conclusion

It has been shown that simultaneous representation of discrete intervals of time in a process simulation can enable efficient monitoring and diagnosis of faults that may manifest themselves dynamically or as a function of time. The key to this technique is to avoid implicit representation of components with state in the simulation model; that is, cells that would be defined as *circular references* in a spreadsheet model. The author believes that most simulations that have instances of such circular references can be easily modified to explicit representation of discrete intervals of time and that improved diagnostic and monitoring performance can be achieved as a result.

[1] E.A. Scarl, J.R. Jamieson, and C.I. Delaune, "Diagnosis and Sensor Validation through Knowledge of Structure and Function, "IEEE-Transactions on Systems, Man, and Cybernetics, SMC-17, No. 3, May/June 1987.