Applying Ecological Interface Design to Experimental Apparatus Used to Monitor a Refrigeration Plant.

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Abstract

A small refrigeration plant, for teaching refrigeration theory, used a control console built to traditional design guidelines: one output in the display for each sensor in the plant. This style of console is notorious for inducing high cognitive loads on operators and for displaying redundant data. Often the high cognitive load is the result of inconsistency between the intent for displaying the data and the format of the displayed data. An interface, based on Ecological Interface Design Theory (EID) was designed and implemented. The completed interface provided the operator with information commensurate with the operator's mental model derived from the system image. During testing of the new interface the expert operator's mental model of the refrigeration system was modified due to improved observation of the refrigeration plant's operational parameters. The application achieved the desired result and reduced the operator's workload by removing a cognitive task - determining system stability - from the operator's task list.

Keywords

Ecological Interface Design, Mental Model, System Image, Design Model, Cognitive Load.

1.0 Introduction - Problem Definition

At the University of Southern Queensland, mechanical engineering students learning about the refrigeration process operate a small refrigeration plant and monitor the plant's performance. The data collected is plotted as a Pressure-Enthalpy Diagram, which is used in determining the refrigeration system's coefficient of performance.

The system has to be stable when the data is recorded otherwise the points on the graph move with time and are not a true indication of the system parameters. In the practical class the students used an analog control panel, Figure 1, to interpret the sensor displays and determine when the system was stable. An experienced operator was seconded to operate the plant during the development of the interface and is the "operator" referred to in the text.

An analysis of this operational methodology [9] indicated there were usability issues that needed to be resolved for the practical exercise to be more relevant. The panel displayed refrigerant pressures and temperatures, which had to be interpreted over time to discern when the refrigeration system was stable. The displayed data required specialised training to interpret. This constituted a cognitive gap between the displayed data and the intended use of that data. The act of interpreting this data constituted a high mental workload for an experienced operator and was an unachievable goal for a student with no experience or training in the operation of the refrigeration system. To alleviate this problem the control artefacts required properties with a close correlation between the control mechanisms and how the operator used them.

The operator used the following method to determine stability:

- set T_3, the temperature of the refrigerant leaving the condenser, to 20^0 C by varying the flow rate of the cooling water to the condensor,
- adjust the refrigeration gas flow valve, know as a Johnson Valve, to set T_4, the temperature of the refrigerant entering the evaporator, to the desired temperature,
- adjust the heat input into the evaporator by varying the amount of electrical energy entering the evaporator, so that the temperature difference (superheat) between T_1 and T_4 remained at 10^0 C,
- monitor these settings for 5 to 10 minutes, making any fine adjustments, as required, to maintain them,
- let the system settle for 15 minutes.

The focus of this paper is to describe the design and development of a computer interface to assist an unskilled operator in controlling the refrigeration plant and determining when the plant is stable.

- when all other avenues seem inadequate, standardize to ensure usability.

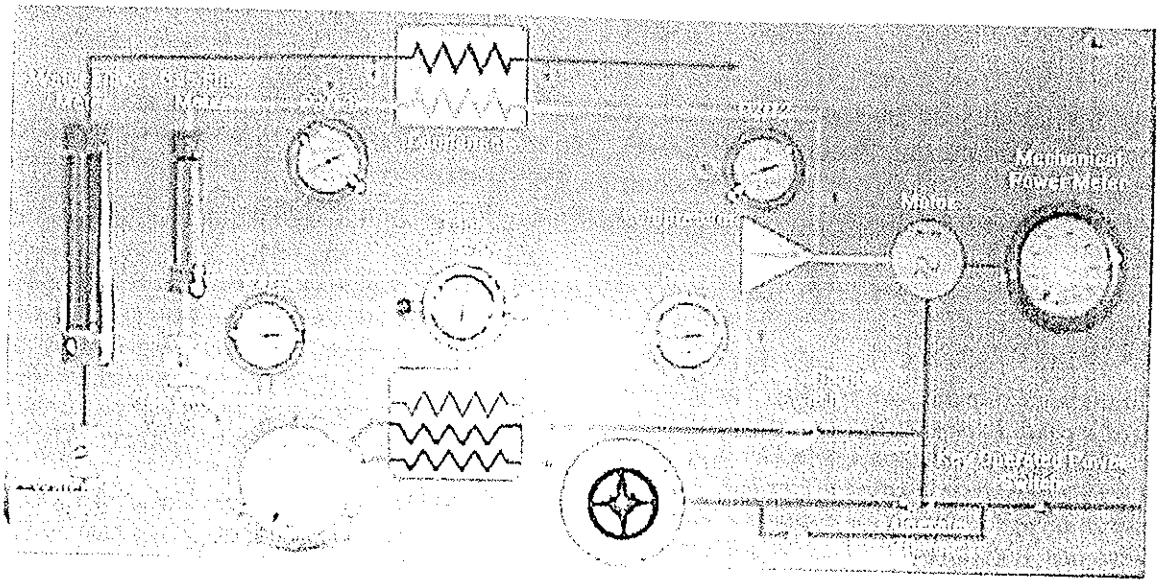


Figure 1 Analog Control Panel

2.0 Ecological Interface Design

Ecological Interface Design supports operator problem solving within the framework of Rasmussen's skills, rules and knowledge taxonomy [8]. The interface should display the physical and the functional properties of the work domain in a multilevel abstraction hierarchy. The physical representation facilitates activities in skills based behaviour (SBB) and rules based behaviour (RBB). The functional representation supports problem solving as knowledge based behaviour (KBB).

The principles of Ecological Interface Design (EID) can be viewed from a distributed cognition perspective [3], [5] and [6].

- cognition is not in the mind but distributed through the people and objects of a situation,
- surface representation conveys task-goal affordances of device features,
- object mappings have to be right for the context,
- constraints are forcing functions that compel conscious consideration,
- simplify the structure of the individual tasks,
- design for human error,

The EID concepts [7] were adopted and used to develop design criteria for the user interface, Figure 2.

- present the sensor data in an information format consistent with the operator's mental model of the plant.
- reduce the operator's workload by removing a cognitive processing task from the operator's role.
- develop a stability-determining algorithm for the application and indicate the system's stability status on the interface.

The interface was based on a schematic representation of the physical system and was designed to show instantaneous data as the default mode. However access, on demand, to historical data was incorporated. The historical data is presented graphically in two modes: as a single trace when associated with an individual digital display and as a dual trace when associated with a system entity e.g. the Condenser. The multimodes of display support the operator in SBB, RBB and KBB depending on the situation.

The stability criteria incorporated into the interface are the functional representation of the system and were not previously displayed to the operator by the analog control panel. The interface simulated coloured light emitting diodes (LEDs) to display the stability status of the pressure and temperature transducers. The indicator colour selection was based on the observed practice of using red for an unstable condition, yellow for an unchanged condition and green for a stable condition [1]. When the system is stable, all the refrigerant pressures and temperatures are automatically saved, once per minute. While the application is running all the transducers are monitored and their values stored as a record, at operator set intervals, in a history file separate from the test results. Each historical record includes the state of the system status LED and a timestamp.

Where there is an operational limit or constraint, that limit is displayed along with the instantaneous data or historical information. These constraints are part of the relational structure that serves as an externalised mental model and supports KBB. The only fixed operational limit applies to the evaporator tank pressure. There is a one-to-one mapping of the transducers and their status indicators providing functional or abstract information on the system. A separate LED provides an overview of the collective status of the transducers. This collective status LED and the time that the plant is in the invariant state represent the primary criteria in determining stability, which is the abstract property of the plant that is of primary interest to the operator. These parameters are displayed in a manner such that the operator can readily monitor them.

2.1 Rationale

A cognitive task analysis was carried out to obtain a schema for determining stability. This analysis was to define the control algorithm within the work domain. A function allocation analysis, of the schema used by the operator to control the plant, determined the allocation of tasks between the stability program and the operator. One usability issue was considered before designing the interface - a link analysis with data obtained by observational and interview methods identified the sensor monitoring patterns to determine stability from the analog control panel. During the interface design another link analysis was undertaken to evaluate the design of the schematic interface.

Once the first prototype was commissioned, a usability analysis of the interface determined the effectiveness of the interface and the stability-determining algorithm. The subjective assessment data of this analysis was collected by observing operator behaviour and from a series of operator debriefing interviews. The information collected was used as the basis for the modifications to improve the design during prototyping in the development phase of the system development life cycle (SDLC). Prototyping was an iterative process. The effect that each new system image had on the operator's mental model was also investigated during interviews.

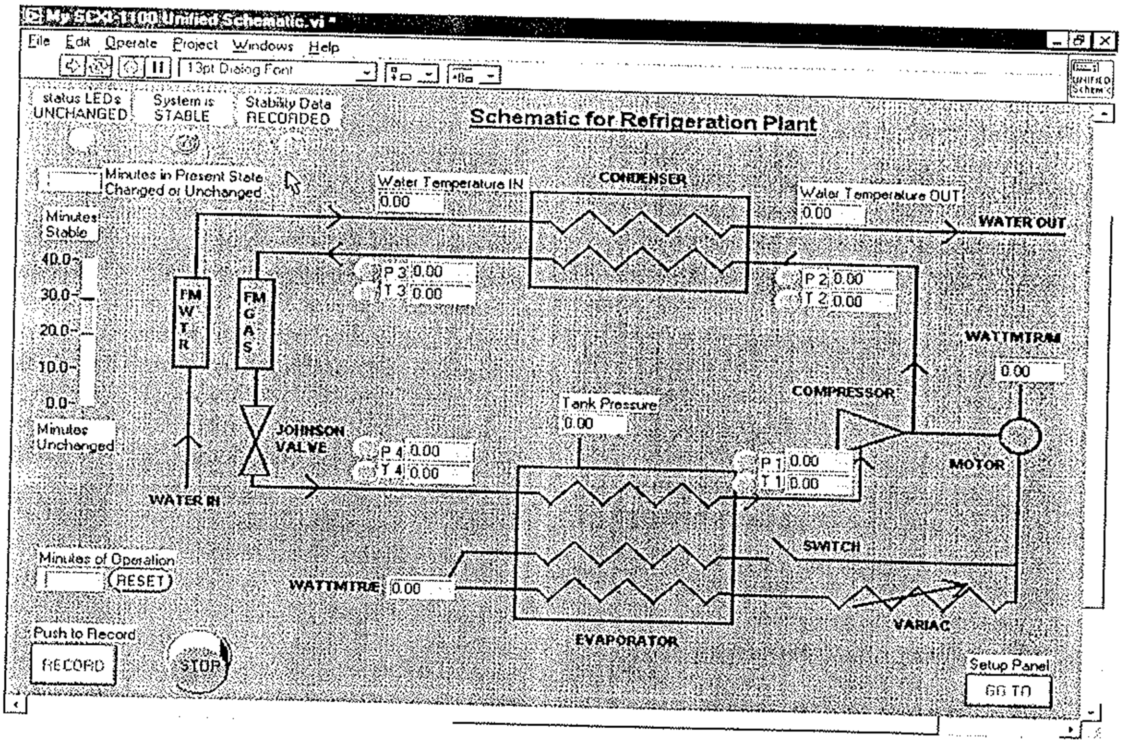


Figure 2 Operational Interface

3.0 Mental Model: How the operator 'sees' the plant.

The operator's mental model was important to this design process because the cognitive task analyses (CTA) carried out indicated that the operator's mental model changed with the development of the prototype interface. The system view was that the improved information from the interface enhanced the operator's mental model and, from the operator's perspective, the artefact changed the way that stability was determined.

The system image is the visual representation of the designer's mental model that is displayed on the user interface [3] and [5]. The system image is designed to:

- assist the operator in building up a mental model that is similar to the design model,
- fully depict how the user interacts with the interface.

The design model considers the physical representation, the users' existing perceptions of the physical object and the relative industry standards. The designer uses these properties of the object to build up and support the user's mental model of that reality. The mental model is the key to how the user manipulates the artefacts of the system image and understands the operation of the system.

The system image incorporates a strong correlation between supported interface actions and user expectations. The use of standardised Windows GUI objects typecasts these objects as constraints, forcing functions to limit the range of possible operational actions. In addition, visual and audio feedback positively reinforce the operator's actions while using the GUI artefacts [5].

Tasks and operations that are of use to cognitive processes enhance the mental model. While performing these activities, the operator modifies the mental model of the system by relating what is practical in the operation of the system to the existing mental model. A number of issues should be considered when designing activities that reinforce the mental model [2].

- A cognitive task associated with the mental model of a process is built up over time.
- Humans require extensive hands-on experience in order to develop and maintain physical and cognitive skills.
- The importance of expertise in complex tasks leads to an emphasis on training.
- Cognitive skills can only be retained if the associated activities are regularly practiced.
- The learning of knowledge separate from using it in the commensurate task is the least successful way of learning that knowledge.
- Extensive and continuous training is necessary.
- Passive participation in demonstrations is not adequate training.
- Building up and maintaining a temporary inference structure, which is the current state of a person's understanding and planning is an essential part of performing a complex task.
- Equipment interfaces need to be designed to support the operator in maintaining an overview of the state of the task.

These issues affect the knowledge base of the operator [3]. The knowledge base is changed by accretion, tuning or restructuring. Accretion is the acquisition of new knowledge without affecting any existing knowledge. Tuning changes the extent to which a subject is known and understood. Restructuring knowledge changes the existing knowledge, how it is understood and its relationships with other existing knowledge.

3.1 Discussion of the Effect of the Interface on the Operator's Mental Model

Four characteristics were of interest.

1. Had the operator's mental model of how the plant responded to a step input changed? In particular, had that part of the mental model associated with the interaction of the refrigeration plant's components changed?
2. Had the operator's scanning practices changed? Were the same sensor inputs still used for the same purposes in the operator's response to plant conditions? Were the same scanning sequences and scanning rates still used?
3. How, if at all, were the operational procedures changed in response to the input from the interface?
4. Had there been a translation of skills from the analogue control panel operation to software interface operation? If not a translation, had new skills been developed?

3.1.1 Changes to the Mental Model

When using the analog control panel, after a change was introduced into the system, T_1 was monitored to the exclusion of all other sensors except the evaporator tank pressure. There were several reasons for this:

- the analog gauges did not have the sensitivity of the digital readouts,

- trends could not be readily observed on the analog gauges,
- the tank pressure was the best indicator of long term temperature trends,
- this procedure fitted in with the operator's mental model of how the plant performed.

Prior to using the interface, the operator's mental model was developed from the observable phenomenon that temperature T_1 best indicated the effects of significant change with heat input to the evaporator tank and consequently the tank pressure was used as an indicator to fine tune these changes to T_1. Use of the interface caused the operator's mental model to be modified: knowledge restructuring [3]. The operator could see that after T_4 was set, T_1 initially followed the trend of T_4. This change carried on to T_2, leading to commensurate changes in P_3 and P_4. The pressure change to P_4 caused a further change in T_4. Then the cycle recommenced, starting with T_1. The onset of stable conditions was indicated by a decrease in the cycling frequency. No cycling indicated a steady state condition.

The instantaneous feedback and appropriate function allocation of the plant components led to a cleaner system image and brought the operator's mental model closer to an understanding of the actual phenomena that occurred in the refrigeration process.

3.1.2 Changes to Scanning Patterns

Prior to using the interface, the operator's procedure to determine stability was to regularly monitor, at 15-minute intervals, the temperature T_1 and the evaporator tank pressure. Use of the interface still required monitoring T_1 but the evaporator tank pressure was no longer referenced. The slope of T_1 (rate of change) and the distance between the traces T_1 and T_4 were monitored continuously within the first 10 to 15 minutes of inputting the system change. Fine tuning the heat input was made in response to the slope of T_1 and the temperature difference between T_1 and T_4.

Figure 3, is the comparative eye and hand movement link analysis for scanning the control panel to determine stability and control the evaporator temperature. Link analysis is a Human Factors methodology. A link is any relationship between a person and a machine, between one person and another or between one machine and another. These relationships have significant implications for design. The optimum arrangement of equipment and system components can be resolved by link analysis. Frequency of interaction, sequence of interaction, importance of interaction, communication between components, control activities and component movement can all be analysed by link analysis.

In the analog panel scanning pattern the operator observed the time and then checked T_1 at the control panel scan rate. Later, at a slower scan rate, the Tank Pressure and temperature T_4 were also checked. The scan sweep was made across the control panel and to a remote clock, i.e. a wrist watch or stop clock. All observations were of un-interpreted data that the operator assimilated in the working memory to interpret as a time series.

The scanning pattern for the interface was concentrated solely on the upper left hand corner of the screen. The collective status LED was monitored first. If the LED was red then the time since the last invariant period was checked, this completed the scan. If the LED was yellow the system status LED was checked to see if the plant was stable. If the system was not stable the invariant time was checked, otherwise the time check ascertained the period the system had been stable. The operator was not required to interpret data. The interface presented information on the stability status of the plant.

3.1.3 Changes in Operational Procedures

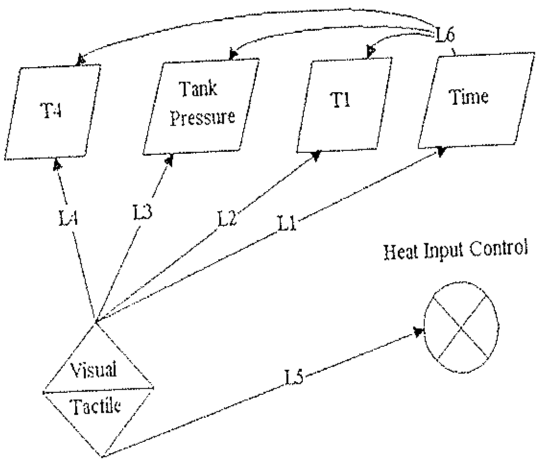
Use of the interface caused the operator to change the mental model of the plant as outlined in Section 3.1.1. There were new sources of information and more accurate data available for the operator to monitor and control the plant. Existing procedures were modified to use these new inputs.

The operational procedure for adjusting the heat input to establish stable operating conditions changed. Initially, a number of fine tuning adjustments were made throughout the entire procedure: a relatively long period of time. The procedure was changed to one or two large scale adjustments, to bring the system close to the desired setting, made early in the procedure. These were followed by a reduced number of fine tuning inputs, concentrated in a relatively short time period, also early in the procedure. After the initial changes to the control settings the system was left to stabilise and then required very little subsequent input.

Also, prior to the use of the interface, it was known that T_1 could change quickly. However, direct observation of the rate of change was hidden by the damped response of the refrigeration plant, as a whole. What was observed was the time delayed effect of a change in T_1. As a result of this delay an unskilled operator could get the plant oscillating wildly over a wide range of temperatures. The trace of T_1 allowed the operator to use continuous observations of the T_1 trace to fine tune the heat input.

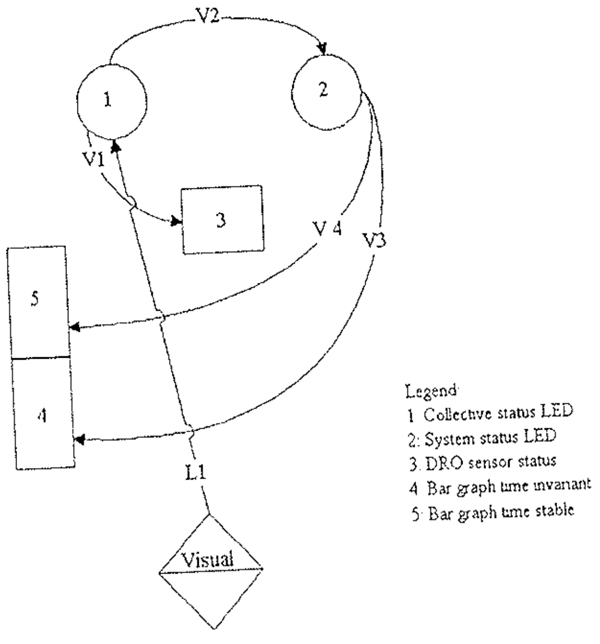
The new indicators to stable operation were the slope of trace T_1 and the temperature difference, between the traces T_1 and T_4. The key to the effectiveness of the interface was the immediate feedback it could provide. The evaporator tank pressure, a safety subsystem, did not have to be monitored for an indication of long term temperature trends. Its role reverted back to a "watchdog" safety system and was consequently removed from the control algorithm of the operator's mental model.

Link Analysis: Stability (analog panel)



L1: Observe Time at highest frequency
L2: Observe T1 at instrument scan frequency
L3: Observe Tank Pressure at period of 10 to 15 minutes
L4: Observe T4 at extended period
L5: Adjust control as function of L2 and L3, refer to text
L6: Intra-object scan, after a time check another object is scanned

LINK ANALYSIS: STABILITY (interface)



L1 Observation Link from operator to status indicators
V1 Redirection when 1 is red (sensors registering significant change)
V2 Redirection when 1 is yellow (sensor values invariant)
V3 Redirection when 1 is yellow and 2 is red (invariant but not stable)
V4: Redirection when 1 is yellow and 2 is yellow (invariant and stable)

Figure 3 Comparative Link Analysis

3.1.4 Skills Translation

The skills required to operate the plant with the analog console, carried over to operating the plant with the computer interface. With the interface, the operator did not have to wait for an overall system response to observe the effects of control inputs. The effects of adjusting the plant control system were immediately observable within the system. The operator used small incremental adjustments of the controls in conjunction with observations of the trace of T_1 for feedback.

The skills, as such, were not modified. The operational practices were changed to accommodate the enhanced information available to the operator. The nature of the task changed, although the end result was the same.

4.0 Conclusions And Future Directions

The interface was designed to provide the operator with a physical representation of the system and functional information, interpreted from system data. A number of Digital Read Outs (DROs), LEDs and popup window charts are used to inform the operator of the system's functional status.

The design objective of transferring the determination of the plant's stability status, from a cognitive process of the operator, to functional information displayed on the interface was met. The stability-determining algorithm, derived from the CTA, provided a monitoring service for system parameters that related specifically to the stability criteria. These tasks, within the supervisory function, were reallocated from the operator to the computer application. However, at all times the operator was in control of the process and used the interface to monitor system performance by operating with skills and rules. The KBB of a skilled operator in determining stability was no longer a problem in the work domain. However the interface was designed to support KBB in unexpected situations and routine SBB and RBB. The interface informed the operator of system status but the decision to accept or reject the information was finally and fully with the operator.

The schematic based interface illustrated the differences between the needs of an expert and a trainee [2] and [4]. An expert has an established mental model that is applied at an abstract level for the purposes of cognitive processing. A trainee has a mental model that is based on the physical representation of the system. As the trainee gains knowledge and skills the mental model is moved from the physical domain to an abstract level, which facilitates cognitive processing of the incoming data. The brief for the engineering aspects of this project specified an interface that was suitable for student use. The schematic interface's success, in changing an experienced operator's mental model, endorses the use of physical models in the design of control interfaces for training.

The interface was used in practical classes during semester one, 1999. Previously the experiment was run as an individual three (3) hour practical exercise. Because the refrigeration system could be controlled with a minimum of operator surveillance and meaningful results obtained, the format of the experiment was changed. The refrigeration exercise was incorporated into a group of experiments run conjointly in a practical session. Prior to use, the students were instructed in the operational procedures of the interface and the plant. For safety and duty of care reasons the operator still supervised the students in their use of the system. The monitoring interface provided instantaneous feedback to the operator on any of the system parameters, which allowed for three sets of stabilised readings to be taken and plotted within an hour where previously this could not be achieved.

4.1 Second Generation Interface

The SDLC entrenches design as an iterative process. The experience gained from the design and implementation of the interface was used to refine the design criteria. The refrigeration plant performance and the operator's understanding of the control process, based on the modified mental model, were analysed. From these analyses, a new representation of the system, biased towards an abstract representation of the plant control criteria, was developed.

The design goal was to produce an interface that displayed the functional properties of the work domain in the form of a multilevel representation based on an abstraction hierarchy [8]. In particular the requirement was to satisfy the identified operator's need to monitor the following functional criteria:

- the rate of change of T_1,
- the distance between T_1 and T_4, temperature across the evaporator tank,
- sequencing of the change in sensor status LEDs, temperature and pressure,
- time – to establish stability criteria,
- overview status indicators – invariant status LED, the system status LED and the time indicators.

The design, Figure 4, is not implemented yet but is presented as one possible alternative, for the logical next step, in the production of an effective interface.

The layout is an attempt to represent the operator's mental model solely as an abstract interface with no physical representation. The operator may not have to process data with this screen. The functional information required for control of the plant and to determine the status of the plant is displayed directly.

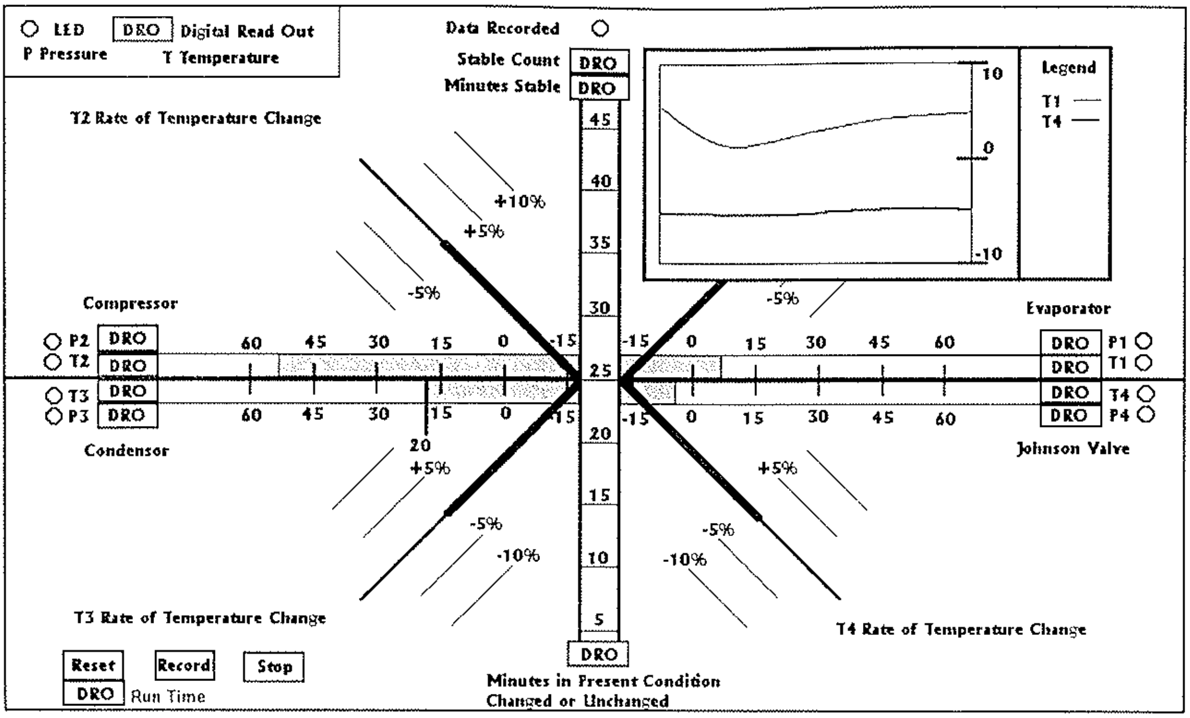


Figure 4 Second Generation Interface

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