

AN EXPERT DISPLAY SYSTEM AND NUCLEAR POWER PLANT CONTROL ROOMS

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ABSTRACT

An expert display system controls automatically the display of segments on a cathode ray tube's screen to form an image of plant operations. The image consists of an icon of: 1) the process (heat engine cycle), 2) plant control systems, and 3) safety systems. A set of data-driven, forward-chaining computer stored rules control the display of segments. As plant operation changes, measured plant data are processed through the rules, and the results control the deletion and addition of segments to the display format. The icon contains information needed by control rooms operators to monitor plant operations.

One example of an expert display is illustrated for the operator's task of monitoring leakage from a safety valve in a steam line of a boiling water reactor (BWR). In another example, the use of an expert display to monitor plant operations during pre-trip, trip, and post-trip operations is discussed as a universal display.

The viewpoints and opinions expressed herein are the author's personal ones, and they are not to be interpreted as Nuclear Regulatory Commission criteria, requirements, or guidelines.

INTRODUCTION

Graphics speak faster than words and numbers. Interactive computer graphic techniques facilitate the processing, display, and communication of data. Properly designed graphics, such as icons, may be used to convey large quantities of information that is easy to read, easy to understand, and free of clutter.

For example, a trend plot of a process variable on the screen of a cathode-ray tube (CRT) is much easier to understand than two columns of numbers, one representing time, and the other the magnitude of the process variable.

Foley (Ref. 1) states that the system designer must first develop interaction techniques that minimize the work required by three basic human processes: perception, cognition, and motor activity. To achieve this goal, the designer must have a thorough understanding of the performance and characteristics of interactive devices. The designer must also perform function and task analyses to identify the data needed by humans to perform their assigned work. One critical problem for the designer is how to format and present the data and information needed with a minimum number of display pages. The goal is to minimize human search time and maximize communication from a large data base.

The Electric Power Research Institute (EPRI) published display design guidelines (Ref. 2) for the development of computer-generated display systems. The guidelines support a three-step design process: 1) analysis, 2) synthesis, and 3) evaluation. The analysis step includes function and task analysis with a goal of identifying information requirements. In the synthesis step display formats are developed using the products from the analysis step. The evaluation step includes the assessment of computer-based operator aids, such as the compatibility of the display with a user's sensory and perceptual capabilities.

With CRTs as display devices, a designer may use color to code information. Murch (Ref. 3) states that most often color is used in a qualitative rather than a quantitative fashion to show that one item is different from another. However, the use of color becomes more complex as the number of bit planes in display systems increase allowing for thousands of colors. As Murch correctly notes, to maximize the potential of graphics systems, a designer must draw upon science's understanding of how the human eye creates color sensations. Because of sensor limitations in the human eye, only a few colors may be used to effectively code data. Murch's guidelines on the use of color are excellent.

Hayes-Roth's tutorial (Ref. 4) on knowledge-based expert systems states that computer-stored skills of specialists may be used to aid operators in solving problems. A major benefit from such systems is the consistent application of logic and timely solutions to problems. An example of an expert system in the nuclear industry is in a technical paper by Gimmy (Ref. 5). In this example, the automatic diagnosis of multiple alarms by an expert system is discussed. From the description provided by Gimmy, the knowledge base appears thorough, the inference engine is based upon table-driven logic, and the user's interface appears to be very effective. Gimmy's paper provides excellent guidelines on how to implement expert systems in nuclear facilities.

Computer-driven cathode ray tubes are used as display devices in the control rooms of nuclear power plants. The format of the data on the screens takes many shapes. For example, vertical bars, with labels and process parameter values, mimic analog meters on the control board. Also, trend plots of process parameters are color and shape coded to facilitate the operator's use of this data.

The digital computer may mimic the human operator by automating operator tasks and then displaying processed data. The expert display discussed in this paper integrates individual process parameters from the plant to form and display a model of the process. In doing these tasks, the computer mimics an expert operator by integrating and structuring the data to support decision making by the human. The specific displays in this paper are prototypes developed by the author on a graphics workstation. They serve to illustrate a different type of display design and automation, but they are by no means a complete design.

To provide a basis for a discussion, the following terms are defined:

Graphic primitives: 1. The graphic elements displayed on a terminal;
2. The fundamental units of a display.

Segment: 1. A combined series of graphic primitives;
2. A reusable collection of graphic primitives and primitive attributes stored in memory.

Attribute: A characteristic of a primitive, such as color, width, etc.

Dynamic attribute: Those attributes that can be changed after the segment is defined.

Panel: The set of pixels that lie inside a closed boundary on a display surface. A "panel definition" is a series of MOVES and DRAWS that form a panel boundary. A "panel" may be identified as a segment.

Icon: An image composed from segments. A "process icon" models the process within the plant. A "system icon" mimics plant systems.

Object: A computer-generated graphic element that can be acted upon by the human user.

Background elements: The time invariant segments in an icon.

Active elements: The time variant segments in an icon.

Graphic primitives are the basic graphic elements that a terminal displays in response to a command. One graphic primitive is a vector, a straight line drawn between two points on a display surface. A series of vectors is used to form a circle, a rectangle, or a panel. Attributes of a graphic primitive may include color, line style (solid, dashed, etc.), and width. For example, a temperature-entropy diagram of two-phase water (liquid and vapor) may be shown on a CRT as a series of vectors that form a panel. The color of the surface, such as white, is a designer-specified attribute of the panel.

A segment is a collection of graphic primitives and their attributes that the display terminal treats as a single object. A segment may contain as little as a single graphic primitive, or as much as an entire display. An example of a segment is a symbol for a valve, which is composed of several straight lines (primitives).

In the following discussion, segments are used to code data and information for process functions and for plant systems. Several segments are then used to compose an icon that models plant operations. Some segments are used to compose the background elements in the display format. The use of active segments in the display format is controlled by pre-determined rules stored in the memory of a computer. The rules are data driven, with the data obtained from sampling plant sensors. For example, when a measured process variable, such as pressure, exceeds a setpoint for a valve to open, a new segment for the valve (indicating an open valve) is added to the display. This overview provides an introduction to an expert display.

EXPERT SAFETY VALVE MONITOR

An important task assigned operators is monitoring safety valves for leakage after a safety valve has lifted and then closed. Many times these valves do not fully close and leakage occurs. Generally, a safety valve serves as a single component and is not backed up by a block valve. Thus, leakage of coolant from a safety valve is a fault in the pressure boundary and a concern in maintaining safe plant operation.

During normal operation of a BWR, the safety valve in the steam line is closed. Should a large increase in pressure occur during a transient and the pressure in the steam line exceed the setpoint for the safety valve, the valve opens. The setpoint for the safety valve is typically 1230 psig. When the valve is open, steam escapes to the discharge pipe, then to the drywell, and ultimately to the suppression pool.

Obert (Ref. 6) defines a throttling process as one that occurs when a fluid expands from a region of high pressure to a region of lower pressure. In doing so, the fluid dissipates energy that could have been transformed into work. The steam expanding through the safety valve achieves a high velocity, which is dissipated in aimless turbulence in the discharge pipe. Thermodynamically, the enthalpy of the dissipated steam in the discharge pipe is the same as the enthalpy of the steam in the steam line. However, the entropy of the dissipated steam is much greater than the entropy of the steam in the steam line. The amount of entropy increase during the throttling process is a measure of the dissipated energy.

For the purpose of this discussion, the discharge pipe for the safety valve is instrumented with a thermocouple and with an acoustic monitoring device. The thermocouple measures the temperature of the fluid in the discharge pipe. Acoustic monitors, such as piezoelectric sensors (accelerometers and acoustic emission sensors), are excellent devices to monitor the status of valves (Ref. 8). These sensors measure the acoustic response that results from the flow of fluid through the safety valve.

Figure 1 depicts the steam line, the safety valve, the discharge pipe, the drywell, the suppression pool, and the sensors in the discharge pipe. The symbol P1 represents the operating pressure in the steam line, and h1 represents the enthalpy of the steam in the steam line. For a BWR operating at 1000 psia steam line pressure, the steam is generally saturated steam (or at most, a few degrees superheated). The enthalpy of saturated steam at 1000 psia is 1192.9 BTU/#m. In the case of a leaking safety valve, the enthalpy of the throttled, dissipated steam is also 1192.9 BTU/#m. For the purpose of this discussion, it is assumed that the pressure of the dissipated steam, P2, is atmospheric pressure, 14.7 psia. Thus, based on the properties of steam and the throttling process, T2, the temperature of the dissipated steam is 300 degrees Fahrenheit (300 F). The thermocouple's measured temperature of the steam should read about 300 F, which is reached after the initial response lag of the sensor. At 300 F and atmospheric pressure, the steam is superheated because the saturation temperature is 212 F at atmospheric pressure. In addition to temperature, the signal from the acoustic monitor would be used to confirm valve leakage.

Thus, steam line pressure, steam line enthalpy, pressure of the dissipated steam in the discharge pipe, the discharge pipe's thermocouple reading, and the analytically determined temperature (from the steam tables) of the dissipated steam are used to detect leakage from the safety valve. Readings from the acoustic monitor also confirm the presence of leakage.

The thermodynamic properties of steam for a throttling process may be harnessed to detect an open safety valve. Of course, the pressure in the steam line must be greater than or equal to the setpoint pressure for the valve to open. Table 1 contains examples that illustrate numerically the throttling process for an open valve with setpoint steam line pressure, and for a closed, leaking valve with normal steam line pressure.

The process of detecting an open safety valve, or leakage from a closed safety valve, may be automated. A digital computer implements rules that are driven by measured plant data to control the display of messages and segments on the screen of a CRT.

This discussion assumes that the rules used are those stated in Table 2, which are self-explanatory. The status of each rule is determined by comparing measured

plant data with the appropriate, pre-defined set-point(s) and tolerance(s). The results from applying each rule are then used to determine the messages and segments displayed to control room personnel.

Figure 2 contains an icon of the boiling process in a BWR, with a steam line pressure of 1000 psia and saturation temperature of 544.6 F. For the purpose of this and subsequent discussion, this icon is a process icon. This figure and subsequent figures are drawings of colored prints made from a CRT screen (they lack detail, but are much more economical to use than the colored version). Several segments are used to compose the icon. The central, bell-shaped panel is the segment that represents the temperature (vertical) - entropy (horizontal) properties of two-phase water (liquid and vapor). The temperature grid is another segment. The thin band that serves as a border is another segment, which represents containment. The title, date, and time comprise another segment. The process of boiling saturated water to saturated steam in the reactor core and the water level in the core form a segment that is located in the two-phase region of water.

The safety valve in the steam line (Figure 2) is fully seated; this condition is determined from the execution of the stored rules (Table 2) driven by the measured variables of steam line pressure, the discharge pipe thermocouple reading, and the acoustic monitor reading. The analytically calculated temperature of the dissipated steam from the throttle process is also needed. This is determined from the drywell pressure, and the saturation properties of the steam in the steam line. Thus, the message: SRV 50201 SEATED is displayed as a segment.

Figure 3 contains a process icon that illustrates a leaking safety valve. The path of the throttling process, from 1000 psia steam line pressure to atmospheric pressure in the drywell, is a display segment. The use of this segment and of the message segment is controlled by the appropriate rules in Table 2. The temperature of the throttled steam is 300 F, which is superheated steam.

Figure 4 contains a process icon that illustrates operation with an open safety valve. The operating conditions illustrated are those stated in Table 1. The displays of the throttle path and the message are controlled by the appropriate rules and measured plant data.

Figures 2, 3, and 4 are copies of display screens generated on a Tektronix 4115B Display System. The rules (Table 2) were coded in FORTRAN 86 by the use of logical IF and BLOCK IF program statements. The figures illustrate how an expert display may be used in monitoring a safety valve. With an expert display of this type, the need for a human to search the computer's data base is eliminated because the display is updated automatically.

The rules in Table 2 are for illustration purposes only. New rules must be added to generate a robust and comprehensive set. For example, rules to detect a stuck open valve would be useful. Also, a probability factor to assess the certainty of a solution would be helpful. If insufficient or conflicting data are present, a low probability factor is assigned, which essentially gives the problem to the human to resolve. With validated plant data, the rules could be expanded to resolve conflicts. Furthermore, the rules should be expanded to test for and detect saturated steam at the measured pressure within the discharge pipe. However, this steam may be present for other reasons. As the rules become more complex, a greater effort is needed

to design and accurately implement the software, because great care must be taken to avoid misleading the operator.

A UNIVERSAL DISPLAY

Much more powerful uses of an expert display are possible other than the case discussed above. For example, on a reactor trip, control room operators must monitor large quantities of data to determine the status of the plant's process, of the plant's operating systems, and then to respond to component failures, should they occur. Furthermore, the reactor trip may demand the operation of safety systems to sustain safe plant operations. When the safety systems are operating, the principal heat removal path from the reactor core (heat source) to the environment (heat sink) may be other than the plant's condenser. Because many possible heat removal paths may exist after a trip, operators must quickly identify the path in use and monitor performance of the associated plant systems to ensure that adequate liquid-phase water is available to remove the heat. An expert display system could be a powerful tool for operators in performing these functions and tasks.

Figure 5 contains an iconic display of a pressurized water reactor (PWR) at design power. The iconic display is composed of process segments and system segments. The process segments present the process functions and variables for the primary coolant system and secondary coolant system (in terms of temperature and entropy properties of water, see Reference 7 for further details). Also, the process segments contain data on: 1) subcooled water in the primary coolant system and the secondary coolant system, and 2) water level data for the pressurizer, steam generators, and condenser hotwell (see Reference 7 on how these data are encoded as process knowledge).

Several system segments are contained in the PWR HEAT ENGINE icon (Figure 5). The segment for the condenser cooling water system is near the condensation process function portion of the process icon. The segments for the condensate storage tank (CST) and associated piping, valves, and pump are near the segment for the condensation process. The system segments for the makeup and letdown system contain the volume control tank (VCT), regenerative heat exchanger (RHX), letdown heat exchanger (LHX), and associated piping, valves, and pumps. Finally, the high pressure charging system, with the refueling water storage tank, boron injection tank (BIT), valves, and pump is also shown in the icon.

Mnemonics are also encoded in Figure 5. The temperature grid and scale serve a user's task to evaluate coolant temperatures within the process. Also, the reactor power level (99.6%) is stated numerically and positioned near the display segment for primary coolant. Furthermore, additional data could be coded into Figure 5 and still not result in clutter. For example, the temperature of the water entering and leaving the LHX and RHX could be added along with the water flow rates. Figure 5 is an illustration only, not a completed design.

A normal reactor trip is one where: 1) the control rods insert into the reactor and a safety injection signal is not present, 2) the turbine bypass valve opens on demand, 3) the auxiliary feedwater system responds on demand, 4) the turbine valves close on demand, 5) the feedwater system trips on demand, and 6) the condenser serves as a component in the heat removal cycle. These conditions may be formed into rules that with the appropriate measured plant data, would be used to control the display of segments. Figure 6 illustrates how the icon presents operation of the plant following a normal

trip. The source of the auxiliary feedwater for the steam generators is the condensate storage tank.

Figure 7 illustrates how the icon would look when the auxiliary feedwater system fails to respond upon a reactor trip. The word *may* is used because the author did not have data from a computer simulation of the event to generate the display. Several important events are coded into this icon: 1) the blowdown of the steam generators to the condenser by a throttle process through the turbine bypass valve, 2) a pressurizer that is nearly full of water, and 3) a blowdown of the pressurizer to the pressurizer relief tank (PRT) by a throttle process through the pressure relief valves. The safety systems consist of 1) the accumulators (ACUM), 2) the upper head injection system (UHI), 3) the safety injection system (SI), and 4) the charging system (CHG). The primitives of the display segments would be updated on a real-time basis to reflect the current status of the plant. The main heat removal path from the reactor to the environment consists of the throttle process through the relief valves in the pressurizer, containment sump, and the heat exchangers in the residual heat removal system.

Figure 8 illustrates how the icon would display plant operations after a reactor trip in which all turbine bypass valves fail to open on demand. The auxiliary feedwater system responds and provides water to the steam generators. The afterheat from the reactor is removed in the process of boiling the auxiliary feedwater in the steam generators. The steam is then released to the atmosphere by a throttling process through the generator's relief valves.

Finally, Figure 9 illustrates a primary coolant system that is thermodynamically uncoupled from the secondary coolant system. The vertical bar between the pressure bar of the primary system and the steam generator's saturation temperature would be colored red; it serves as a perceptual cue to attract the user's attention. The triangular symbol located on the pressure bar indicates the water level in the reactor core. The position of the square symbol on the pressure bar, located near the saturated steam line, indicates a pressurizer empty of water.

An expert display to assist operators in monitoring plant operations during normal operations, anticipated transients, and emergency conditions is a universal display and technically feasible. Afterheat removal from the core following a reactor trip must be achieved successfully to maintain safe operation of the plant. An expert display that automatically identifies and presents the current heat transfer path from the heat source (reactor) to heat sink (environment) would simplify the functions and tasks assigned operators.

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CONCLUSIONS

Knowledge of the plant's heat engine cycle/heat removal cycle is encoded as computer-controlled display segments on a cathode-ray tube's screen. This knowledge is based on the thermodynamic principles and models used by mechanical engineers to design a nuclear power plant. The graphical segments on the screen form an icon of the plant's operation, which facilitates the communication of the encoded knowledge to the user.

The data within the icon allow a user to evaluate the interaction between plant systems and the process.

The rules (collection of expertise) needed to control the display of segments, as described herein, are few in number. However, the rules are extremely important because their implementation automates the tasks of acquisition and communication of knowledge, in real time, as a function of plant status. This technique allows the designer to display the most relevant data; that is, the data an expert would use to monitor and evaluate the current state of the plant.

These features reduce a user's workload by eliminating the search for data and they enhance a skill-based response from the operator through the logical structure of the displayed data.

The illustrations in this paper - an expert safety valve monitor and a universal display - are illustrations only. A considerable amount of work remains to be done to design and validate the system described. However, from the illustrations, it may be seen that additional functions, such as process control and annunciators, could be added to expand the utility of the universal display. Furthermore, the use of a video recorder, with a fast replay feature, provides a useful means of monitoring and diagnosing plant transients and trips. With a fast replay, function trends could be monitored as a near real time aid in the diagnosis of an event. A new level of human factors for the operator-plant interface is achievable with technology that currently exists!

The use of the expert displays presented in this paper will:

- + eliminate the need to gather and process related data from diverse points within the control room;
- + eliminate the peephole effect of a CRT screen as a viewport to a large data base of information;
- + eliminate the search effort needed in interacting with a keyboard to find the display formats pertinent to current plant operations.
- + eliminate display clutter because only segments pertinent to current plant operations are presented rather than all display segments at the same time; and
- + give control room operators information an expert would use in evaluating the current status of the plant.

However, these benefits can only be achieved if:

- the knowledge base is accurately and thoroughly defined; and
- the rules implemented into computer code are free of error and conflict.

A structured design process, along with effective quality assurance programs and design verification and validation programs, will minimize the design errors in the code.

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TABLE 1
THE THROTTLE PROCESS

1. Safety valve open	2. Safety valve leaking
Steam line:	Steam line:
Pressure: 1250 psia	Pressure: 1000 psia
Temperature: 572.4 F	Temperature: 544.6 F
(saturated steam)	(saturated steam)
Enthalpy: 1182.6 BTU/#m	Enthalpy: 1192.9 BTU/#m
Safety valve setpoint: 1245 psia	Discharge pipe:
Discharge pipe:	Pressure: 14.7 psia
Pressure: 14.7 psia	Temperature: 300 F
Temperature: 279 F	(superheated steam)
(superheated steam)	

TABLE 2
EXPERT RULES

Rules	Status				
Steam line pressure \geq safety valve's setpoint	True	False	F	T	T
Acoustic monitor reading \geq setpoint value	T	F	T	F	T
Thermocouple reading \geq (calculated temp-tolerance)	T	F	T	T	F
Message on valve status	Valve Open	Valve Closed	Valve Leaking	Insufficient Data	

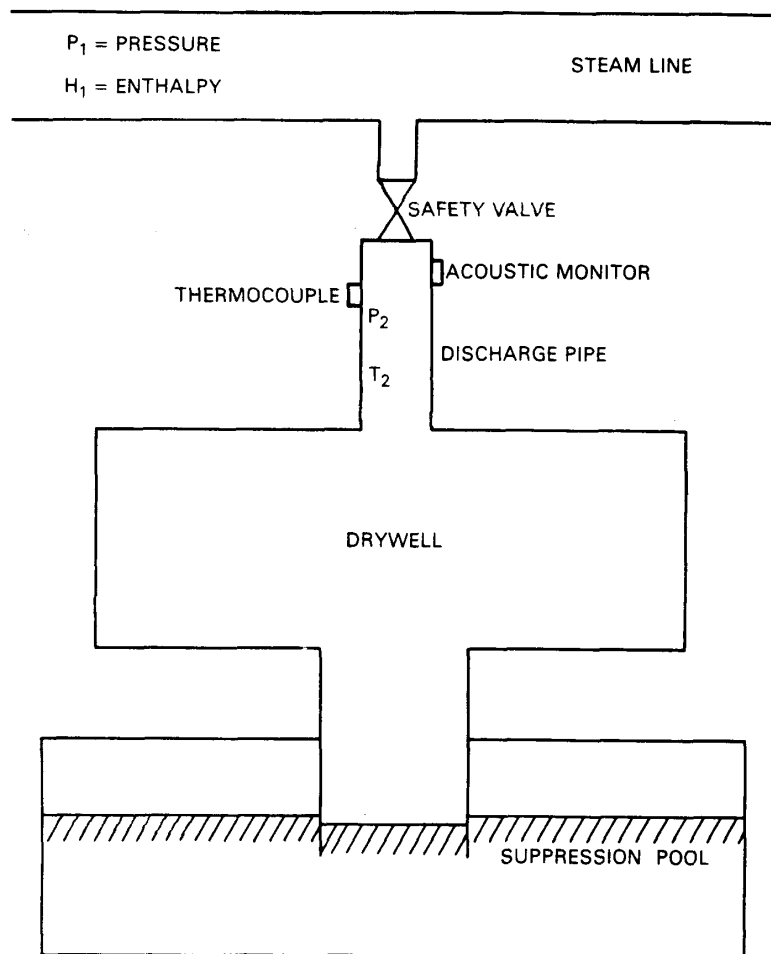


Figure 1 BWR steam line safety valve

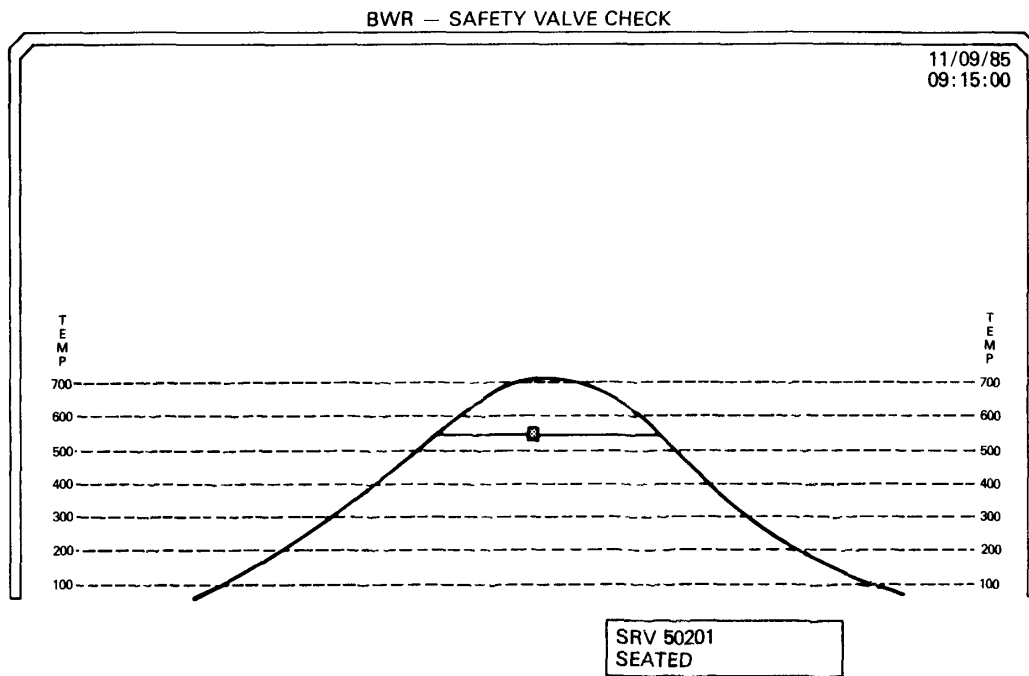


Figure 2 Icon: Safety valve fully seated

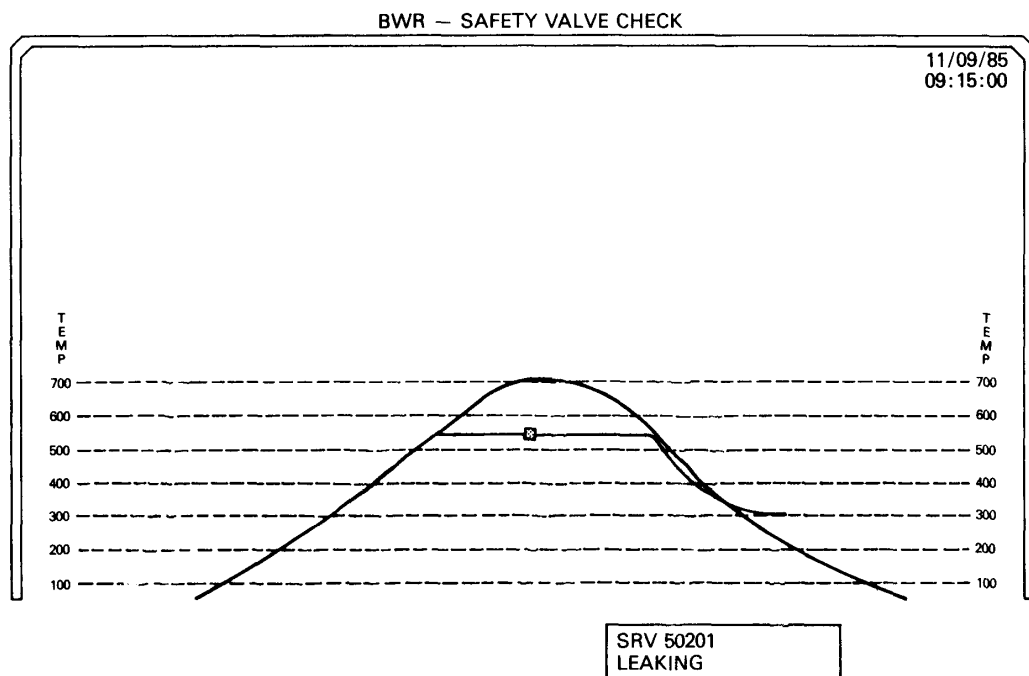


Figure 3 Icon: Safety valve leaking

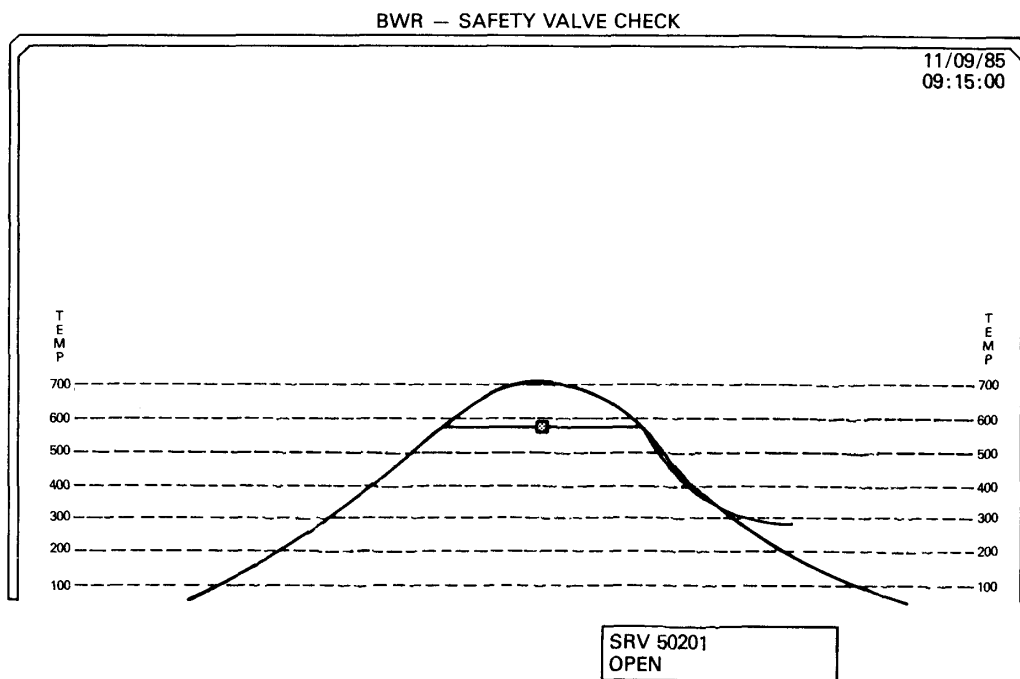


Figure 4 Icon: Safety valve open

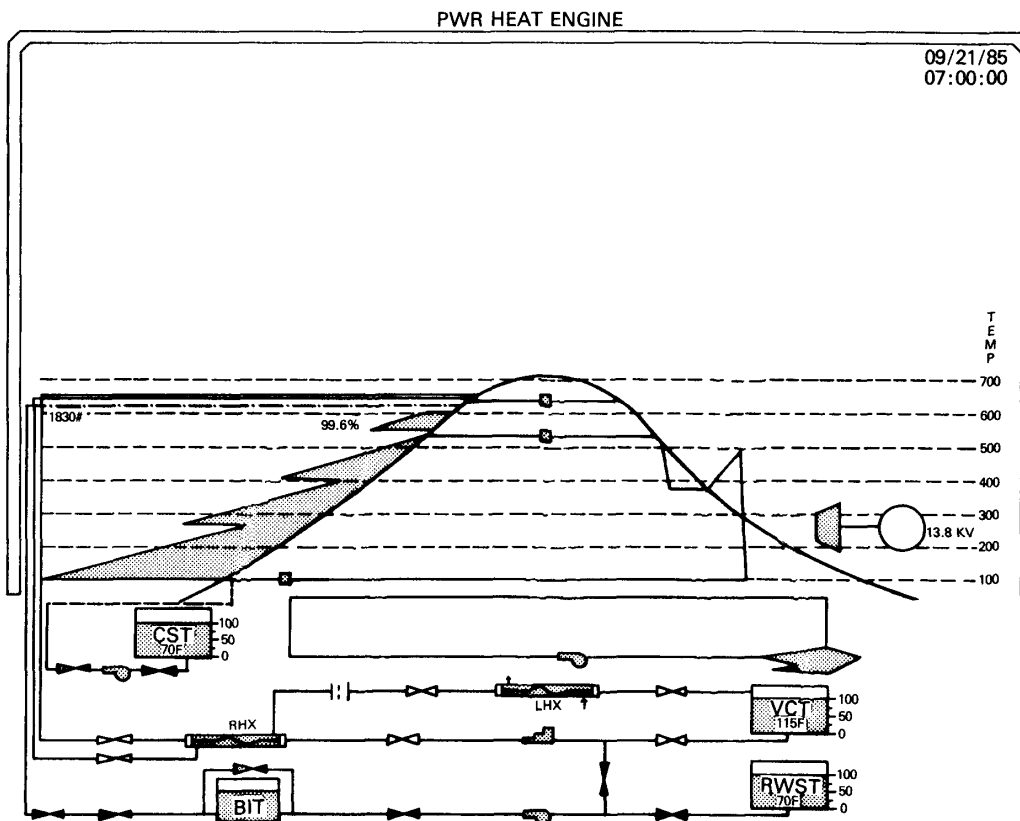
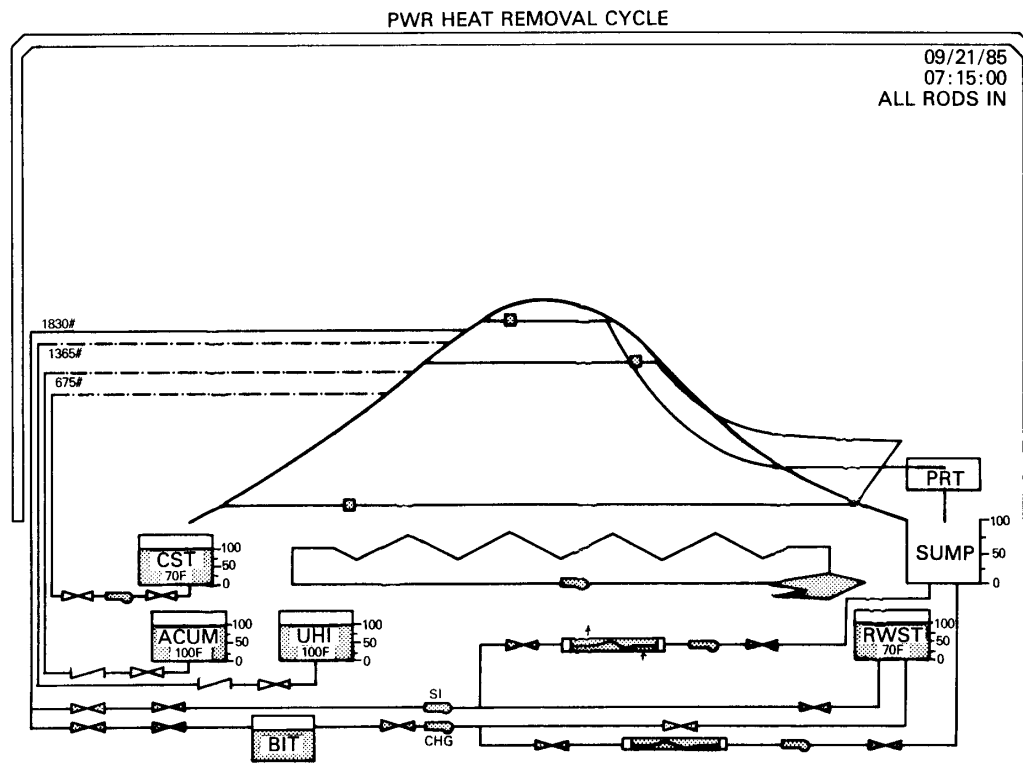
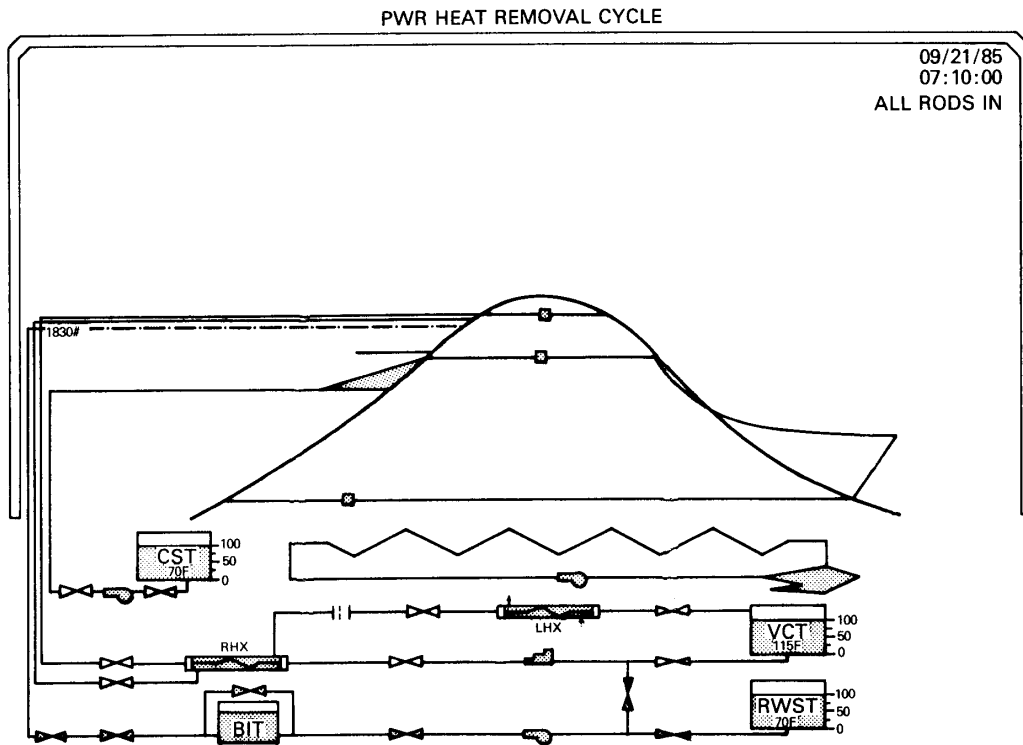


Figure 5 Icon: PWR heat engine



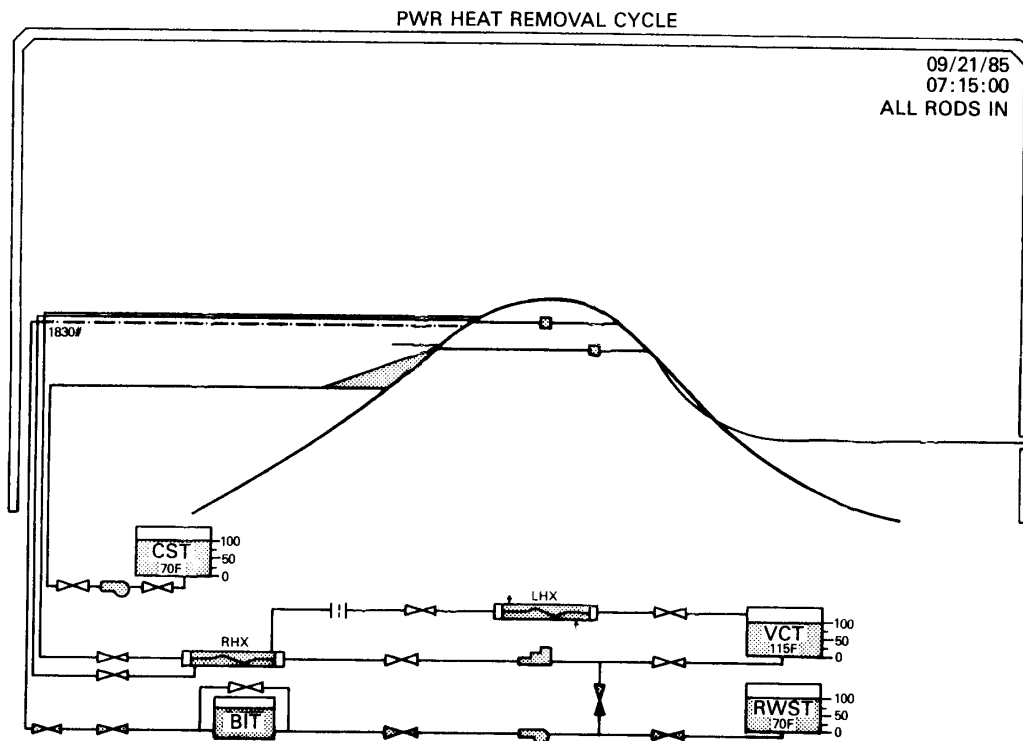


Figure 8 Icon: PWR heat removal cycle, bypass valves fail to open

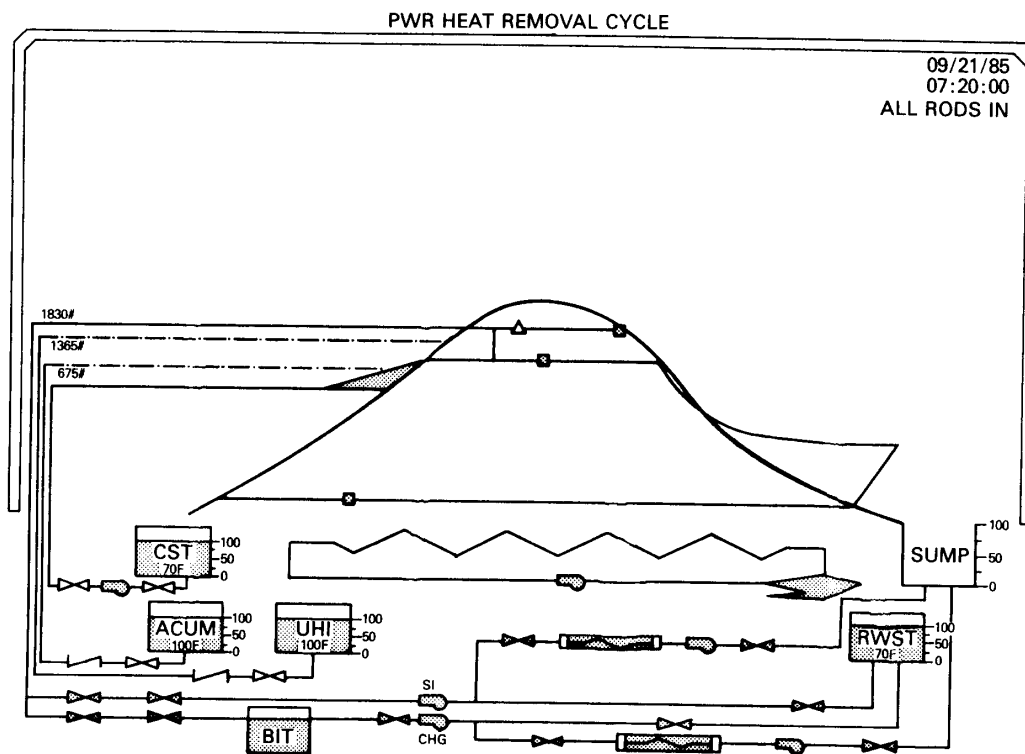


Figure 9 Icon: PWR heat removal cycle, uncoupled primary system