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RCIES : an expert system for aiding reactor operators based on the Rankine cycle

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RCIES, an expert system for aiding reactor operators based on the Rankine cycle

by

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ABSTRACT

The purpose of this thesis is to describe an expert system which can be used for assisting nuclear power plant operators during reactor operation under off-normal conditions. The idea is to use the Rankine cycle representation of the plant, to depict cycle states.

A Rankine cycle interpretation expert system (RCIES) has been developed which combines the idea of a temperature-entropy diagram (T-S diagram) representation of the Rankine cycle with the information of the corresponding plant status. The interpretation of the information shown by the T-S diagram comes from the expert system. The rule-based shell LEVEL5 was used to write the expert system.

I. INTRODUCTION

A. Role of Computer Technology in Reactor Operations

Computer systems are playing very important roles in nuclear reactor applications. These applications include computer programs for reactor operations, fuel management, calculating nuclear parameters, etc.

In order for computer systems to functions as expected, hardware and software systems must work correctly. Hardware is assumed to include all of the equipment that comprises a computer system. Software is the programs that cause the computer to do particular tasks. Beside computers which are intended to be used for general purpose applications, there are a number of computer systems which do specific tasks. For instance, there are computer systems to control reactor operation, computer systems to control traffic operation, etc.

A branch of computer science that in some sense attempts to duplicate human intelligence is called Artificial Intelligence (AI). AI has the capability to emulate human cognitive skills such as problem solving, visual conception and language understanding. One of the branches of AI is expert systems; these are computer programs which attempt to fulfill a function that normally requires human expertise [1]. An expert system displays reasoning power related to a specific domain of knowledge. Provided with certain facts, these programs can provide advice, interpret data, etc., to aid operators of large complex systems, e.g., nuclear power plants, chemical processing plant, etc. Other typical tasks for expert systems involve the interpretation of data, diagnosis of faults and planning a sequence of actions.

AI is scarcely younger than conventional programming. The earliest attempt to make a computer intelligence was a paper presented by Turing in 1963. He proposed a 'Turing test' for intelligence. This machine was used to test for the intelligence of a program. The testing was done by giving questions to the program and a human at the same time. The questions could be any subject from mathematical logic to favorite foods, and so on. If the observer could not distinguish that the responses come from either source, then it is said that the machine shows intelligence.

The actual development of AI began to be seen shortly after World War II. This period of developing AI is called the classical period [1]. During this early research period an idea called state space search was introduced. This approach assumes the problems can be formulated as a starting state, a termination state and a set of operations. One of the example forms of state space search is generate-and-test; it generates a possible solution and tests to see if the state is actually the solution. The famous algorithms of generate-and-test known as depth-first-search and breadth-first-search are of this type. One important outcome from this period of expert system development is the DENDRAL project. DENDRAL uses a special algorithm developed by Lederberg and was implemented in INTERLISP [2]. It was developed at Stanford University in 1965. The program determines the molecular structure of an unknown organic compound by manipulating symbols that stand for atoms and molecules using a modified form of generate-and-test.

The second period of the development of AI is called the romantic period [1]. During this period, researchers were concentrating on trying to make the computer 'understand.' One of the leading system was the SHRDLU system by Winograd (1972). The program was capable of understanding English by representing and reasoning about a very restricted domain. The main outcome of this period was the recognition that expert systems do not have to 'understand' a domain in the way that humans do to solve problems [3].

The modern period [1], which stretches until the present day, is denoted by the introduction of specific applications of AI. This can be compared to the romantic period where people were trying to make very general programs for intelligence systems. The expert system programming technique that emerged during this period, includes some important considerations. Firstly, two parts were identified in expert system programs, the knowledge base and the inference engine. The knowledge base contains representation of domain-specific knowledge. The inference engine is the part of the program that performs reasoning. Secondly, it was recognized that people should use as uniform a representation of knowledge as possible; so it is easier to encode and understand. Thirdly, expert systems are expected to offer the user explanation as to how the conclusion was achieved. An example of this period is the computer program called MYCIN [1]. This program assists a physician, who is not an expert in the field of antibiotics, with the treatment of blood infections. The work was done by collaboration between medical and AI communities at Stanford University in 1972. The features of this program are rule-based, backward-chaining, certainty handling, explanation and acquisition. The program generates hypotheses with respect to offending organisms and makes recommendations based on these hypotheses.

A rule-based expert system consists of a set of rules that represents the domain knowledge. A rule is a formal way of specifying a recommendation, directive or strategy expressed as IF premise THEN conclusion or IF condition THEN action [2]. When the premise is satisfied by the facts, the action specified by the THEN portion is performed. When this happens it is said that the rule is fired or executed.

There are three problem characteristics that serve to indicate that an expert system might be used successfully. The first characteristic is ill-structured problems for which known algorithms are not available. In this case, the algorithm is not definitely known, as opposed for instance, to a standard mathematical formula. The second characteristic is a problem in which knowledge availability is in the form of loosely defined rules. As an example, consider a situation in which a combination of symptoms can lead to a variety of accidents, and there is no definite rule to determine which specific accident will result. In this case only highly trained human expertise can solve the problem. The third characteristic is that a data-driven computing-system should be able to respond to incoming data from sensors, since expert systems are intended to be used in real-world problem.

In designing an expert system the programmer (referred to as a knowledge engineer) interviews the expert to obtain the knowledge to be incorporated in the program. This knowledge acquisition phase is said to be a 'bottleneck problem', because it is often difficult for experts to communicate their knowledge in a way that is easy to encode in the expert system. Buchanan et al., said that knowledge acquisition is the transfer and transformation of potential problem-solving expertise from some knowledge source to a program [4]. Two proposed solutions to the 'bottleneck problem' are machine learning and automated knowledge elicitation [1]. These methods can replace the interviews between the knowledge engineer and the domain expert and produce a similar quality output.

B. Description of Nuclear Reactor Systems

A nuclear reactor is a device where controlled nuclear reactions take place. The reactions can be divided into two types: fission and fusion reactions. The nuclear fission reaction is now economical for the production of electricity.

There are two widely and economically competitive nuclear reactors which are used today to produce electricity. They are the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). Both reactors are in the category known as the Light Water Reactor (LWR), because they use ordinary light water for moderation and coolant.

The steam cycle is the standard cycle used for generation of electrical power. It continues to grow in importance with the perfection of nuclear reactor systems, and conventional fossil fueled plants. The power cycle used in the LWR can be approximated by the Rankine cycle. This cycle is usually shown in a temperature-entropy diagram (T-S diagram), which shows the secondary cycle of the system for the PWR and the primary cycle for the BWR.

In a BWR, saturated steam is produced in the reactor vessel. In the PWR, the liquid in the primary loop is maintained at a subcooled state at all time.

As shown in Figure I.1, a PWR has primary and secondary loops. The coolant in the primary loop passes through the reactor core where the energy released in fission is removed and transported to the steam generator. Here the energy is transferred to the coolant in the secondary loop converting it to steam. The steam expands through the turbine, is converted back to liquid in the condenser, and returned to the steam generator. Several stages of feedwater heaters are employed to reheat the feedwater.

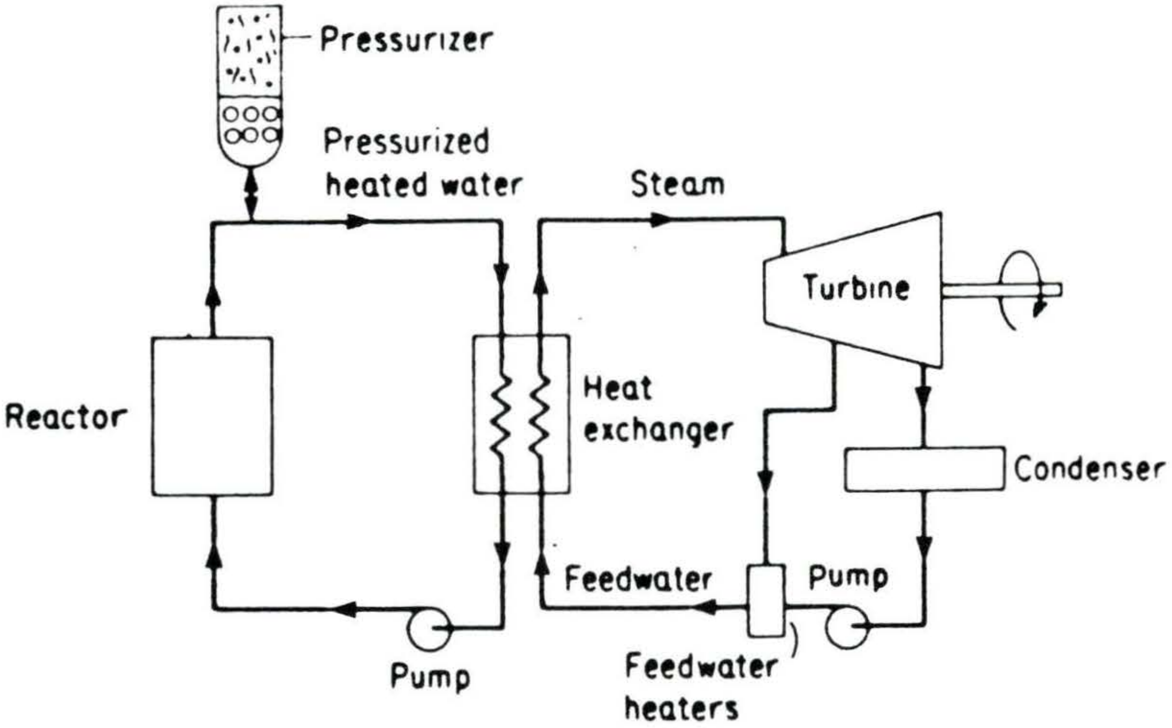

Figure I.1. A simplified diagram of a PWR system [5]

As seen in Figure I.2, the Rankine cycle can be used to show the processes in both the primary and secondary loops of the PWR. The figure shows the steady state operation at 100 % full power.

Line B-C and the constant pressure bar show the representation in the primary loop. The pressure bar shows the operating condition of the pressurizer. The pressurizer consists of saturated vapor and saturated liquid. The quality of the mixture is denoted by a point A. Point B is the cold leg and point C is the hot leg. The small space between the line B-C and the saturated liquid line indicates the degree of subcooling of the primary coolant. The vertical space between point A and point C indicates the amount of subcooling for the average core exit coolant.

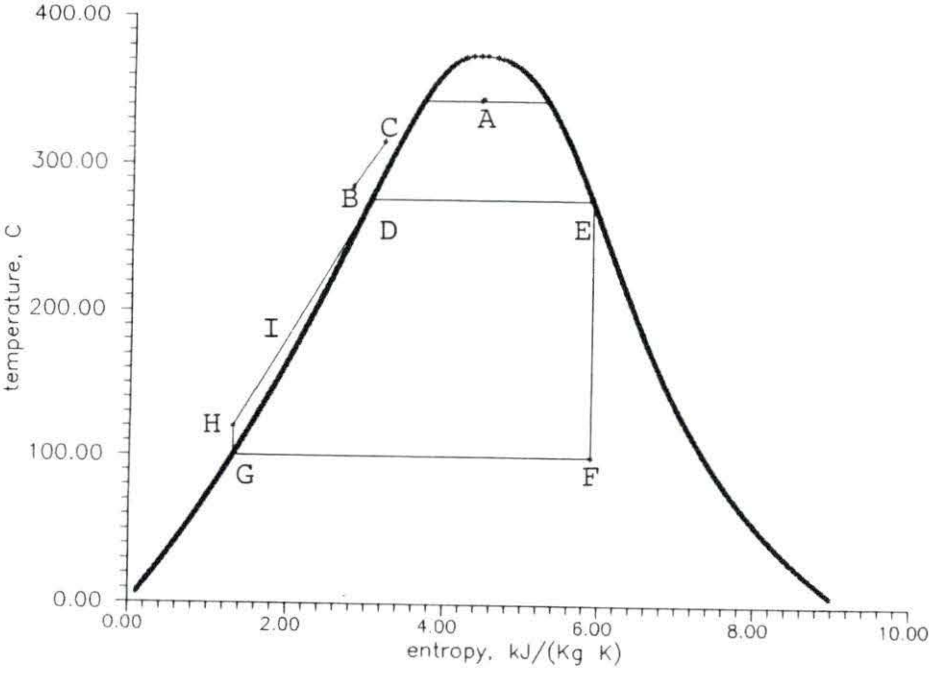

Figure I.2. Rankine cycle for primary and secondary loops of a PWR

The secondary loop of the system is represented by line D-E-F-G-H-I; this is the Rankine cycle with no reheat. Line D-E shows heat addition at constant temperature, converting the working fluid from a saturated liquid into saturated vapor. Line E-F shows isentropic expansion through the turbine. Line F-G shows condensation of the mixture to a saturated liquid. Line G-H represents isentropic compression through the pump and line H-I represents sensible heat addition from the feed-water heaters and in the steam generator.

C. Relevant Research

There have been a number of expert system applications for nuclear power plants. The expert system program is a very attractive and promising tool to use in an operator support system, because it offers a way of dealing with the information overload that can occur during a reactor transient by focusing attention on what really matters. Without an expert systems, in such conditions the volume of information presented to the operators is such that their decision for correct diagnosis of the initiating fault may be delayed.

Mizumoto et al., suggest that the reactor operators should be able to carry on a dialogue using an expert system under four modes; explanation, evaluation, hypothetical and guidance modes [6]. Here the knowledge-based support system serves as a framework for diagnosis and decision-making.

In the human factor area the application of an expert system for reactor safety is also very promising. Woods and Roth describe several studies related to human factors as they pertain to nuclear power plant safety [7]. The physical layout of the control room, and an effort to improve the control room displays for better performance is the topic of a paper presented by Beltracchi [8]. In this paper, Beltracchi illustrates the ergonomics of an integrated display, which will allow operators to monitor the heat engine cycle during normal operation of the plant and the heat removal cycle during emergency operation of the plant. Both reports show the importance of the human contribution to the safety of reactor operation. These reports also suggest a possible role for expert systems in the nuclear power plant. Reactor emergency response procedures meet one of the characteristics of the problems suggest as appropriate for expert systems, that is, it is an ill-structured problem.

A computer program called REACTOR, written by Nelson, is an expert system for diagnosis and treatment of nuclear reactor accidents [9]. The purpose of this program is to monitor a nuclear reactor facility, detect deviations from normal operating conditions, determine the significance of the situation, and recommend an appropriate response. An interesting feature of this expert system is that the knowledge base consists of two types of knowledge: function-oriented knowledge and event-oriented knowledge. Function-oriented knowledge concerns the configuration of the reactor system and how its components work together to perform a given function. Event-oriented knowledge describes the expected behavior of the reactor under known accident conditions. In compliment to this work, another attempt was made using response trees. This tree represents knowledge in a fault diagnosis task [10].

The REALM computer program is an expert system developed by Touchton, which is designed to provide expert assistance in the determination of the appropriate emergency status for a nuclear power plant [11]. The REALM reasoning process uses event-oriented knowledge and symptom-based rules. Event-oriented knowledge codifies the logic embodied in the traditional industry Emergency Action Level (EAL). Symptom-based rules identify and classify emergency conditions whether or not a specific causal event can be found.

Another important innovation introduced in expert systems is the usage of the confidence level or confidence factor. An application that uses the confidence level in reactor transient analysis is the TAMUS computer program [12]. It was designed to diagnose reactor transients by analyzing plant thermal hydraulic information and correlating it to confidence levels and existing emergency nuclear power plant operating guidelines.

A real-time application of expert systems in reactor operation is also desired. The EOPTS computer program was developed to assists reactor operators in monitoring and carrying out emergency operating procedures during reactor transient events and accidents [13]. The results show that the use of EOPTS can reduce the rate of errors as well as the time required for operator responses.

Underwood developed a computer-based nuclear power plant consultant [14]. The algorithm network model uses a commonsense algorithm (CSA) representation. The inference procedures interpret the observations and determine whether the system is in normal or abnormal conditions.

D. Objectives of Research

The purpose of this thesis is to describe the development of an expert system which can be used for assisting nuclear power plant operators during reactor operation under off-normal conditions. The idea is to develop an expert system that utilizes the Rankine cycle representation of the plant, to depict cycle states.

The basis for this idea comes from the concept presented by Beltracchi [8,15,16], in which he suggests that nuclear power plant operation can be represented as an iconic display on a T-S diagram with the Rankine cycle shown in the diagram.

Using the display of the plant cycles on a T-S diagram, an operator can determine the status of the power plant at any instant in time.

Although the display is practical for use by the operator, it requires highly trained personnel to interpret what is being shown, since the changing of the iconic display corresponds to different plant conditions. Therefore, the operator must know that a given iconic display corresponds to a particular plant status.

A Rankine cycle interpretation expert system (RCIES) has been developed which combines the idea of the iconic display with the information of the corresponding plant status. The interpretation of the information comes from the expert system.

The language used in the development of the expert system is the LEVEL5 shell [17]. The LEVEL5 shell features are rule-based and backward-chaining. It uses a production rule language that has the capability to interface with procedural language programs, such as those written in FORTRAN and PASCAL.

E. Overview of Thesis

This thesis consists of 5 chapters plus a table, figures, appendix and bibliography. Chapter I serves as an introduction of the area of the research, including descriptions of the relevant research that has been done and the objectives of the research.

Chapter II discusses the process of knowledge acquisition and knowledge representation in an expert system. This chapter distinguishes between conventional programming and expert systems. The 'bottleneck problem' is discussed in more detail. The process of building an expert system using a rule-based expert system shell is described.

Chapter III discusses the LWR system. The emphasis is on the PWR system. The discussion relates to the thermal hydraulics processes relevant to nuclear power systems and their safety features.

Chapter IV describes in greater detail the programming of RCIES. Early sections of the chapter give some idea of how the LEVEL5 shell works and how it is applied to the objective of the research. Later in the chapter, the coupling between the iconic display of the T-S diagram with the expert system is shown. Sample runs of accidents sequences and illustrations of the operator's responses are presented.

Finally, chapter V summarizes the thesis and notes the advantages and disadvantages of RCIES. Some suggestions for possible improvement of the program for future work are discussed.

II. DESIGN AND IMPLEMENTATION OF EXPERT SYSTEMS

A. Expert Systems Versus Conventional Programs

In many ways expert systems differ from conventional programs. The basic difference is that expert systems manipulate knowledge whereas conventional programs manipulate data. The conventional programs are designed to produce the correct and precise answer every time (an algorithm), while expert systems are designed to behave like experts, who sometimes produce correct answers and sometimes incorrect answers (heuristics). However, when expert systems make mistakes, they have the potential to learn from their errors. Unlike expert systems, conventional programs are useless if they produce incorrect answers, so that the programs must be debugged to correct the mistakes. Table II.1 summarizes differences between conventional programs and expert systems.

Table II.1. The differences between conventional programs and expert systems

Conventional programs	Expert systems
Numeric data	Symbolic representation
Algorithmic - exact solution	Heuristic solutions
Repetitive process	Inferential process
Effective manipulation of large data base	Effective manipulation of knowledge base

B. The Basic Characteristics of Expert Systems

Some researchers have a more restricted view of an expert system. They define an expert system as a computer program that has the properties: expertise, symbolic reasoning, depth and self-knowledge [18].

1. Expertise

An expert system does not only simply produce good solutions; it must be able to find them effectively and efficiently. The ability to truly mimic a human expert (robustness), must also be possessed by an expert system [2]. This is the least developed technique in current expert systems.

2. Symbolic reasoning

A symbol is a string of characters that stands for some real-world concept. For instance: temperature, quality, pressure, etc., are symbols we use to represent thermodynamic properties. These symbols can be combined to represent relationships. Used in this way they represent a symbolic structure. For instance:

```
IF   temperature is given
AND  pressure equals saturated pressure
AND  quality equals zero
THEN water is a saturated liquid at that temperature
```

Unlike conventional programming, expert systems manipulate symbols rather than evaluating standard mathematical formulas. Therefore it is important to choose, form, and combine these symbols into usable form. This process is called knowledge representation.

3. Depth

Expert systems work in the real-world problem domain. Therefore, rules in an expert system are usually complicated. In this domain, the human expert applies actual data to a practical problem and produces solutions that are useful. Therefore, an expert system must have a depth; that is, it has the ability to handle difficult problem domains and use complex rules [2].

4. Self-knowledge

It is possible to develop an expert system that has the ability to examine its own reasoning and explain its operation. This is knowledge about knowledge, which is defined as metaknowledge, and represents knowledge in an expert system about how the system operates or reasons [2].

Current expert systems have a capability to explain how the solution is achieved or have an explanation facility. In this explanation facility, the inference chains and reasoning rationale are available to the user.

C. Knowledge Acquisition

Knowledge in an expert system may come from many sources, such as textbooks, data bases, case studies, reports, etc. However, the dominant part of knowledge usually come from the human expert. The process of eliciting knowledge from a human expert and codifying it is called knowledge acquisition. This process involves interaction between the human expert and the knowledge engineer. The knowledge engineer interviews the human expert. The human expert has in-depth knowledge about the problem of interest. Expert systems attempts to model the expert's knowledge in a computer program.

Knowledge engineering is the process of transferring knowledge from a human expert to a computer program. The person who does this is called a knowledge engineer. This person usually has a background in computer science and/or the artificial intelligence field. Special computer programs that have features that facilitate the development of expert systems are referred to as an expert system tool or shell. The availability of these tools or shells has made it possible for the expert to also serve as a knowledge engineer in some cases.

The activities that the knowledge engineer must carry out include: interviewing the experts, organizing the knowledge, deciding how it should be represented in the expert system, and helping write the code if it is to be done by someone else. Figure II.1 shows steps involved in the transfer of knowledge from the human expert to a computer program; this is also referred to as knowledge engineering. As illustrated in this figure, the knowledge engineer interviews the human expert to gather knowledge. He or she then produces the knowledge base as a representation of the human expert. When some rules have been developed, the testing of the expert system can begin. Along with the interviewing process, the program is validated and revised until it has the ability to solve problems in much the same manner as the human experts.

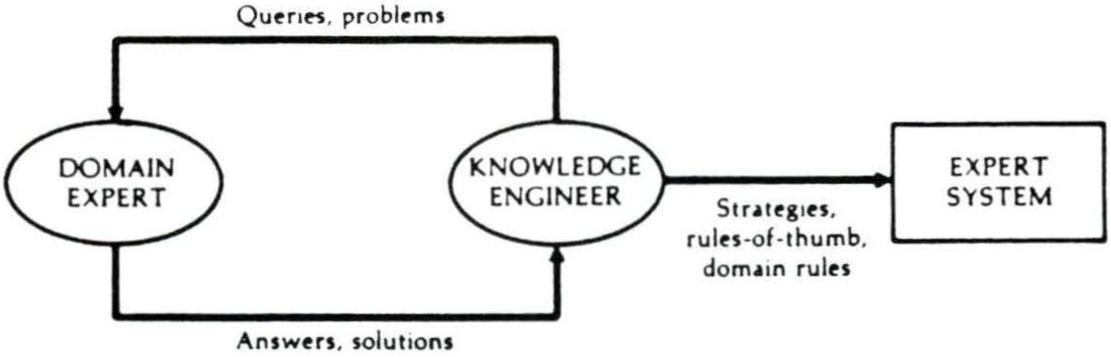

Figure II.1. Knowledge engineering [2]

The acquisition of knowledge and the structuring of the knowledge into rules has long been known as the 'bottleneck' in expert system development. Therefore, as a result of this bottleneck, productivity is poor. It is common to produce between two to five production-rule-equivalents per day [1].

There are a number of reasons why structuring knowledge has been a problem in the development of expert systems [1]:

1. Human experts have their own language or jargon to express their knowledge. This makes it difficult for the knowledge engineer to understand the knowledge they are trying to grasp. Sometimes, the human experts cannot explain their reasoning process. Therefore, the knowledge engineer must enrich his or her knowledge about the domain of interest by reading textbooks, analyzing case studies, etc., before interviewing the human experts.

2. The domain of interest cannot be characterized in terms of mathematical theory. For instance, suppose that the weather today is cloudy, concluding that it will rain is not an exact conclusion. Therefore, this cannot be formulated into mathematical form.

3. Experts tend to think in terms of general principles of a domain in order to solve problems. Experienced or well trained human experts usually know their capability very well. However, much of their capabilities are in the form of general principles about the domain of interest. For instance, a military strategist can explain quickly the weapons possessed by the enemy, but he would be less aggressive in answering

questions such as which weapons would immediately threaten us and which would not.

4. Finding a good notation for expressing knowledge and a good framework for it is itself a hard problem.

Knowledge acquisition is illustrated in Figure II.2. The figure shows the activities which can be represented in five stages: identification, conceptualization, formalization, implementation and testing [1].

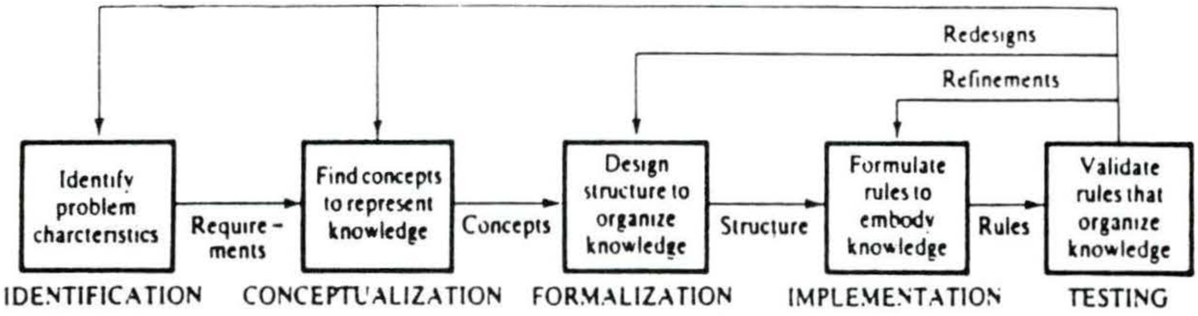

Figure II.2. Stages of a knowledge acquisition [1]

Identification is the process of characterizing the problems of interest and the criteria that solutions must meet. Conceptualization is the steps required to uncover the key concepts and their relationships, including a characterization of the different kinds of data, the flow of information and the underlying structure of the domain. Formalization includes the certainty and completeness of the information, and other constraints on the logical interpretation of data, such as time dependency, and the reliability and consistency of different data sources. Implementation is the steps to formalize the knowledge into an executable program. Here one is primarily concerned with the specification of control and the details of information flow. Testing of expert systems is the task to run the program on a large and representative sample of test cases. Common sources of error at this point are rules which are either missing, incomplete or incorrect. Competition between related rules can cause unexpected bugs.

D. Knowledge Representation

There are four schemes of knowledge representation used [19]: semantic networks, frames, scripts, and production systems.

Semantic networks are a graphical representation of relations between elements in a domain where the basic components are nodes and links. Nodes are used to represent domain elements and links are vectors from one node to another. For instance, to represent the statement, "control rod is part of reactors," the following semantic network can be shown:

CONTROL ROD ----- partof -----> REACTORS

The second scheme is frames, which are a structure for organizing knowledge. For example, suppose we know that a nuclear reactor consists of nuclear fuel elements, control rods, moderator, coolant and undergoes fission reaction. Anytime we have these knowledge elements in mind, we expect that it is true that they refer to a nuclear reactor. These elements are called defining characteristics. Figure II.3 shows a frame that provides a partial description of the class of objects called REACTOR.

- Frame: REACTOR
  - Type: LWR
    - Model: PWR
      - Fuel: Uranium
      - Coolant: Light water
      - Moderator: Light water
      - Number of Cycle: two loops

Figure II.3. A reactor frame

The third scheme is scripts, which is a structure used to store prototypes of expected sequences of events. One of the applications of scripts is causal-effect relations that establish a causal chain. For example, consider the following actions: (1) Pressure increases; (2) Steam voids collapse; (3) Positive reactivity added; (4) Power increases. These activities show event (1) caused event (2) caused event (3) and ultimately caused event (4).

The fourth scheme is production systems, which use rules for knowledge representation. Production systems consist of working memory, production rules and an interpreter. Examples of production systems include OPS5 [20] and the LEVEL5 shell [17].

Working memory is an area of memory that is used to track the current state; it is composed of working memory elements. In the working memory, the working memory elements or the knowledge bases have been formatted using the syntax of the appropriate language used.

The Production Rule (PRL) language used in the LEVEL5 shell consists of the condition portion, that is sometimes called the left hand side (LHS) portion and the action portion, that is sometimes called the right hand side (RHS) portion. The LHS consists of condition elements that describe the premise that must be true for the rule to be applicable. The RHS describes the action that must be taken when the rule fires.

The interpreter or inference engine recognizes and executes a production whose LHS has been satisfied. To recognize applicable rules, the interpreter compares the LHS with the current state of the working memory, this activity is called a reasoning process. The following section discusses the rule-based programming in more detail.

E. Rule-based Programming in Expert Systems

Rule-based programming is another way to represent knowledge in an expert systems. In rule-based programming, there are two kinds of systems or strategies that can be used; backward-chaining systems and forward-chaining systems. Backward-chaining systems sometimes are also called top-down systems. Forward-chaining systems are also sometimes called bottom-top systems.

Backward-chaining systems work by starting from the ultimate goal and breaking down the goal into subgoals. This means, in order for the program to work, one ultimate goal must be stated first, and the program then tries to satisfy the goal by firing the appropriate rules that lead to the ultimate goal. This type of system is an appropriate application particularly for diagnosis.

Forward-chaining systems, on the other hand, work from initial conditions that are known; the current state of knowledge then is used to make a chain of inferences until a goal is reached or a solution is unattainable.

The LEVEL5 shell used in this research is an example of a production rule language which uses either backward-chaining or forward-chaining. LEVEL5 is an advanced development environment and delivery vehicle for expert systems [17]. The LEVEL5 system overview is shown in Figure II.4.

The advantages of LEVEL5 shell are:

1. It has the capability to activate other LEVEL5 knowledge bases and to communicate with them via a file or global facts or shared parameters.

2. It allows external programs to be activated directly by a knowledge base and provides an interface to dBASE II and dBASE III data files.

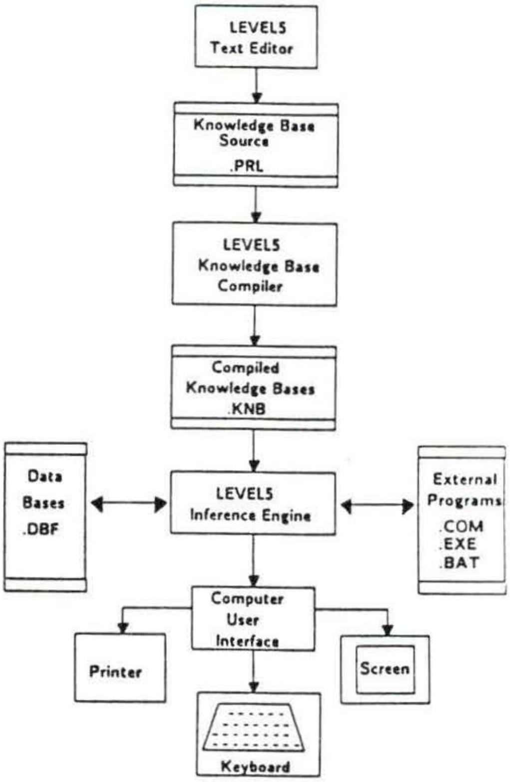

Figure II.4. The LEVEL5 system overview [17]

Figure II.5 shows an example of rules, using the LEVEL5 shell syntax and a backward-chaining system, to determine the current status of a reactor power plant as the goal. The facts given are for the normal conditions of a PWR type reactor using design parameters given in reference [21].

```
Rule for determining primary coolant status
IF   Hot leg pressure greater than saturated pressure 1
AND  Cold leg pressure greater than saturated pressure 2
THEN primary coolant is in subcooled region

Rule for normal operation
IF   primary coolant is in subcooled region
THEN primary coolant is in normal condition

Rule for determining S/G status
IF   S/G outlet pressure equals saturated pressure 3
AND  S/G outlet quality equals one
THEN S/G outlet is in saturated vapor line

Rule for determining turbine status
IF   Turbine outlet pressure equals saturated pressure 4
AND  Turbine outlet quality greater than zero
AND  Turbine outlet quality less than one
THEN Turbine outlet is in mixture region

Rule for determining condenser status
IF   Condenser outlet pressure equals saturated pressure 4
AND  Condenser outlet quality equals zero
THEN Condenser outlet is in saturated liquid line

Rule for determining feedwater pump status
IF   Feedwater pump outlet pressure greater than saturated
     pressure 4
THEN Feedwater pump outlet is in subcooled region

Rule for normal operation
IF   S/G outlet is in saturated vapor line
AND  Turbine outlet is in mixture region
AND  Condenser outlet is in saturated liquid line
AND  Feedwater pump outlet is in subcooled region
THEN Secondary coolant is in normal condition

Rule for steady state operation
IF   primary coolant is in normal condition
AND  secondary coolant is in normal condition
THEN reactor is operating in steady state operation
```

Figure II.5. Rules for current status of power plant

III. THERMODYNAMIC ASPECTS IN LIGHT WATER REACTORS

A. Characteristics of Some Thermodynamic Systems

Thermodynamics is used to analyze systems involving energy transfer. The systems usually contain some working substance, in a liquid or a gas phase, which flows or circulates through the components. One of the valuable method of analysis is to use a T-S diagram for systems that undergo a cyclic process.

The Carnot cycle is an idealized cycle that is based on principle that no engine can produce more work for the same amount of heat added and the same heat source and sink temperature than one operating on a reversible cycle [5]. Since in the Carnot cycle, the temperature difference between the heat source and the fluid during heat addition or between the fluid and the heat sink during heat rejection is zero, this cycle cannot be applied in an actual system. For instance, in the actual cycle like the PWR systems there is a temperature difference during heat addition and heat rejection in the heat exchanger. A practical approximation to the Carnot cycle is the Rankine cycle.

The Rankine cycle can be used to approximate the power cycle used in the LWR which receives most of its heat and rejects all of its heat at constant temperature. The thermal efficiency of the Rankine cycle is less than the thermal efficiency of the Carnot cycle, because of the fact that there are temperature differences between the source and sink and the working fluid.

Figure III.1 shows the T-S diagram for the Carnot cycle. It consists of four reversible processes: two processes of isothermal heat addition and heat rejection (1-2, 3-4), isentropic expansion and isentropic compression (2-3, 4-1). The internally reversible Rankine cycle is shown in Figure III.2.

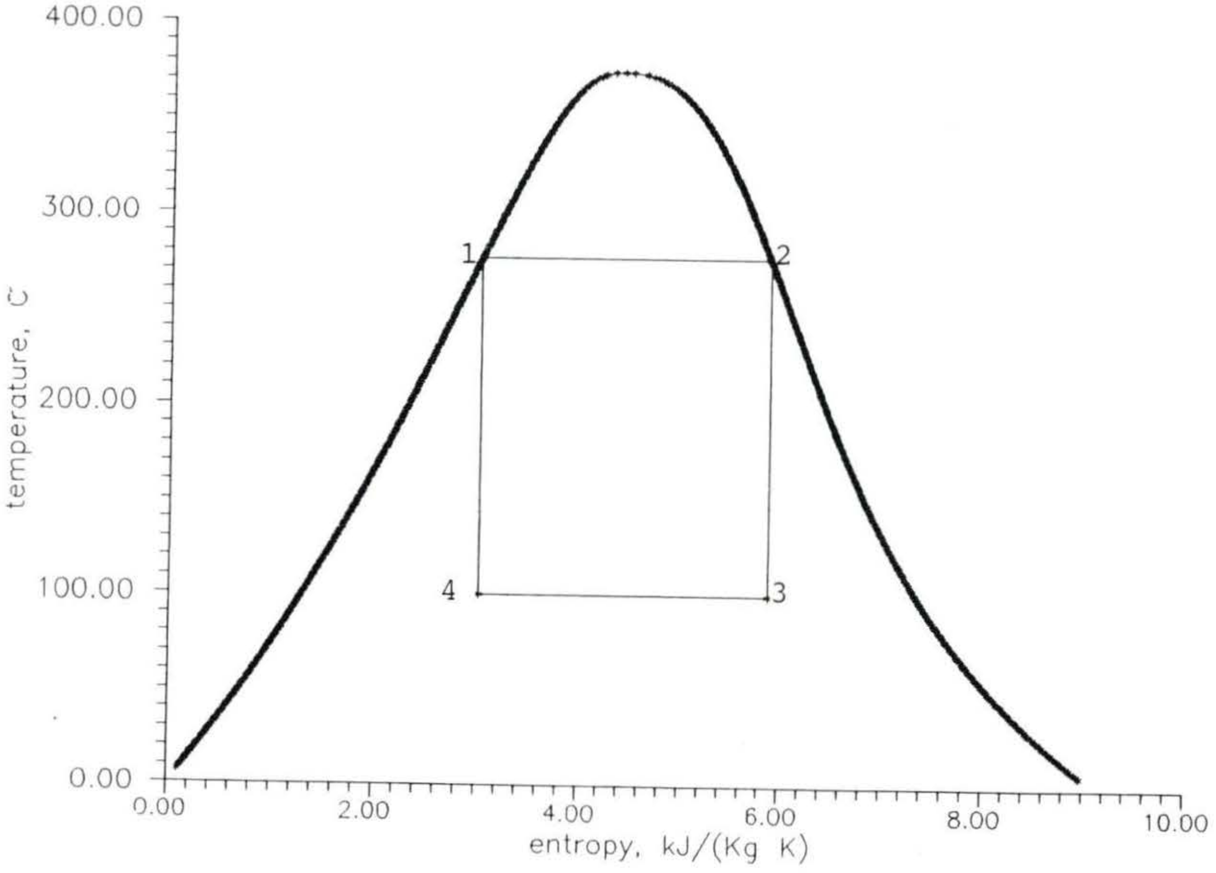

Figure III.1. T-S diagram with the Carnot cycle

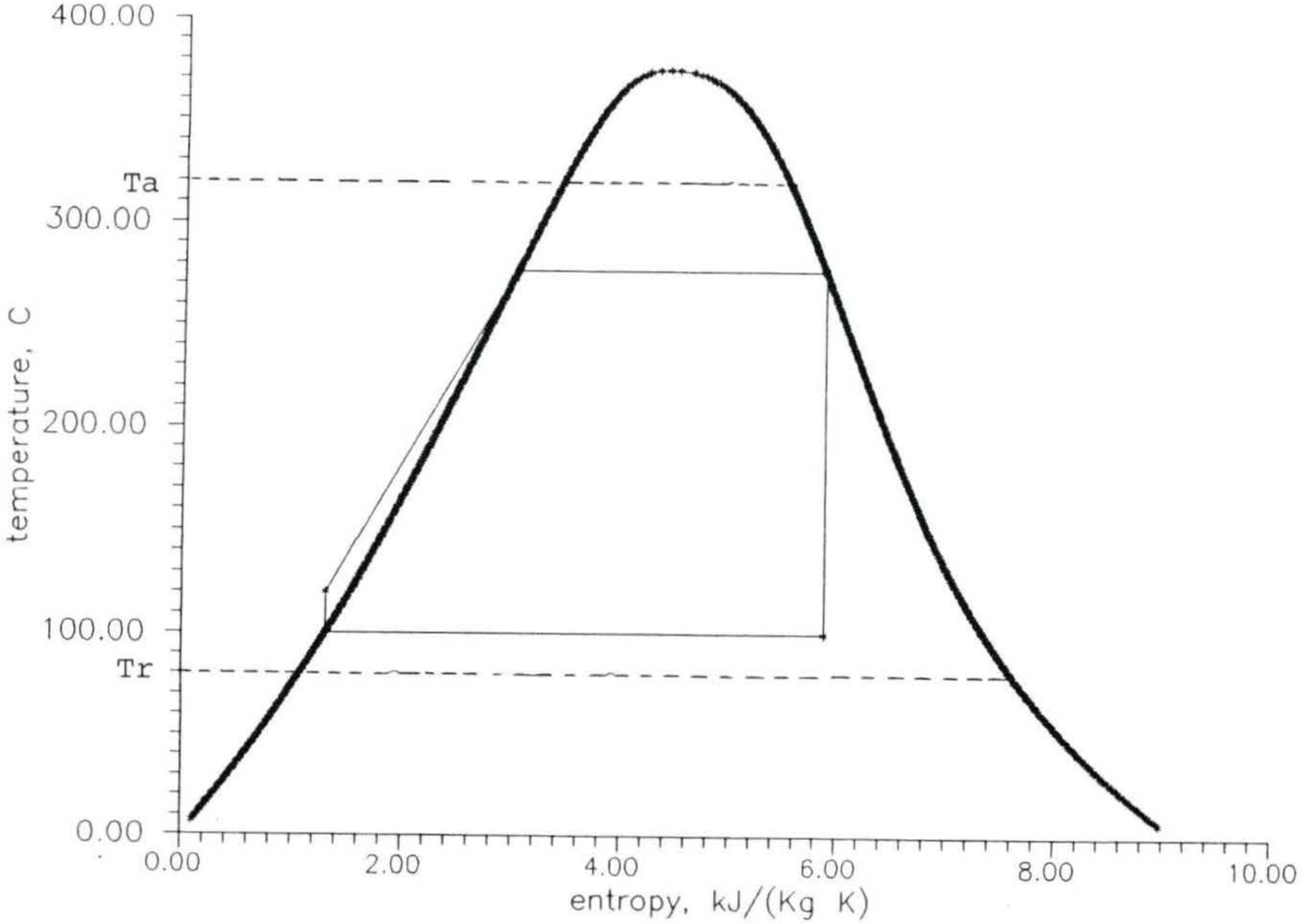

Figure III.2. Internally reversible Rankine cycle

Modern power plants produce superheated steam to improve efficiency and reduce moisture in the turbine. Reheat of the working fluid is also used between turbine stages to reduce the moisture content of the steam. The Babcock & Wilcox PWR systems uses superheated steam [22].

The Rankine cycle can be used to describe the plant conditions for PWR system as well as for BWR system. In BWR, the T-S diagram only shows one cycle, the direct cycle, in which the boiling core is shown in place of the steam generator in PWR. The use of superheat can also be shown in the T-S diagram. Therefore, the B & W type of PWR system may also be represented by the Rankine cycle.

The expert system RCIES described in this thesis is restricted at this time to the Westinghouse PWR system.

B. Boiling Water Reactor

1. Flow diagram

The boiling water reactor (BWR) is a nuclear power plant which boils water in the reactor vessel. The saturated vapor produced is used to drive the turbine. This type of cycle is a direct cycle. Figure III.3 shows the flow diagram of a BWR.

Water is circulated through the reactor core, producing saturated steam. Heat produced by the fission reaction in the core is used to boil the water. The steam produced carries some liquid which is separated from the vapor by a separator and a dryer. The steam then goes to the turbine. The turbine consists of two stages, a high pressure (HP) turbine and two low pressure (LP) turbines. Before the steam enters the LP turbines it is separated from the water content and reheated.

The turbines operate the turbogenerator and produce electricity. Most of the steam from the turbines flows through the condenser, where it is converted to a saturated liquid. The condensate pump, pumps the condensed water through demineralizers and feedwater heaters. The feedwater pump increases the pressure of the coolant to the level in the reactor vessel.

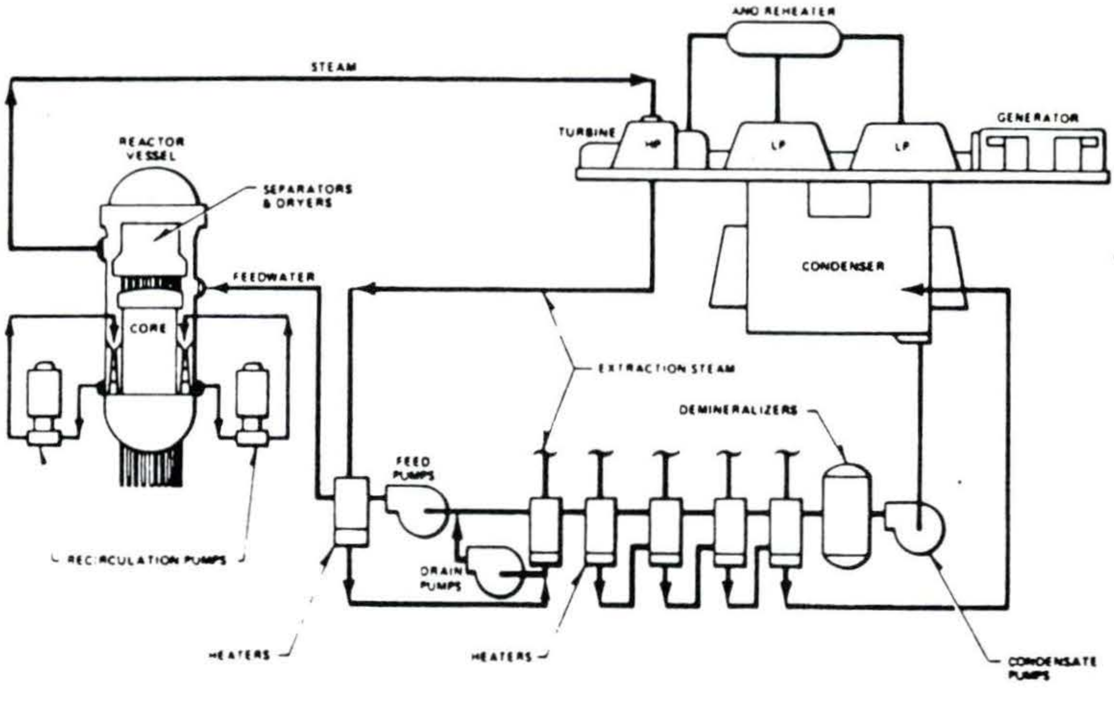

Figure III.3. Flow diagram of BWR [23]

The jet pump recirculation system is used to circulate the required coolant through the reactor core and to control the steam void content of the core. It provides forced circulation flow. This system controls the reactor power through the negative void coefficient.

2. Primary process systems

The jet pump system mentioned in the previous section is located in the main recirculation system within the reactor vessel. This system is used to control the flow through the reactor core. Figure III.4 shows the jet pump recirculation systems.

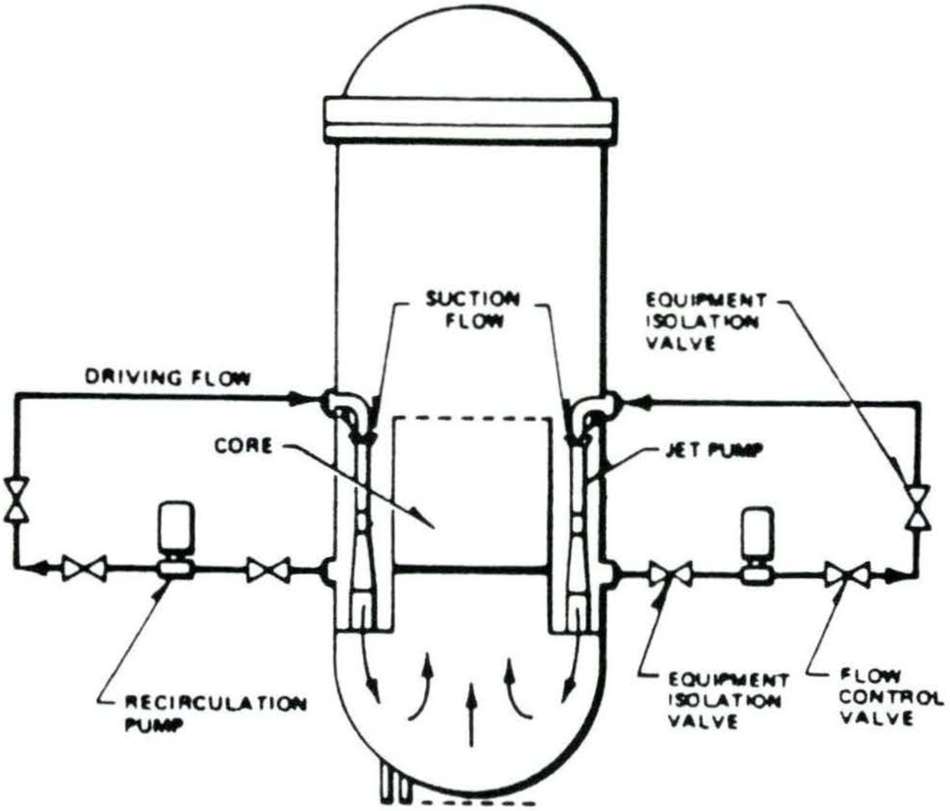

Figure III.4. The jet pump recirculation flow [23]

The primary process systems are used during normal reactor operation. The system consists of the main recirculation system, the main steam lines, and the feedwater system. The purpose of the primary process systems is to supply steam to the turbine and feed water to the reactor and to cool the reactor core.

The purpose of the main steam lines is to carry steam from the reactor to the turbine. There are two isolation valves (internal and external) to close the reactor containment penetration. The internal isolation valves will close and interrupt the outlet steam flow if there is a pipe break outside the containment. The external isolation valves will close and isolate the reactor if there is a pipe break inside the containment. Besides these valves, there are safety/relief valves on each line outside of the reactor vessel. These valves provide protection against overpressure of the reactor primary system.

The feedwater system carries water from the condenser to the reactor vessel. The water usually is in a subcooled state, therefore, it is at high pressure. This high pressure is generated by the feedwater pumps. In the system, there are internal and external isolation valves.

The internal isolation valves are check valves, because the water flow is controlled automatically to maintain the water level constant. The external isolation valves are power-operated, and are operationally controlled in the main control room.

3. Emergency core cooling systems

Besides the system functions required for the reactor during normal condition, there is a system which is used when accidental loss of coolant occurs in the reactor. These systems are called the emergency core cooling systems (ECCS), and are used to keep the reactor core cooled in the event of such an accident.

The primary objective of the ECCS is to prevent fuel cladding failure for any mechanical failure, including the severance of the largest pipe in the plant. This prevention is very important because the release of radioactive materials must not take place during the most severe accident that can happen in the reactor.

C. Pressurized Water Reactor

1. Flow diagram

The pressurized water reactor (PWR) is a nuclear power plant which uses ordinary light water as moderation and coolant. The water is maintained in a subcooled state while in the core, therefore the pressure in the reactor must be greater than the saturated pressure corresponding to the given temperature. Figure III.5 shows a schematic diagram of the PWR system.

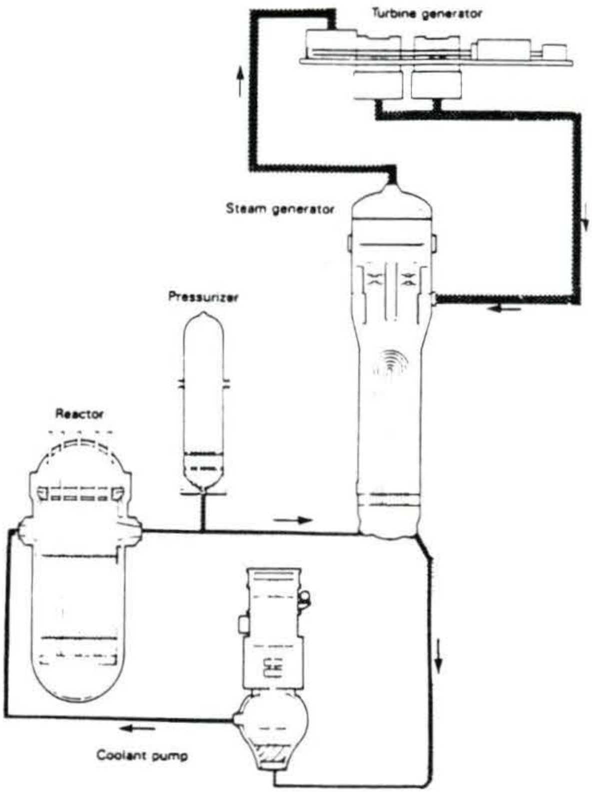

Figure III.5. Schematic diagram of PWR system [24]

2. Functional description

This type of reactor uses a dual cycle; a primary loop and a secondary loop. The water is heated as it flows through the reactor and gives off its energy to the secondary loop through thin-wall tubes in the steam generator. The secondary loop, which is at a lower pressure than the primary loop, produces steam to drive the turbine-generator.

The reactor vessel contains the coolant, nuclear fuel assemblies, and control rods. The control rods control the nuclear fission rate and provide an instantaneous shutdown capability. The water coolant increases in temperature as it flows through the core in direct proportion to the reactor power level.

The steam generator transfers thermal energy from the reactor to the turbine steam system. Therefore, the steam generator consists of two main parts, a primary side and a secondary side. Spent steam from the turbine is condensed by the condenser and pre-heated prior to returning to the steam generator. The steam generator level is controlled automatically to ensure a reactor heat sink and to prevent moisture carry over that could damage the turbine blading. The steam flow, pressure, and steam generator level are always monitored to ensure heat sink integrity. When the values of these parameters exceed the design restriction, safety actions are automatically initiated.

The pressurizer provides an expansion volume for the primary system coolant and controls primary system pressure. The fluid in the pressurizer is at the saturation temperature for the given system pressure. Pressure in the pressurizer is maintained by a combination of electric heaters and spray from the primary system cold leg. Therefore, the pressurizer acts as the surge tank.

The expansion of reactor coolant increases the water level of the pressurizer, and raises the pressure of the pressurizer. At this point, the pressurizer is experiencing insurge flow. In order to decrease the pressure to design pressure, the spray from the primary coolant cold leg is actuated.

When electrical load demand increases, it will result in a temporary decrease in average coolant temperature and coolant volume is decreased. The water in the pressurizer then flows out into the primary loop. At this point, the pressurizer is experiencing outsurge flow, thus reducing the pressurizer level and pressure. When the water level is near the lowest allowable level (approximately above the electric heater), the electric heater is turned on to limit the pressure reduction.

When the pressure increase is beyond the capability of the pressurizer spray system, the relief valves open. The steam from the relief valves flows through the pipe to the pressurizer relief tank.

D. Safety Aspects in Light Water Reactors

The main objective of reactor safety considerations is to prevent radioactive release to the environment. The current LWRs have been proven to be operationally safe for more than 30 years. The basic philosophy of safety incorporates three criteria: fail-safe designs, multiple barriers, and multiple and redundant systems.

The fail-safe designs means that if there is a failure, the emergency system must be able to shut the reactor down (if necessary) in a fail-safe manner. For example, if there is power failure, magnetic contact is lost and the rods fall by gravity back into the core, shutting down the reactor safely.

Nuclear power reactors usually have four barriers: fuel, cladding, reactor vessel, and containment vessel. The first innermost is the fuel, which tends to holds the fission products. The fuel cladding is designed to withstand temperature rise so that the fuel would not melt. The reactor vessel, which is the third barrier, is again used to prevent release of radioactive contamination to the environment. The containment vessel will serve to keep the radioactive substance inside should the other system fail.

A variety of safety systems are used, each of which operates differently for different reactor conditions. For example, there are safety injection systems, recirculation systems, etc. Redundancy is the concept that a system has a backup or standby system. For example, there are two or more motor-operated valves to control flow. In this example, two or more motor-operated valves function and the rest of the valves remain in standby and should be able to operate when the current valves fails to open or close when they are needed.

IV. DESIGN AND IMPLEMENTATION OF RANKINE CYCLE INTERPRETATION EXPERT SYSTEMS (RCIES)

A. Knowledge Acquisition and Representation

RCIES was designed using the LEVEL5 shell which uses the backward-chaining system. The knowledge in RCIES was gathered by interviewing the expert [26,27], case studies, and NRC reports [28]. The basic concept of the design is to utilize the Rankine cycle to depict the cycle state. The parameters needed to construct the expert systems describe the following processes: sensible heat addition, boiling water to generate steam, expansion and turbine work, heat rejection with condensation of steam to water, and compression of water by means of a pump.

To be more specific, the information needed are the temperature and pressure in each subsystem of the Rankine cycle. A modified set of subroutines, originally called QUAL [29], has been used to calculate the thermodynamic parameters, such as entropy. The subroutines were modified so that they may be used to calculate the parameters needed for RCIES.

The output of QUAL is used to construct the Rankine cycle in the T-S diagram. The diagram is displayed by using the package program called VIEW [30]. The program is a two-dimensional graphic program, which has the capability to enlarge or reduce the scale of the diagram shown. Both programs, QUAL and

VIEW, are incorporated in RCIES. Therefore, the control of processes are within the expert system.

Figure IV.1 shows the block diagram of the whole processes of RCIES. The program has the capability to simulate abnormal events and emergency events in the PWR operations (Westinghouse type).

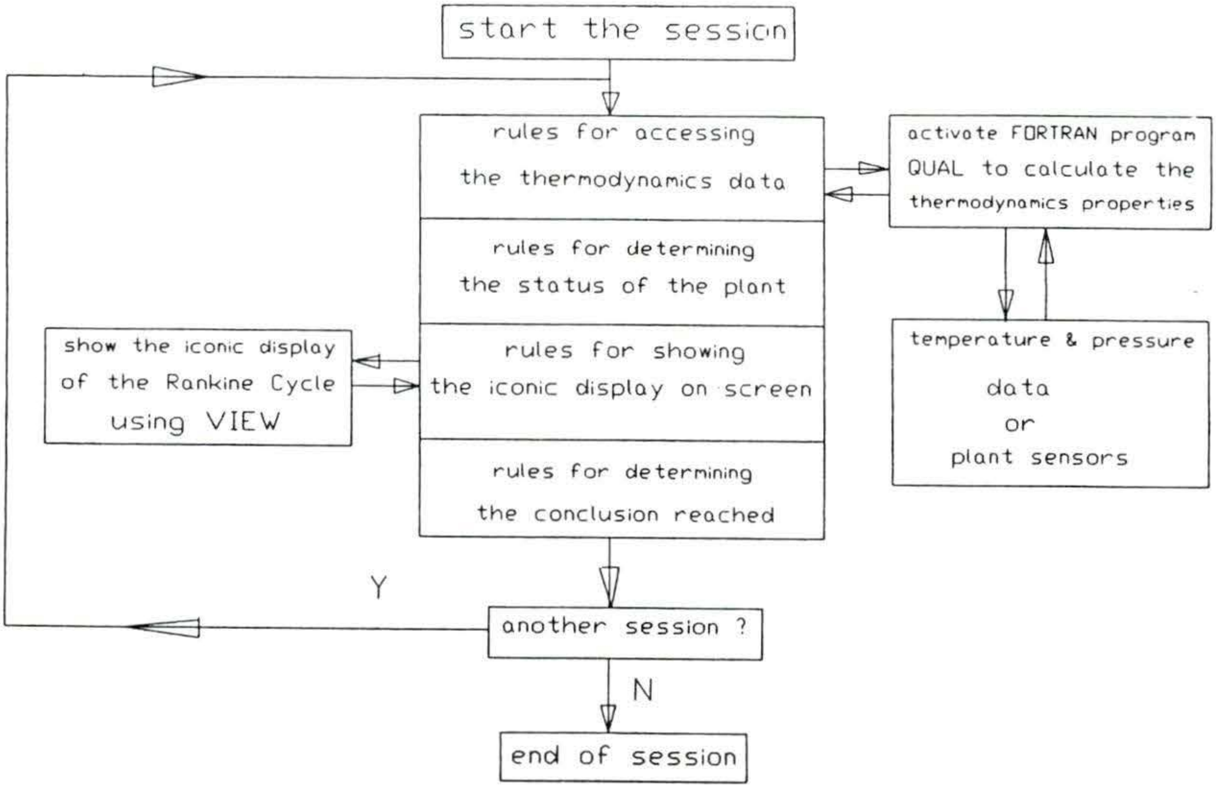

Figure IV.1. Block diagram of RCIES

Figure IV.1 shows the first rules in the knowledge base activate an external program called QUAL, which solves the thermodynamics equations of state for the coolant properties, given the temperature and pressure of each coolant loop in the system. QUAL obtains these input data from a file or from the plant sensors in actual application. This information is then used by the knowledge base to infer the plant coolant conditions.

Another external program called VIEW is also interfaced with the RCIES. This package generates a plot file and displays the T-S diagram on the computer screen. The expert system informs the user of the plant conditions and uses the T-S diagram as part of the explanation of the inference of the plant status. The user is then prompted to indicate if he/she wishes to continue or to terminate the analysis. During an actual event, RCIES would continue to receive changing input data and would continually inform the operator of the changing plant status. As an example of how RCIES activates an external program, Figure IV.2 shows the rules to active QUAL.

```
RULE      to activate access the thermodynamics data
ACTIVATE  c:\prl\QUAL.EXE
DISK      c:\prl\paramkb.dat
SEND      temperatures and pressures of the primary loop
SEND      temperatures and pressures of the secondary loop
RETURN    temperatures and pressures of the primary loop
RETURN    entropies of the primary loop
RETURN    temperatures and pressures of the secondary loop
RETURN    entropies of the secondary loop
THEN      the thermodynamics properties have been determined
```

Figure IV.2. Rule to active the external program QUAL

A more detailed block diagram of RCIES is shown in Figure IV.3. In this figure RCIES consists of a main program and the chain to the other programs. The CHAIN command of LEVEL5 is then used to access the other knowledge base of interest. With this function, a knowledge base of virtually limitless size can be created, therefore any number of events can be added to RCIES.

The first program chained to RCIES is the knowledge base related to the simulation of the emergency event consisting of a steam generator tube rupture (SGTR). RCIES determines the event and gives step by step advice to the operators to secure the reactor. The second knowledge base chained to RCIES is simulation of the abnormal events that might occur in the pressurizer, such as loss of automatic pressurizer pressure control (LOAPPC), and failure of spray valve to close (FOPSV). The other knowledge bases chained to RCIES are simulations of other emergency events such as feedwater line break, steam line break, and a small loss of coolant accident. However, since there is not adequate information for these knowledge bases, they have not been fully developed at this time. When such information is available, RCIES may be modified easily by incorporation of the appropriate chain commands and logic.

The discussions of the states represented by SGTR, PZR knowledge bases can be found in the discussions of implementation of RCIES. The SGTR knowledge base is the knowledge base that simulate the emergency event in the steam generator. The PZR knowledge base contains two abnormal events, LOAPPC and FOPSV. A complete source codes listing of RCIES can be found in the appendix of this thesis.

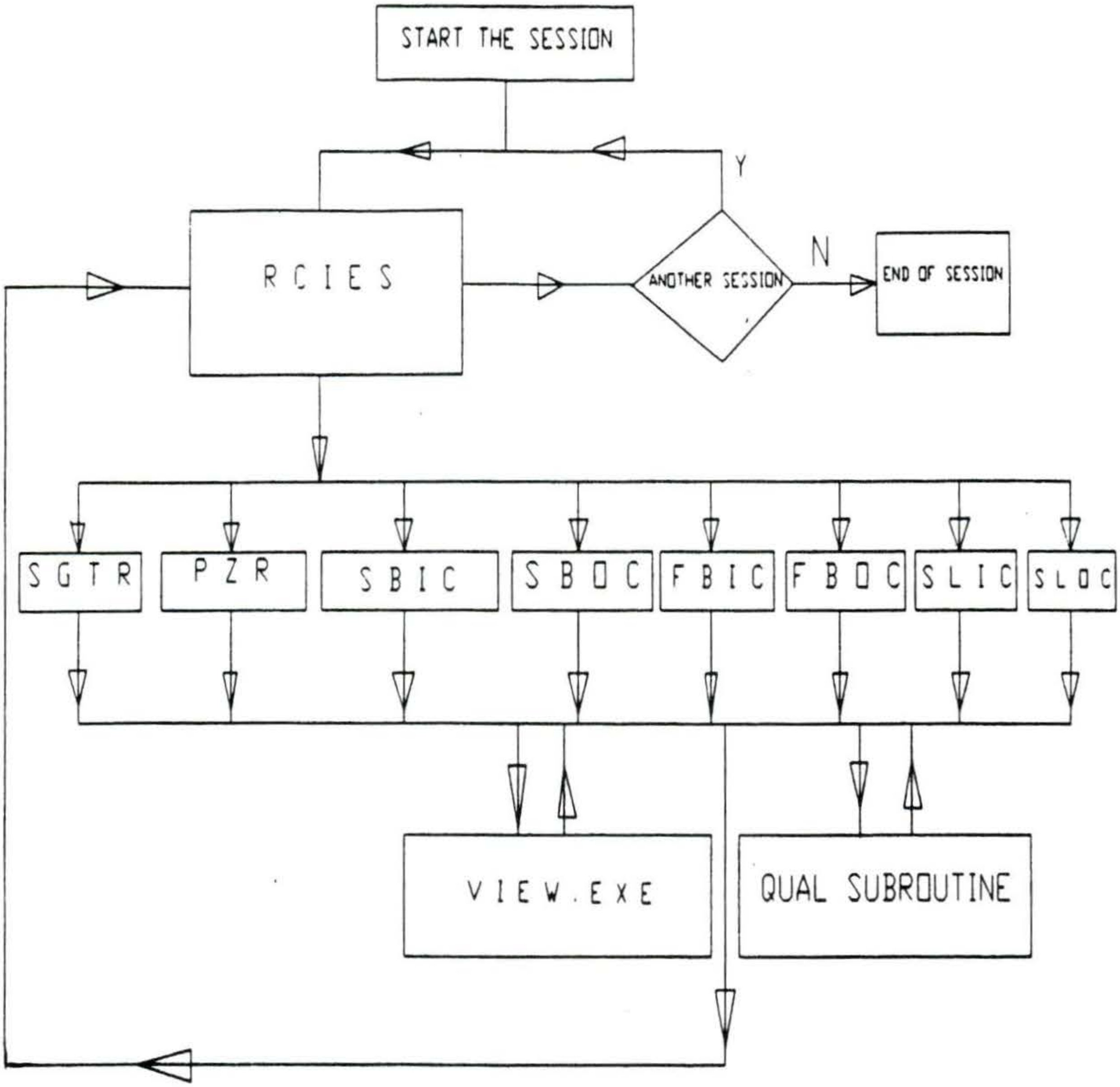

Figure IV.3. A detailed block diagram of RCIES

B. Implementation of RCIES

When the reactor operates at normal condition, RCIES will inform the operators by mentioning that the current status is normal and no action is necessary. In the T-S diagram, all parameters are within the design limit, the Rankine cycle can be illustrated by examining Figure IV.4. Following the suggestion of Beltracchi, the processes taking place in the subcooled region of the T-S diagram are shown on an enlarged scale so changes of state are more readily apparent to the user.

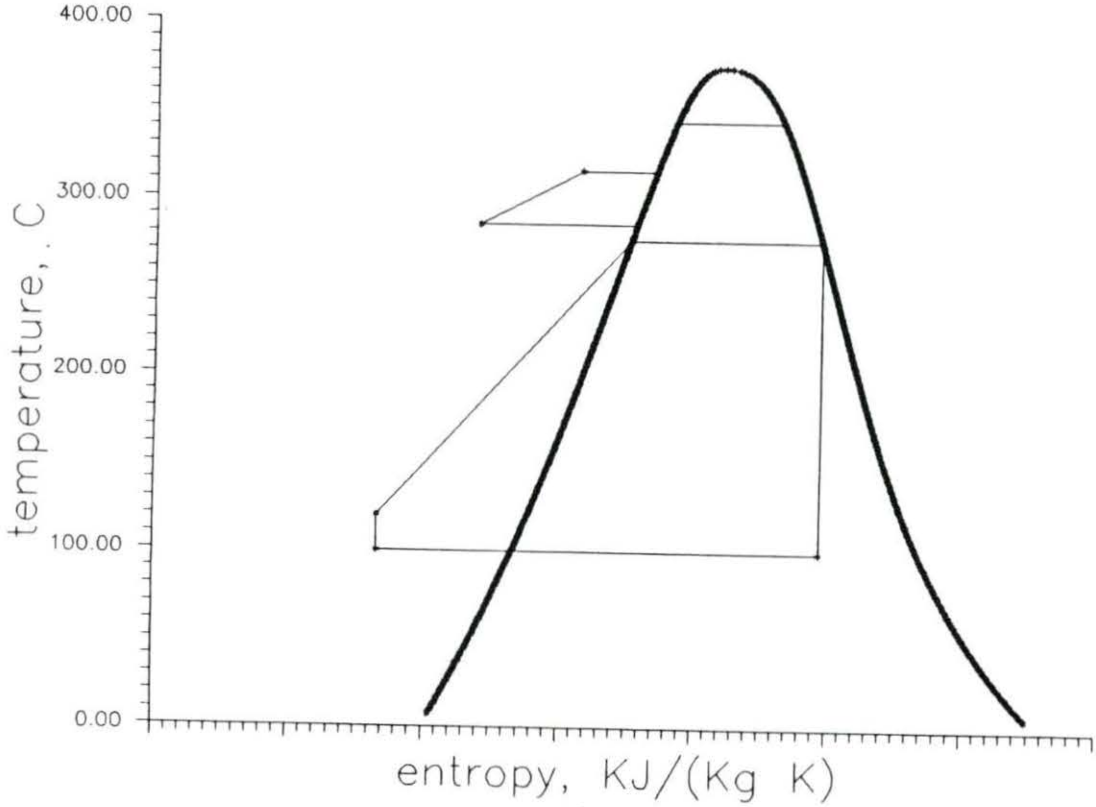

Figure IV.4. Reactor parameters are within the design limit

In the event of a steam generator tube rupture, information for developing the knowledge base is taken from the accident that took place in the R.E. Ginna Nuclear Power Plant on January 25, 1982 [31] and NRC reports [28]. These published sources are in effect the "expert" for this event. In order to determine that there is a rupture in the steam generator, the following rule, as seen in Figure IV.5, is constructed.

```
RULE for steam generator tube rupture
IF   Pressurizer level = decreasing
AND  Pressurizer pressure = decreasing
AND  Volume control tank level = decreasing
AND  Steam generator blowdown activity = increasing
THEN steam generator tube rupture
```

Figure IV.5. Steam generator tube rupture rule

This rule shows that when such symptoms occur, it is likely that a tube rupture in the steam generator has taken place. Based on this conclusion, RCIES gives step by step actions needed for the operator to bring the reactor into a safe condition. The actions are divided into four phase events. The ultimate goal would be to isolate the faulted steam generator.

In the T-S diagram, such an accident can be illustrated by indicating that the primary and pressurizer pressures are falling (corresponding to a lower temperature), as illustrated in Figure IV.6. This event is illustrated as the first phase event.

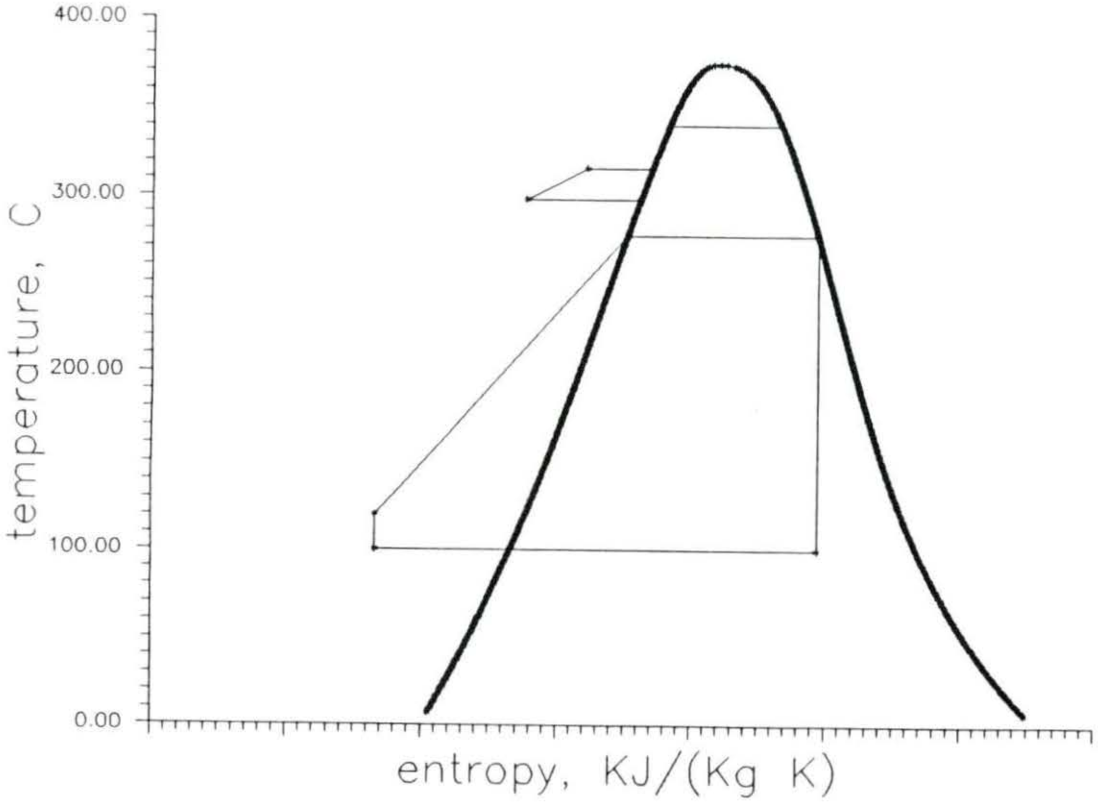

Figure IV.6. The primary and pressurizer pressures are falling

Figure IV.6 indicates that the hot leg and cold leg temperature difference is lower than the one in Figure IV.4. The pressure bar or the pressurizer pressure is also lower.

Figure IV.7 shows the second phase event; the temperature rise across the reactor coolant system (RCS) is minimum, because the reactor has been tripped and full coolant flow rate exists. The steam in the turbine is approaching the saturated vapor line. The action to trip the reactor was necessary since the operator has found out that there has been a leakage in the steam generator. This action followed by injecting safety coolant into the reactor will prevent the reactor core from becoming dry of water. Therefore, the water level can be increased, and fuel melt can also be prevented.

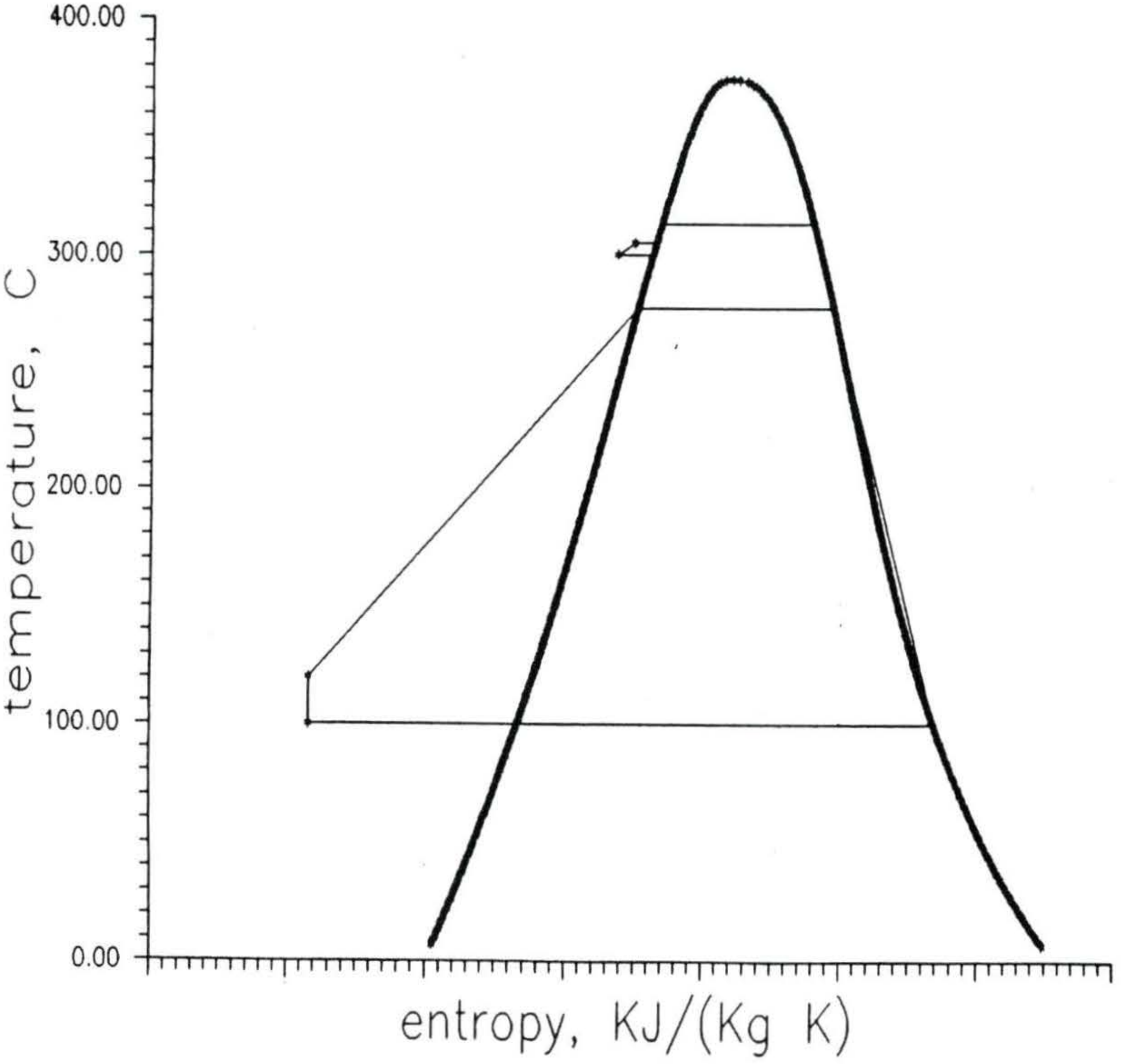

Figure IV.7. The pressure of RCS is minimum

Following the reactor trip, the primary pumps are also tripped. This action increases the temperature rise in the reactor coolant which helps establish natural circulation. Figure IV.8 shows this condition. This is categorized as the third phase event.

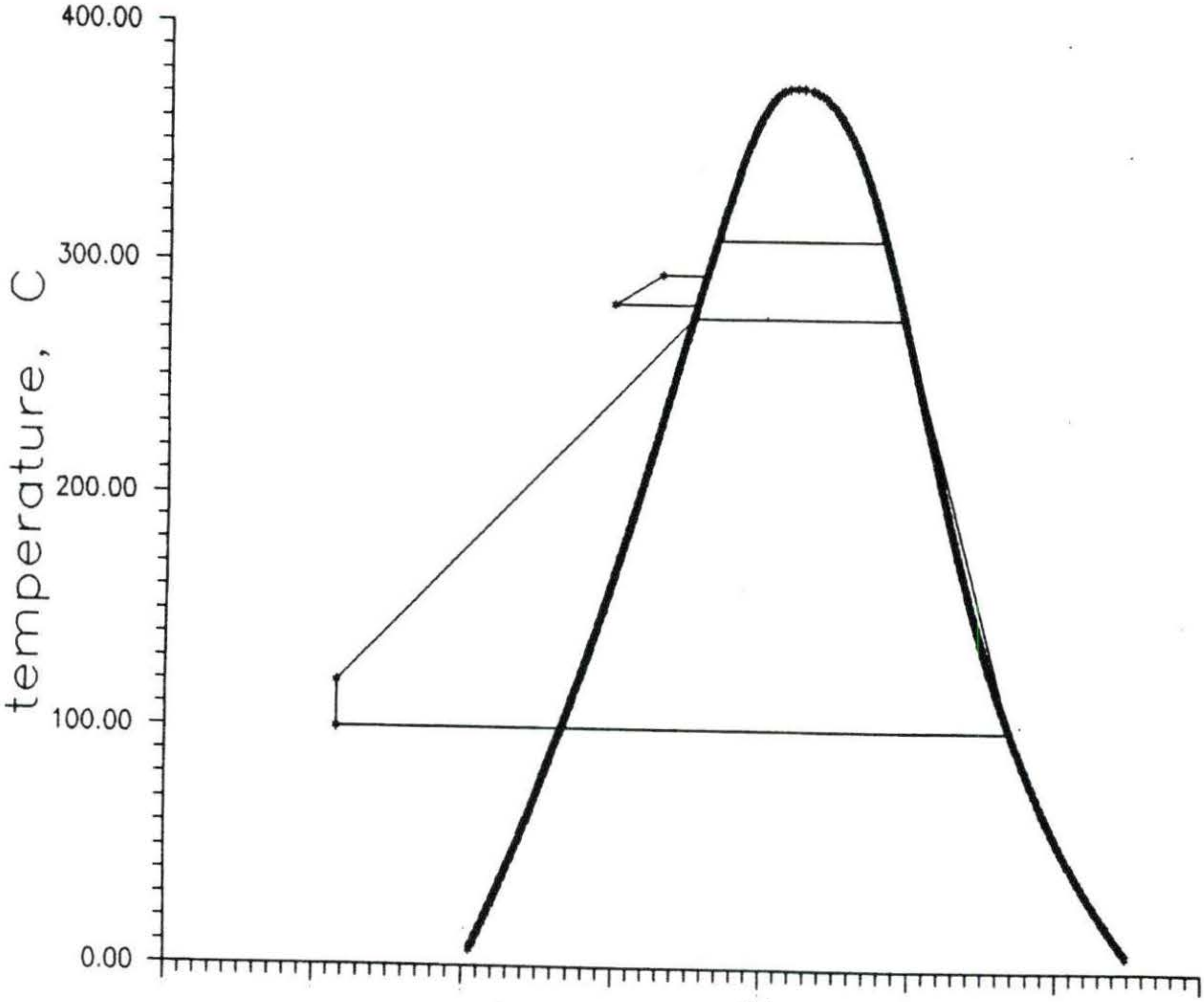

Figure IV.8. The plant status after the primary pumps have been tripped

Finally, the fourth phase event shows that the faulted steam generator has been isolated and the temperature of the coolant has been raised. At this time, the reactor is in secure condition, as seen in Figure IV.9. From this point, the required mechanical work should be done by the technician to take care of the faulted steam generator.

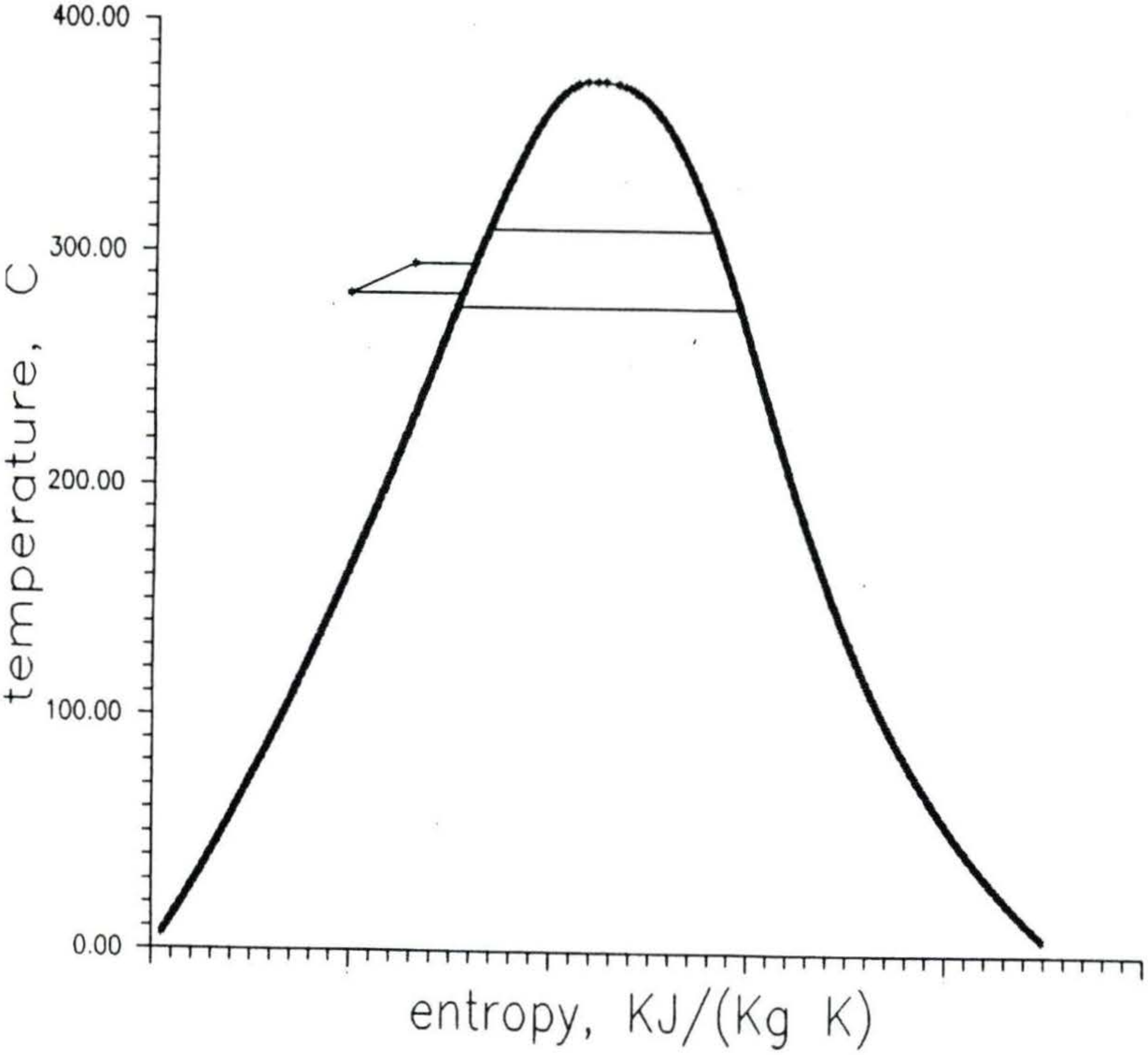

Figure IV.9. The faulted steam generator is isolated

In abnormal events, such as "failure of spray valve to close" and "loss of automatic pressurizer pressure control," the symptoms are seen in the pressurizer level and pressure. The pressurizer experiences either insurge or outsurge flows. The information to construct this knowledge base comes from NUREG-1291 [28] and interviews with the expert [27,28].

The insurge and outsurge flows are not emergency events, since the condition of the reactor can be returned to normal if the operators take the right actions and/or the control instruments function properly.

One simulation of abnormality in the pressurizer is the failure of the spray valve to close (FOPSV). When the pressurizer experiences an outsurge flow, the water level is decreased and the pressurizer pressure is decreased as well. The electric heaters should be energized to increase the pressure. The spray valve will open to reduce the pressure when the pressure rise, caused by the electric heaters, is beyond the design limit. However, in this scenario, it remains open. Therefore, the pressurizer pressure is decreasing below the design limit. The necessary action to be taken by the operator is to select an alternate channel to close the spray valve or manually close the spray valve and electric heater should be energized. If the spray valve remains open, then the reactor should be tripped and an emergency event declared. The emergency response procedure should be followed. Figure IV.10

shows the rules pertaining to the failure of the pressurizer spray valve to close. The ultimate goal is to go to a normal plant status.

```
RULE for operator's response
   IF outsurge flow
  AND spray valve = open
 THEN transient determined

RULE for operator's response
   IF transient determined
  AND select alternate channel = verified
  AND heaters energized = verified
 THEN status normal

RULE for operator's response
   IF transient determined
  AND select alternate channel = not verified
  AND control valve manually = verified
  AND heaters energized = verified
 THEN status normal

RULE for operator's response
   IF transient determined
  AND select alternate channel = not verified
  AND control valve manually = not verified
  AND spray valve = open
  AND trip the reactor = verified
  AND trip the coolant pump = verified
 THEN emergency response procedure
```

Figure IV.10. Rules for failure of spray valve to close

The first rule of Figure IV.10 determines that the pressurizer is experiencing an outsurge flow with the spray valve remaining open. The T-S diagram of this status is shown in Figure IV.11. The figure shows that the pressurizer pressure is very low. The hot leg and the cold leg status are less subcooled than the one illustrated in Figure IV.4.

Since the second rule of Figure IV.10 shows that an alternate channel could be activated, the spray valve is closed automatically. The T-S diagram after this action is the same as Figure IV.4.

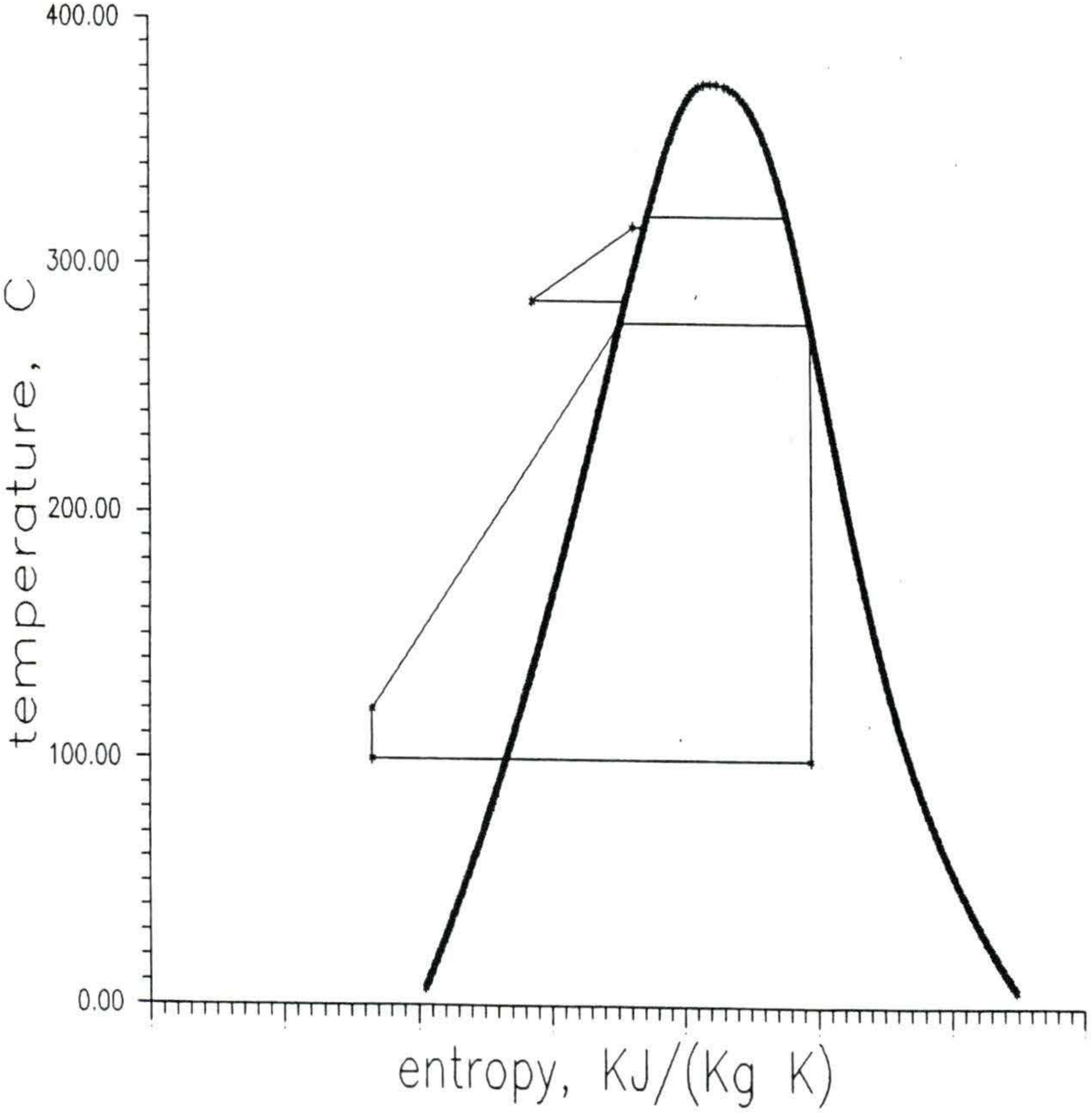

Figure IV.11. The T-S diagram for spray valve remains open

The third rule of Figure IV.10 shows that neither automatic nor manual action to close the spray valve was successful, therefore at this point the pressurizer pressure keeps decreasing and the emergency response procedure should be followed. The T-S diagram of this condition is shown in Figure IV.12.

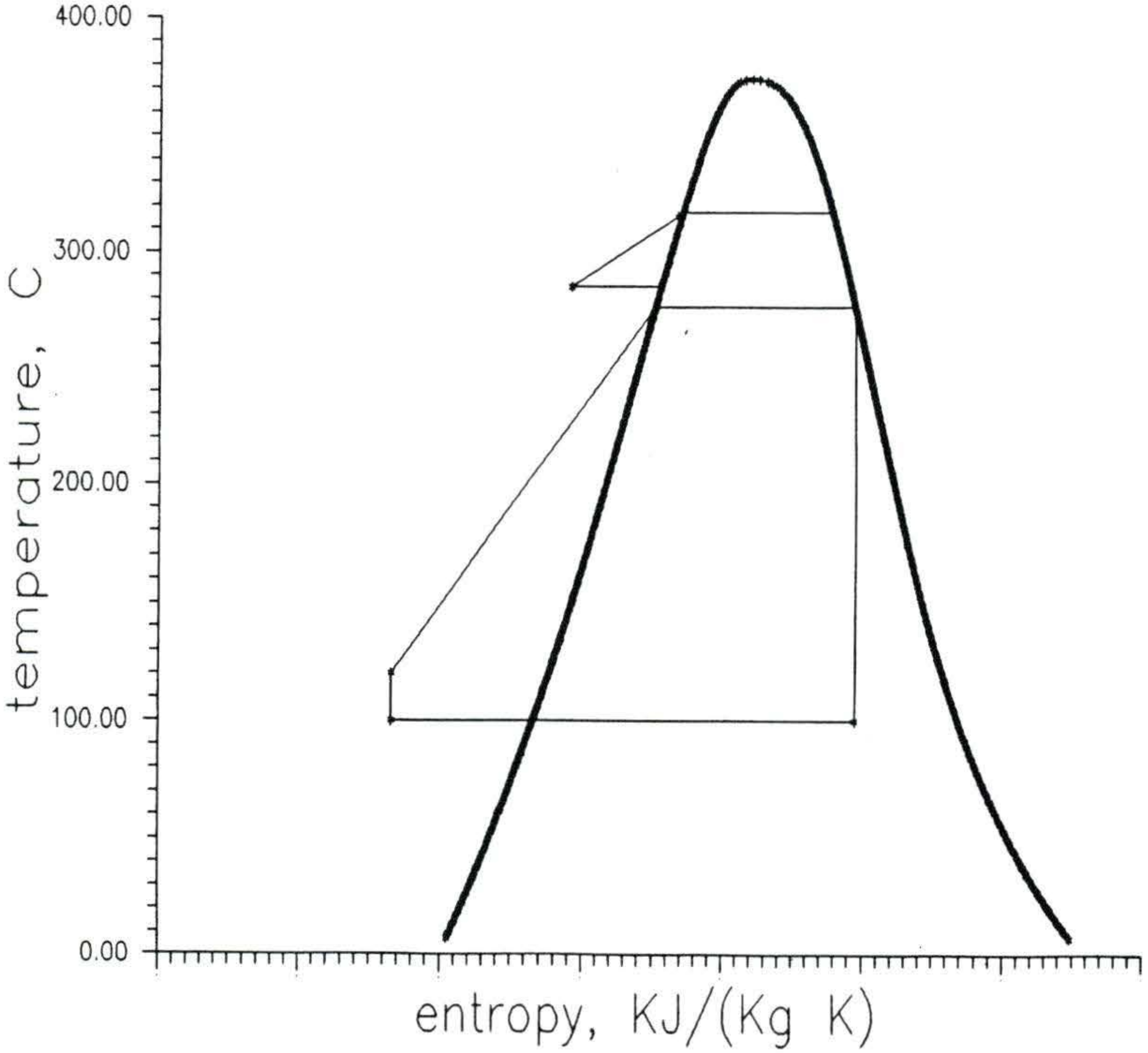

Figure IV.12. The pressurizer pressure and level are very low

In Figure IV.12 the pressurizer pressure is very low, because the water sprayed from the spray valve, which comes from the cold leg of the primary systems, keeps decreasing the temperature in the pressurizer. Therefore, the pressurizer pressure is very low. The hot leg of the primary systems could become saturated liquid. This condition is not desired, because the coolant in the primary system should be maintained in the subcooled region. This effect means that the reactor coolant could experience boiling.

Another abnormal event simulated by RCIES is the loss of automatic pressurizer pressure control (LOAPPC). The simulation is for the case of an insurge flow. During the insurge flow, the water level and pressure are increasing. The necessary action to bring the plant back to the design value is to open the spray valve, followed by energizing the electric heater to bring the liquid water to saturation. If the spray valve cannot help to prevent the pressure increase, the power operated relief valve (PORV) should open, so that the steam can flow to the pressurizer relief tank. Figure IV.13 illustrates the rules that are used to simulate this transient.

The first rule of this abnormal event shows that there is an insurge flow taking place in the pressurizer. Therefore, the pressure and level are increasing. The necessary action is to open the spray valve in order to reduce the pressurizer pressure.

In this simulation, the electric heater remains off and the PORV remains closed. Therefore there is no pressurizer pressure control function in this abnormal event. RCIES would help the operators take the required actions to bring the reactor into normal condition.

```
RULE for operator's response
IF   insurge flow
AND  spray valve = open
AND  heaters energized = not verified
AND  power operated relief valve = not verified
THEN transient determined

RULE for operator's response
IF   transient determined
AND  heaters energized = verified
THEN status normal

RULE for operator's response
IF   transient determined
AND  heaters energized = not verified
AND  power operated relief valve = not verified
THEN loappc determined

RULE for operator's response
IF   loappc determined
AND  power operated relief valve = verified
THEN status normal
```

Figure IV.13. Rules for loss of automatic pressurizer pressure control

The second rule on Figure IV.13 shows that the electric heaters have been energized, this causes some volume of the liquid water to become saturated. Therefore, the pressurizer level and pressure are decreasing to stay within the design limit. The T-S diagram of this condition is the same as in Figure IV.4.

In the fourth rule, the PORV has been opened. This condition brings the pressurizer pressure down to meet the design limitation. Therefore, the presurizer now is operating at normal condition or plant status is normal.

The T-S diagram showing that the pressurizer pressure or pressure bar is increasing beyond the design limit is illustrated in Figure IV.14. This figure determines the status of the plant as the first rule in Figure IV.2 fired.

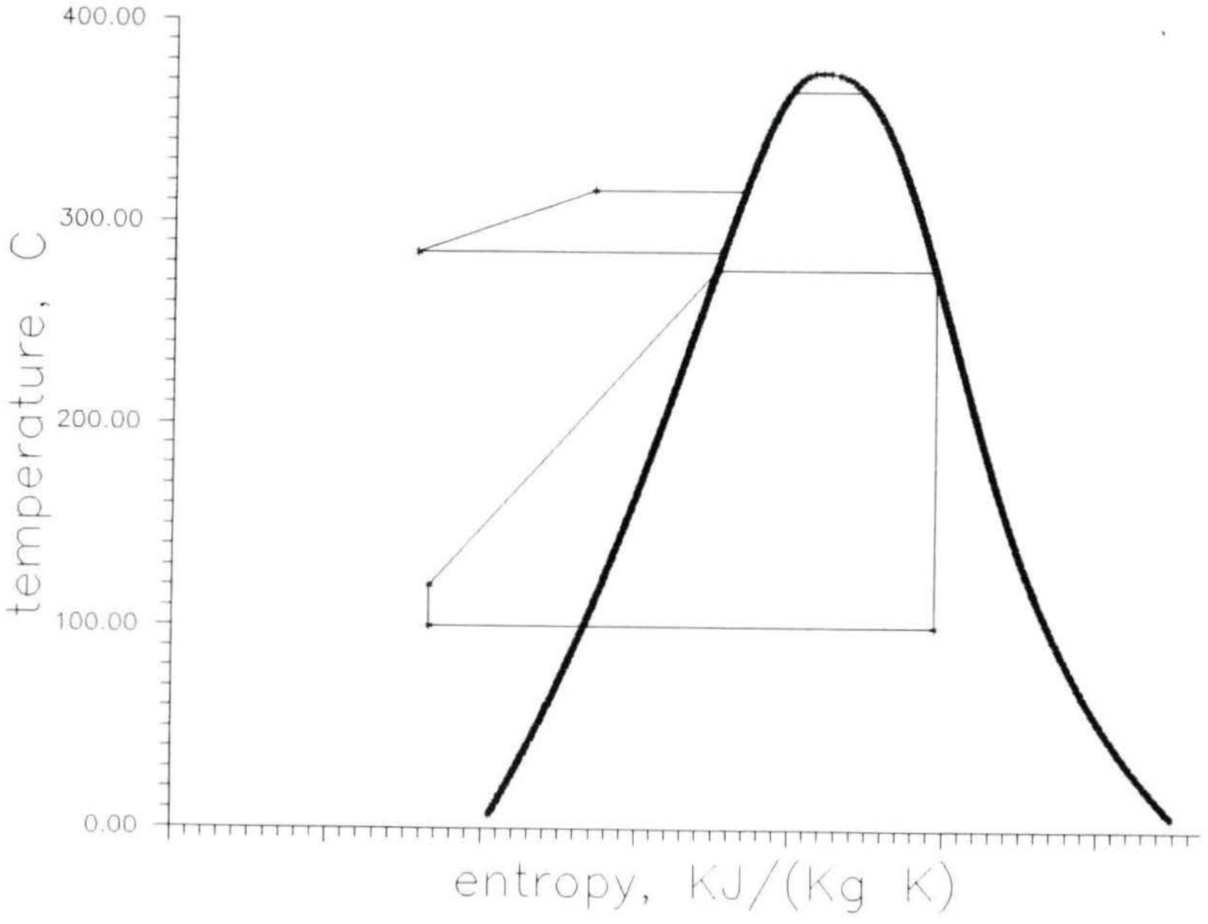

Figure IV.14. The pressure bar is increasing

V. CONCLUSION AND SUGGESTIONS

A. Conclusion of the Research

The RCIES computer program has been developed using the LEVEL5 shell. The program has the capability to simulate emergency events and abnormal events related to the plant thermodynamics processes that might take place in a Westinghouse type PWR. To demonstrate the concept of RCIES, a steam generator tube rupture was selected as the emergency event simulated by the program. Pressurizer transients consisting of the loss of automatic pressurizer pressure control and the failure of the pressurizer spray valve to close, were selected as the abnormal events that are simulated by the program. More events can be added to RCIES using the LEVEL5 chain function as more knowledge bases about other events can be constructed.

RCIES uses a backward-chaining system, and it chains to other knowledge bases to guide the responses that the operators must make. It was demonstrated that RCIES also can incorporate external software package programs, such as VIEW to display the Rankine cycle on the T-S diagram. The thermodynamic properties are calculated using the subroutine QUAL.

The program works in a cycle when the current session is completed. The user has the option to continue or to terminate the cycle. In actual practice, the program may be connected to plant sensors to receive the necessary input from the plant. During the session, the program asks the user or the operator about the parameters needed to derive the conclusion. The user may respond by providing qualitative answer, such as pressure is decreasing or increasing. Therefore, the decision about the conditions of the plant still relies on the operator.

Since the operators are guided to specific information, they are helped to focus on what really matters during the current status of the plant. With the help of the Rankine cycle display and verbal information about the display, the operator should have insight as to where the reactor stands at a given instant in time.

The main disadvantage of RCIES is that the program does not function in a real-time basis. Therefore, the information load is delayed. With the use of real-time programming techniques, such a delay may be avoided.

B. Suggestions for Future Work

The program can be further developed by adding some more emergency or abnormal events to the program. This addition should be easy because of the chaining function capability of LEVEL5 shell.

A better graph program that has the capability to display

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APPENDIX - THE RCIES SOURCE CODES LISTING

RCIES.PRL

```
TITLE rankine cycle interpretation expert system
!
!      The RCIES program, Rankine Cycle Interpretation Expert
!     System, is an expert system which interprets the Rankine
!     cycle to determine the current status of PWR power plant
!     - Westinghouse type -
!
!                         Written by Yudi U. Imardjoko
!                            Iowa State University
!                     Department of Mechanical Engineering
!                         Nuclear Engineering Program
!                                  Ames, Iowa
!                                     1991
!
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. goal achieved
!
!-------------------------------------------------------------
! Rule for achieving ultimate goal                           !
!-------------------------------------------------------------
!
RULE for pursuing the goal
  IF small loca inside containment
  OR small loca outside containment
  OR steam break inside containment
  OR steam break outside containment
  OR feedwater break inside containment
  OR feedwater break outside containment
  OR steam generator tube rupture
  OR outsurge flow
  OR insurge flow
  OR status normal
THEN goal achieved
 AND CYCLE
!-------------------------------------------------------------
! Rule for normal operation                                  !
```

```
!-------------------------------------------------------------
!
RULE for normal operation
  IF Taverage = normal
 AND Reactor coolant system pressure = normal
 AND Pressurizer level = normal
 AND Volume control tank level = normal
 AND Containment pressure = normal
 AND Containment temperature = normal
 AND Containment humidity = normal
 AND Containment airborne radiation = normal
 AND Steam flow = normal
 AND Steam pressure = normal
 AND Feedwater flow = normal
 AND Steam generator level = normal
 AND Steam generator blowdown activity = normal
THEN status normal
 AND DISPLAY 1
 AND ACTIVATE c:\prl\normal.bat
!
!-------------------------------------------------------------
! Rules to determine the emergency events                     !
!-------------------------------------------------------------
!
RULE for small LOCA inside containment
  IF Reactor coolant system pressure = decreasing
 AND Pressurizer level = decreasing
 AND Volume control tank level = decreasing
 AND Containment pressure = increasing
 AND Containment temperature = increasing
 AND Containment humidity = increasing
 AND Containment airborne radiation = increasing
THEN small loca inside containment
 AND DISPLAY 2
 AND CHAIN SLIC
!
RULE for small LOCA outside containment
  IF Reactor coolant system pressure = decreasing
 AND Pressurizer level = decreasing
 AND Volume control tank level = decreasing
 AND Containment airborne radiation = increasing
THEN small loca outside containment
 AND DISPLAY 3
 AND CHAIN SLOC
!
RULE for steam break inside containment
  IF Taverage = decreasing
 AND Reactor coolant system pressure = decreasing
 AND Pressurizer level = decreasing
 AND Volume control tank level = decreasing
 AND Containment pressure = increasing
```

```
 AND Containment temperature = increasing
 AND Containment humidity = increasing
 AND Steam flow = increasing
 AND Steam pressure = decreasing
 AND Feedwater flow = increasing
 AND Steam generator level = decreasing
THEN steam break inside containment
 AND DISPLAY 4
 AND CHAIN SBIC
!
RULE for steam break outside containment
  IF Taverage = decreasing
 AND Reactor coolant system pressure = decreasing
 AND Pressurizer level = decreasing
 AND Volume control tank level = decreasing
 AND Steam flow = increasing
 AND Steam pressure = decreasing
 AND Feedwater flow = increasing
 AND Steam generator level = decreasing
THEN steam break outside containment
 AND DISPLAY 5
 AND CHAIN SBOC
!
RULE for feedwater break inside containment
  IF Taverage = decreasing
 AND Reactor coolant system pressure = decreasing
 AND Pressurizer level = decreasing
 AND Volume control tank level = decreasing
 AND Containment pressure = increasing
 AND Containment temperature = increasing
 AND Containment humidity = increasing
 AND Steam flow = increasing
 AND Steam pressure = decreasing
 AND Feedwater flow = decreasing
 AND Steam generator level = decreasing
THEN feedwater break inside containment
 AND DISPLAY 6
 AND CHAIN FBIC
!
RULE for feedwater break outside containment
  IF Feedwater flow = decreasing
 AND Steam generator level = decreasing
THEN feedwater break outside containment
 AND DISPLAY 7
 AND CHAIN FBOC
!
RULE for steam generator tube rupture
  IF Pressurizer level = decreasing
 AND Pressurizer pressure = decreasing
 AND Volume control tank level = decreasing
 AND Steam generator blowdown activity = increasing
```

```
THEN steam generator tube rupture
 AND DISPLAY 8
 AND CHAIN SGTR
!
!
!----------------------------------------------------------------
! Rules for abnormal events                                     !
!----------------------------------------------------------------
!
RULE for failure of pressurizer spray valve
  IF Pressurizer pressure = decreasing
 AND Pressurizer level = decreasing
THEN outsurge flow
 AND FORGET Pressurizer pressure
 AND FORGET Pressurizer level
 AND DISPLAY 9
 AND CHAIN PZR
!
RULE for loss of automatic pressurizer pressure control
  IF Pressurizer pressure = increasing
 AND Pressurizer level = increasing
THEN insurge flow
 AND FORGET Pressurizer pressure
 AND FORGET pressurizer level
 AND DISPLAY 10
 AND CHAIN PZR
!
!----------------------------------------------------------------
!
TEXT Taverage
How is the average temperature across the coolant?
- normal
- increasing
- decreasing

TEXT Reactor coolant system pressure
How is the reactor coolant system pressure?
- normal
- increasing
- decreasing

TEXT Pressurizer level
How is pressurizer level?
- normal
- increasing
- decreasing

TEXT Volume control tank level
How is volume control tank level?
- normal
- increasing
```

```
- decreasing

TEXT Containment pressure
How is containment pressure?
- normal
- increasing
- decreasing

TEXT Containment temperature
How is containment temperature?
- normal
- increasing
- decreasing

TEXT Containment humidity
How is containment humidity?
- normal
- increasing
- decreasing

TEXT Containment airborne radiation
How is containment airborne radiation?
- normal
- increasing
- decreasing

TEXT Steam flow
How is the steam flow?
- normal
- increasing
- decreasing

TEXT Steam pressure
How is the steam pressure?
- normal
- increasing
- decreasing

TEXT Feedwater flow
How is the feedwater flow?
- normal
- increasing
- decreasing

TEXT Steam generator level
How is the steam generator level?
- normal
- increasing
- decreasing

TEXT Steam generator blowdown activity
```

```
How is the steam generator blowdown activity?
- normal
- increasing
- decreasing

TEXT Pressurizer pressure
How is the pressurizer pressure?
- normal
- increasing
- decreasing
!
DISPLAY 1
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   :                Status    : normal operation             :
   :                Action    : none                         :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :      press function key 2 to show the T-S diagram       :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :        press function key 10 to end the session         :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 2
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: small L O C A                               :
   : Location  : inside containment                          :
   : Status    :                                             :
   :     1. Taverage                                  normal :
   :     2. Reactor coolant system pressure       decreasing :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                  increasing :
   :     6. Containment temperature               increasing :
   :     7. Containment humidity                  increasing :
   :     8. Containment airborne radiation        increasing :
   :     9. Steam flow                                normal :
   :    10. Steam pressure                            normal :
   :    11. Feedwater flow                            normal :
   :    12. Steam generator level                     normal :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 3
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: small LOCA                                  :
   : Location  : outside containment                         :
   : Status    :                                             :
   :     1. Taverage                                  normal :
```

```
   :     2. Reactor coolant system pressure       decreasing :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                      normal :
   :     6. Containment temperature                   normal :
   :     7. Containment humidity                      normal :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                                normal :
   :    10. Steam pressure                            normal :
   :    11. Feedwater flow                            normal :
   :    12. Steam generator level                     normal :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 4
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: steam break                                 :
   : Location  : inside containment                          :
   : Status    :                                             :
   :     1. Taverage                              decreasing :
   :     2. Reactor coolant system pressure       decreasing :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                  increasing :
   :     6. Containment temperature               increasing :
   :     7. Containment humidity                  increasing :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                            increasing :
   :    10. Steam pressure                        decreasing :
   :    11. Feedwater flow                        increasing :
   :    12. Steam generator level                 decreasing :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 5
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: steam break                                 :
   : Location  : outside containment                         :
   : Status    :                                             :
   :     1. Taverage                              decreasing :
   :     2. Reactor coolant system pressure       decreasing :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                      normal :
   :     6. Containment temperature                   normal :
```

```
   :     7. Containment humidity                      normal :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                            increasing :
   :    10. Steam pressure                        decreasing :
   :    11. Feedwater flow                        increasing :
   :    12. Steam generator level                 decreasing :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 6
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State      : off-normal operation                       :
   : Indication: feedwater break                             :
   : Location   : inside containment                         :
   : Status     :                                            :
   :     1. Taverage                              decreasing :
   :     2. Reactor coolant system pressure       decreasing :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                  increasing :
   :     6. Containment temperature               increasing :
   :     7. Containment humidity                  increasing :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                            increasing :
   :    10. Steam pressure                        decreasing :
   :    11. Feedwater flow                        decreasing :
   :    12. Steam generator level                 decreasing :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   ;         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 7
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State      : off-normal operation                       :
   : Indication: feedwater break                             :
   : Location   : outside containment                        :
   : Status     :                                            :
   :     1. Taverage                                  normal :
   :     2. Reactor coolant system pressure           normal :
   :     3. Pressurizer level                         normal :
   :     4. Volume control tank level                 normal :
   :     5. Containment pressure                      normal :
   :     6. Containment temperature                   normal :
   :     7. Containment humidity                      normal :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                                normal :
   :    10. Steam pressure                            normal :
   :    11. Feedwater flow                        decreasing :
```

```
   :    12. Steam generator level                 decreasing :
   :    13. Steam generator blowdown activity         normal :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 8
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: Steam generator tube rupture                :
   : Location  : Steam generator                             :
   : Status    :                                             :
   :     1. Taverage                                  normal :
   :     2. Reactor coolant system pressure           normal :
   :     3. Pressurizer level                     decreasing :
   :     4. Volume control tank level             decreasing :
   :     5. Containment pressure                      normal :
   :     6. Containment temperature                   normal :
   :     7. Containment humidity                      normal :
   :     8. Containment airborne radiation            normal :
   :     9. Steam flow                                normal :
   :    10. Steam pressure                            normal :
   :    11. Feedwater flow                            normal :
   :    12. Steam generator level                     normal :
   :    13. Steam generator blowdown activity     increasing :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :         press function key number 2 now.........        :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 9
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: Pressurizer                                 :
   : Status    :                                             :
   :      2. Pressurizer pressure                 decreasing :
   :      3. Pressurizer level                    decreasing :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :          press function key number 2 now.........       :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 10
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : State     : off-normal operation                        :
   : Indication: Pressurizer                                 :
   : Status    :                                             :
   :      2. Pressurizer level                    increasing :
   :      3. Pressurizer pressure                 increasing :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :          press function key number 2 now.........       :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
END
```

SGTR.PRL

```
TITLE steam generator tube rupture
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. steam generator tube rupture verified
!
!
!-------------------------------------------------------------
! rules for operator's action necessary pertaining to the S/G!
! accident                                                    !
!-------------------------------------------------------------
!
!
RULE for responses due to steam generator tube rupture
  IF steam generator tube rupture
THEN action needed
!
!
RULE for responses due to steam generator tube rupture
  IF action needed
THEN accident has been determined
 AND DISPLAY 9
 AND ACTIVATE c:\prl\sgtr2.bat
!
!
RULE for responses due to steam generator tube rupture
  IF accident has been determined
 AND safety Injection Flow = verified
 AND isolate faulted steam generator = verified
THEN next action needed
!
!
RULE for responses due to steam generator tube rupture
  IF next action needed
THEN initial actions have been determined
 AND DISPLAY 10
 AND ACTIVATE c:\prl\sgtr3.bat
!
!
RULE for responses due to steam generator tube rupture
  IF initial actions have been determined
 AND level in affected steam generator = verified
 AND Isolate all feed to affected steam generator = verified
 AND Close pressurizer PORV's = verified
THEN more action needed
```

```
!
RULE for responses due to steam generator tube rupture
  IF more action needed
THEN final actions have been accomplished
 AND DISPLAY 11
 AND ACTIVATE c:\prl\sgtr4.bat
!
!
RULE for responses due to steam generator tube rupture
  IF final actions have been accomplished
 AND Reset Safety Injection = verified
 AND Cooldown Reactor Coolant System = verified
 AND Establish pressurizer level = verified
 AND Terminate Safety Injection Flow = verified
 AND Establish normal charging = verified
 AND Verify pressurizer level = verified
 AND Establish normal makeup to VCT = verified
 AND Establish normal letdown = verified
 AND Secure diesel generators = verified
 AND Verify if leakage rate is minimized = verified
 AND Ensure subcriticality = verified
THEN steam generator tube rupture verified
 AND DISPLAY 12
 AND ACTIVATE C:\PRL\SGTR5.bat
 AND FORGET ALL
 AND CHAIN RCIES
!
TEXT Safety Injection Flow
Verify the safety injection flow and then stop reactor coolant
pump!
 - verified
 - not verified

TEXT isolate faulted steam generator
Isolate faulted steam generator!

action necessary =
   - close MSIV
   - close PORV
   - blowdown

 - verified
 - not verified

TEXT level in affected steam generator
Verify level in affected steam generator!
 - verified
 - not verified

TEXT Isolate all feed to affected steam generator
Isolate all feed to affected steam generator!
```

```
 - verified
 - not verified

TEXT Close pressurizer PORV's
Close pressurizer power operated relief valves!
 - verified
 - not verified

TEXT Reset Safety Injection
Reset safety injection!
 - verified
 - not verified

TEXT Cooldown Reactor Coolant System
Verify cooldown reactor coolant system!
 - verified
 - not verified

TEXT Establish pressurizer level
Check pressurizer level!
 - verified
 - not verified

TEXT Terminate Safety Injection Flow
Terminate safety injection flow!
 - verified
 - not verified

TEXT Establish normal charging
Establish normal charging!
 - verified
 - not verified

TEXT Verify pressurizer level
Check pressurizer level!
 - verified
 - not verified

TEXT Establish normal makeup to VCT
Establish normal makeup to volume control tank!
 - verified
 - not verified

TEXT Establish normal letdown
Establish normal letdown!
 - verified
 - not verified

TEXT Secure diesel generators
Secure diesel generators!
 - verified
```

```
 - not verified
TEXT Verify if leakage rate is minimized
Verify if leakage rate is minimized!
 - verified
 - not verified

TEXT Ensure subcriticality
Verify to ensure subcriticality!
 - verified
 - not verified
!
DISPLAY 9
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   :              Primary pressure is falling                :
   :      Pressurizer pressure and level are decreasing      :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :      press function key 2 to show the T-S diagram       :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 10
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   :   The temperature rise across the core is very small,   :
   :    because of the reactor trip and full coolant flow    :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :      press function key 2 to show the T-S diagram       :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 11
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   :   The temperature of the coolant has been raised, this  :
   :   helps to establish natural circulation.               :
   :   The affected steam generator has been isolated        :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :      press function key 2 to show the T-S diagram       :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 12
   IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
   : Status    :                                             :
   :      1. The affected steam generator has been isolated  :
   :      2. Pressure difference at primary/secondary loop   :
   :         is minimum                                      :
   :      3. Reactor coolant system cooldown has commenced   :
   :      4. Subcooling is being maintained                  :
   :                                                         :
   : Action     : none                                       :
   LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
   :           press function key 2 for new input            :
   HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
END
```

PZR.PRL

```
TITLE abnormality in pressurizer system
!
$ SHARED.PRL
!
FORGET ALL
!
!
1. abnormality in pressurizer solved
!
!-------------------------------------------------
! Rules for failure of pressurizer spray valve   !
!-------------------------------------------------
!
RULE for operator's response
  IF outsurge flow
THEN outsurge flow determined
 AND DISPLAY 1
 AND ACTIVATE c:\prl\fopsv2.bat
!
RULE for operator's response
  IF outsurge flow determined
 AND spray valve = open
THEN fopsv determined
 AND DISPLAY 2
 AND ACTIVATE c:\prl\fopsv3.bat
!
RULE for operator's response
  IF fopsv determined
 AND select alternate channel = verified
 AND heaters energized = verified
 AND pressurizer pressure = normal
THEN abnormality in pressurizer solved
 AND DISPLAY 3
 AND ACTIVATE c:\prl\normal.bat
 AND FORGET ALL
 AND CHAIN RCIES
!
RULE for operator's response
  IF fopsv determined
 AND select alternate channel = not verified
 AND control valve manually = verified
 AND spray valve = closed
 AND heaters energized = verified
 AND pressurizer pressure = normal
THEN abnormality in pressurizer solved
 AND DISPLAY 3
 AND ACTIVATE c:\prl\normal.bat
 AND FORGET ALL
```

```
 AND CHAIN RCIES
!
!
RULE for operator's response
  IF fopsv determined
 AND select alternate channel = not verified
 AND control valve manually = verified
 AND spray valve = open
 AND trip reactor = verified
 AND trip reactor coolant pump = verified
 AND safety injection = verified
THEN emergency operating procedure
 AND abnormality in pressurizer solved
 AND DISPLAY 4
 AND ACTIVATE c:\prl\fopsv4.bat
 AND FORGET ALL
 AND CHAIN RCIES
!
!-------------------------------------------------
! loss of automatic pressurizer pressure control !
!-------------------------------------------------
!
RULE for operator's response
  IF insurge flow
 AND spray valve = open
 AND heaters energized = not verified
 AND power operated relief valve = not verified
THEN insurge flow determined
 AND DISPLAY 5
 AND ACTIVATE c:\prl\loappc2.bat
!
RULE for operator's response
  IF insurge flow determined
 AND heaters energized = verified
THEN abnormality in pressurizer solved
 AND DISPLAY 3
 AND FORGET ALL
 AND ACTIVATE c:\prl\normal.bat
 AND CHAIN RCIEs
!
RULE for operator's response
  IF insurge flow determined
 AND power operated relief valve = open
THEN abnormality in pressurizer solved
 AND DISPLAY 3
 AND FORGET ALL
 AND ACTIVATE c:\prl\normal.bat
 AND CHAIN RCIES
!
TEXT Pressurizer pressure
check to see the pressurizer pressure!
```

```
- normal
- abnormal
!
TEXT Pressurizer level
check to see the pressurizer level!
- normal
- abnormal
!
TEXT spray valve
Check to see if the spray valve remains open or closed!
- open
- closed
!
TEXT power operated relief valve
Check to see if the power operated relief valve is open or
closed!
- open
- closed
!
TEXT select alternate channel
Select alternate channel to control the valve!
- verified
- not verified
!
TEXT control valve manually
Control spray valve mauanlly!
- verified
- not verified
!
TEXT spray valve
Check to see if the spray valve has been open or closed!
- open
- closed
!
TEXT heaters energized
Check to see if the heaters has been energized!
- verified
- not verified
!
TEXT trip reactor
Since the spray valve cannot be closed, trip the reactor now!
- verified
- not verified
!
TEXT trip reactor coolant pump
Following the trip of the reactor, then trip the reactor
coolant pump!
- verified
- not verified
!
TEXT safety injection
```

```
The plant is in emergency condition, verify safety injection!
- verified
- not verified
!
DISPLAY 1
       IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
       :       Pressurizer pressure and level are low         :
       LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
       :     press function key 2 to show the T-S diagram     :
       HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 2
        IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
        :       Pressurizer pressure starts increasing        :
        LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
        :     press function key 2 to show the T-S diagram    :
        HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 3
       IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
       :              Plant at steady state                   :
       :      failed valve has been manually closed           :
       LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
       :     press function key 2 to show the T-S diagram     :
       HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 4
       IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
       :  Please refer to emergency response procedure for    :
       :                safety injection                      :
       LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
       :     press function key 2 to show the T-S diagram     :
       HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
DISPLAY 5
       IMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM;
       :        Pressurizer pressure and level are high       :
       LMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9
       :     press function key 2 to show the T-S diagram     :
       HMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM<
!
END
```

SLIC.PRL

```
TITLE small loca inside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. small loca inside containment verified
!
!
RULE for responses due to small loca inside containment
 IF  small loca inside containment
THEN small loca inside containment verified
AND  CHAIN RCIES
!
!
END
```

SLOC.PRL

```
TITLE small loca outside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. small loca outside containment verified
!
!
RULE for responses due to small loca outside containment
  IF small loca outside containment
THEN small loca outside containment verified
 AND CHAIN RCIES
!
!
END
```

SBIC.PRL

```
TITLE steam break inside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. steam break inside containment verified
!
!
RULE for responses due to steam break inside containment
  IF steam break inside containment
THEN steam break inside containment verified
 AND CHAIN RCIES
!
!
END
```

SBOC.PRL

```
TITLE steam break outside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. steam break outside containment verified
!
!
RULE for responses due to steam break outside containment
  IF steam break outside containment
THEN steam break outside containment verified
 AND CHAIN RCIES
!
!
END
```

FBIC.PRL

```
TITLE feedwater break inside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. feedwater break inside containment verified
!
!
RULE for responses due to feedwater break inside containment
  IF feedwater break inside containment
THEN feedwater break inside containment verified
 AND CHAIN RCIES
!
!
END
```

FBOC.PRL

```
TITLE feedwater break outside containment
!
!
$ SHARED.PRL
!
FORGET ALL
!
1. feedwater break outside containment verified
!
!
RULE for responses due to feedwater break outside containment
  IF feedwater break outside containment
THEN feedwater break outside containment verified
 AND CHAIN RCIES
!
!
END
```

SHARED.PRL

```
SHARED STRING Taverage
   AND STRING Reactor coolant system pressure
   AND STRING Pressurizer level
   AND STRING Pressurizer pressure
   AND STRING Volume control tank level
   AND STRING Containment pressure
   AND STRING Containment temperature
   AND STRING Containment humidity
   AND STRING Containment airborne radiation
   AND STRING Steam flow
   AND STRING Steam pressure
   AND STRING Feedwater flow
   AND STRING Steam generator level
   AND STRING Steam generator blowdown activity
!
!-----------------------------------------
! shared facts for major severe accident !
!-----------------------------------------
!
SHARED SIMPLEFACT status normal
   AND SIMPLEFACT small loca inside containment
   AND SIMPLEFACT small loca outside containment
   AND SIMPLEFACT steam break inside containment
   AND SIMPLEFACT steam break outside containment
   AND SIMPLEFACT feedwater break inside containment
   AND SIMPLEFACT feedwater break outside containment
   AND SIMPLEFACT steam generator tube rupture
   AND SIMPLEFACT outsurge flow
   AND SIMPLEFACT insurge flow
!
!
!-----------------------------------
! Shared string for sgtr responses !
!-----------------------------------
!
SHARED STRING Safety Injection Flow
   AND STRING Isolate faulted steam generator
   AND STRING Level in affected steam generator
   AND STRING Isolate all feed to affected steam generator
   AND STRING Close pressurizer PORV's
   AND STRING Reset Safety Injection
   AND STRING Cooldown Reactor Coolant System
   AND STRING Establish pressurizer level
   AND STRING Terminate Safety Injection Flow
   AND STRING Establish normal charging
   AND STRING Verify pressurizer level
   AND STRING Establish normal makeup to VCT
```

```
   AND STRING Establish normal letdown
   AND STRING Secure diesel generators
   AND STRING Verify if leakage rate is minimized
   AND STRING Ensure subcriticality
!------------------------------------
! Shared string for pressurizer     !
!------------------------------------
!
SHARED STRING spray valve
   AND STRING select alternate channel
   AND STRING safety injection
   AND STRING control valve manually
   AND STRING heaters energized
   AND STRING trip reactor
   AND STRING trip reactor coolant pump
   AND STRING power operated relief valve
!
```