REACTOR: AN EXPERT SYSTEM FOR DIAGNOSIS AND TREATMENT OF NUCLEAR REACTOR ACCIDENTS

William R. Nelson

EG&G Idaho Inc.
P.O. Box 1625
Idaho Falls, ID 83415

ABSTRACT

REACTOR is an expert system under development at EG&G Idaho, Inc., that will assist operators in the diagnosis and treatment of nuclear reactor accidents. This paper covers the background of the nuclear industry and why expert system technology may prove valuable in the reactor control room. Some of the basic features of the REACTOR system are discussed, and future plans for validation and evaluation of REACTOR are presented. The concept of using both event-oriented and function-oriented strategies for accident diagnosis is discussed. The response tree concept for representing expert knowledge is also introduced.

I BACKGROUND

The responsibilities of an operating crew of a commercial nuclear reactor can be compared with those of a medical doctor. During normal operation, little care is required to monitor and maintain the reactor. When an emergency occurs, however, quick and efficient diagnosis and treatment of the problem is essential. If the diagnosis and treatment are effective, most incidents can be terminated without serious consequences. However, if the diagnosis is incorrect or the treatment improper, the consequences could be severe.

A commercial nuclear power plant is a complex combination of systems. There are two types of reactors in commercial service--the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). This paper discusses the PWR. The reactor core itself is contained in a large reactor vessel (see Figure 1). Control rods provide one mechanism for controlling the rate of the nuclear reaction. Heat is removed by the Primary Coolant System (PCS), which circulates water through the reactor vessel. Sufficient pressure to prevent boiling in the PCS is provided by the pressurizer. If a pipe break occurs in the primary coolant system (the so-called LOCA or Loss of Coolant Accident), the reactor is automatically shut down and the Emergency Core Cooling System (ECCS) provides cooling water to the reactor core. Continued cooling is required after shutdown to remove radioactive decay heat. Any radioactive materials which escape the PCS are contained in the Containment Building.

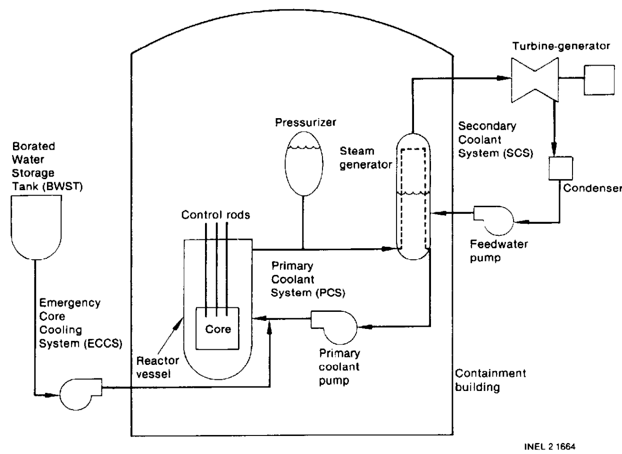

Figure 1. Schematic of a pressurized water reactor facility.

Heat is removed from the primary coolant system by the Secondary Coolant System (SCS). Water is turned to steam in the steam generator. Then the steam flows to the turbine-generator assembly where electrical energy is produced. The steam is then condensed back to the liquid state and returned to the steam generator by the feedwater pump.

The accident at the Three Mile Island (TMI) nuclear power plant in 1979 demonstrated that the information resources available to the reactor operator were not adequate to meet his decision making needs under all circumstances. For example, during the first few minutes of the TMI event, at least 100 annunciators alarmed in the control room. In the face of this extreme information overload, the TMI operators misinterpreted the situation and shut off the ECCS. As a result, the nuclear fuel was severely damaged.

Since the TMI accident, many groups have recommended changes that would assist the operator in diagnosing and responding to reactor accidents [1,2]. In particular, many recommend that computerized decision aids be developed. These aids would help the operator integrate the large amount of information in the control room and interpret its significance.

The Augmented Operator Capability (AOC) Program was initiated by EG&G Idaho in 1979 to help provide an improved, decision making environment for the reactor operator. The program has been funded by the Nuclear Regulatory Commission (NRC). One of the goals of the AOC program has been to develop and evaluate advanced decision aids for reactor operators. An early effort involved the application of the response tree technique [3,4] as a computerized decision aid for reactor operators. It soon became apparent [5] that the knowledge based expert system [6,7] would provide a powerful tool for reactor operators, using response trees to represent some of the expert knowledge required. The integration of color graphic displays, response trees, and expert system technology has resulted in REACTOR, an expert system for the diagnosis and treatment of nuclear reactor accidents.

II REACTOR

The purpose of REACTOR is to monitor a nuclear reactor facility, detect deviations from normal operating conditions, determine the significance of the situation, and recommend an appropriate response. It performs these tasks by operating on a large knowledge base with a procedure that reasons both forward and backward. The reasoning process is quite basic, having been adapted from Winston and Horn's animal identification system.[8] The system reasons forward from known facts until a conclusion can be reached. If not enough information is available to reach a conclusion, the system reasons backward to determine what information it needs to know. REACTOR will then query plant instruments or the operator in order to fill the gaps in its knowledge.

REACTOR's knowledge base contains 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. Event-oriented knowledge has been gathered from past experience with actual accidents, experiments in test reactors, and analysis of computer simulation models. Event-oriented knowledge is useful for identifying an accident which fits the pattern of pre-analyzed events. However, when an event occurs which does not match an expected pattern, "mindset" can occur and operators may ignore relevant information in an attempt to confirm their assumed diagnosis. In such a situation it is very important to consider function-oriented information so that all relevant facts are given adequate consideration.

REACTOR's event-oriented knowledge is contained in a series of IF-THEN rules. A sample of the IF-THEN rules is shown in Figure 2. The same rules are shown in an AND/OR tree in Figure 3. Notice that REACTOR knows about four different accidents: loss of feedwater, steam line break, steam generator tube rupture, and LOCA. Figure 4

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((RULE 1
     (IF (PCS PRESSURE DECREASING)
         (HPIS ON))
     (THEN (PCS INTEGRITY CHALLENGED)))

 (RULE 2
     (IF (PCS TEMPERATURE INCREASING))
     (THEN (PCS-SCS HEAT TRANSFER INADEQUATE)))

 (RULE 3
     (IF (SG LEVEL DECREASING))
     (THEN (SG INVENTORY INADEQUATE)))

 (RULE 4
     (IF (HIGH CONTAINMENT RADIATION)
         (HIGH CONTAINMENT PRESSURE))
     (THEN (CONTAINMENT INTEGRITY CHALLENGED)))

 (RULE 5
     (IF (PCS-SCS HEAT TRANSFER INADEQUATE)
         (LOW FEEDWATER FLOW))
     (THEN (ACCIDENT IS LOSS OF FEEDWATER)))

 (RULE 6
     (IF (SG INVENTORY INADEQUATE)
         (LOW FEEDWATER FLOW))
     (THEN (ACCIDENT IS LOSS OF FEEDWATER)))

 (RULE 7
     (IF (PCS INTEGRITY CHALLENGED)
         (CONTAINMENT INTEGRITY CHALLENGED))
     (THEN (ACCIDENT IS LOCA)))

 (RULE 8
     (IF (PCS INTEGRITY CHALLENGED)
       (SG LEVEL INCREASING))
     (THEN (ACCIDENT IS STEAM GENERATOR TUBE
     RUPTURE)))

 (RULE 9
     (IF (SG INVENTORY INADEQUATE)
         (HIGH STEAM FLOW))
     THEN (ACCIDENT IS STEAM LINE BREAK))))
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Figure 2. Event-oriented IF-THEN rules.

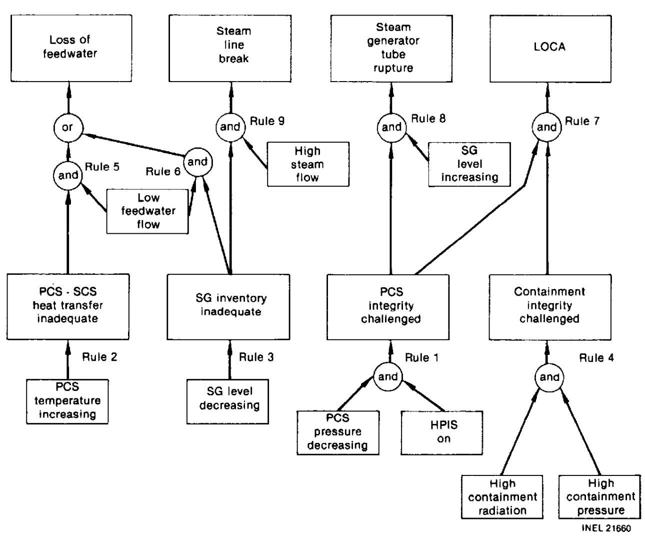

Figure 3. AND/OR tree.

(DIAGNOSE)

(IS THIS TRUE? PCS TEMPERATURE INCREASING)

?NO

(IS THIS TRUE? SG LEVEL DECREASING)

?NO

(IS THIS TRUE? PCS PRESSURE DECREASING)

?YES

(IS THIS TRUE? HPIS ON)

?YES

(RULE 1 DEDUCES PCS INTEGRITY CHALLENGED)
(IS THIS TRUE? HIGH CONTAINMENT RADIATION)

?NO

(IS THIS TRUE? SG LEVEL INCREASING)

?YES

(RULE 8 DEDUCES ACCIDENT IS STEAM GENERATOR TUBE RUPTURE)
(ACCIDENT IS STEAM GENERATOR TUBE RUPTURE)

Figure 4. Diagnosis of steam generator tube rupture.

shows a sample dialogue between a reactor operator and REACTOR to diagnose a steam generator tube rupture.

If an accident cannot be diagnosed using the event-oriented approach, it is then necessary to use the function-oriented strategy. The function-oriented capabilities of REACTOR are handled by the response tree technique. A response tree is a diagram which shows the success paths which can be used to provide a given safety function. A safety function[9] is a group of actions which prevents damage to the reactor core or release of radioactivity outside the containment building. Each specific set of actions provides a safety function which is called a success path. Because of the redundancy of nuclear plant systems, each safety function can be provided by more than one success path. When component failures cause success paths to be unavailable, another success path can be implemented automatically or by operator action.

Figure 5 is a piping diagram of the Low Pressure Injection System (LPIS), which is part of the emergency core cooling system. The system shown is from the Loss of Fluid Test (LOFT) reactor, a test reactor designed to represent a commercial PWR. The LPIS is used to provide the core cooling safety function during an emergency. Figure 6 is a response tree which shows the success paths which can be used to provide core cooling using components of the LPIS. Each path

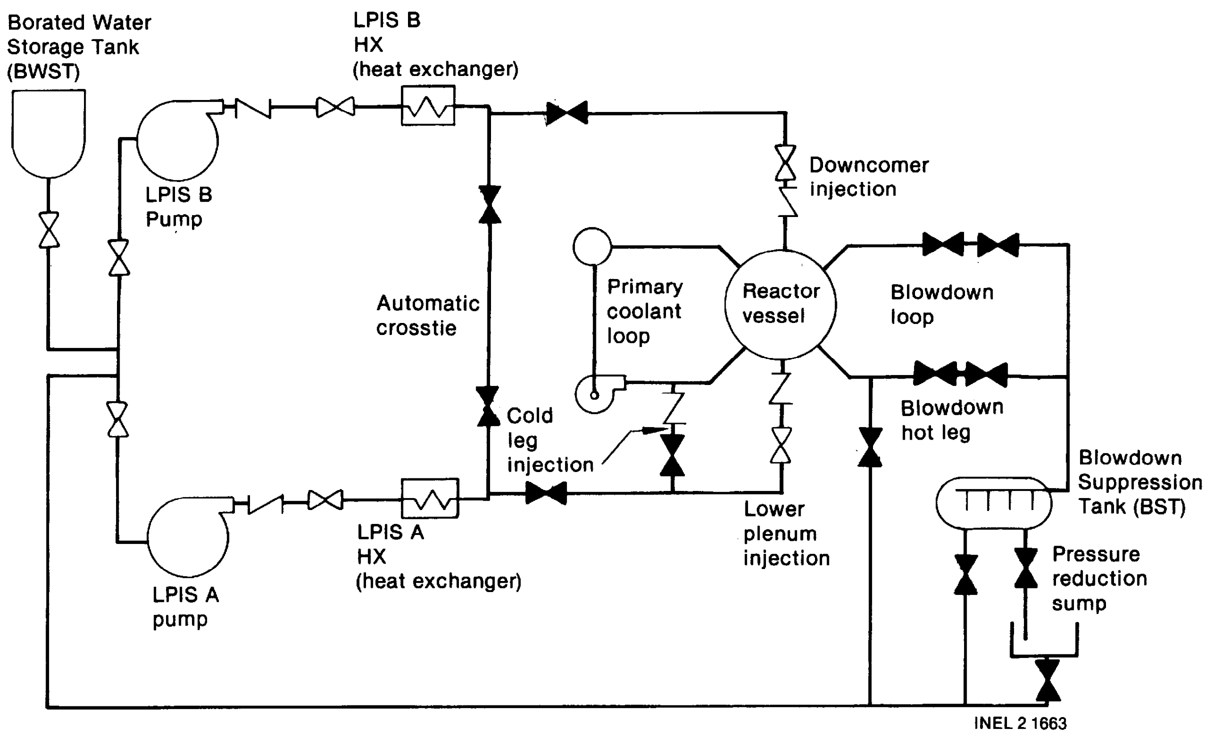

Figure 5. Schematic of Low Pressure Injection System (LPIS).

from the bottom of the tree to the top represents a different success path. Each success path has been assigned a mode number which reflects its relative effectiveness in providing core cooling. The lowest mode numbers are the most desirable. When an accident disables LPIS components, the success path with the lowest mode number is chosen from those which are still available.

Figure 6 shows how REACTOR would evaluate the response tree for an event which disables LPIS Pump A, the downcomer injection point, and the Borated Water Storage Tank (BWST). REACTOR determines which success paths are not available (as indicated by shading) and selects path number 24B for implementation. This success path is displayed schematically to the operator as shown in Figure 7.

To exercise the response tree logic, REACTOR has access to a large knowledge base concerning the LPIS. A property list for each component contains information such as its electrical power supply. The response tree structure itself is also contained in the knowledge base. Each success path has a property list of the elements which make up the success path. Each element of a success path has a property list of the components it contains.

Figure 8 shows the overall structure of the REACTOR system. Normally, REACTOR will receive data directly from plant instruments. However, it can also query the operator for further information. The operator can modify the knowledge base either by answering REACTOR's questions or by directly modifying the knowledge base or rule structure. At present, REACTOR monitors a reactor simulation rather than an actual nuclear plant. This allows REACTOR to be exercised with a wider range of events than would be possible using an actual nuclear facility.

III STATUS AND PLANS

We are currently in the process of integrating the elements of the REACTOR system. The response tree technique was developed in 1978 and implemented in the procedures of the LOFT facility. In 1980 work was begun to implement the response tree approach as a computerized decision aid for reactor operators. Implementation of the event-oriented portions of REACTOR's knowledge base was begun in early 1982 when a LISP interpreter became available. A LISP program for evaluating response trees was written in April 1982. Our current efforts emphasize the development of a more complete set of event-oriented IF-THEN rules and completion of a Fortran program which produces color graphic displays for the operator.

Future work will include trials of the REACTOR system using a realistic operating

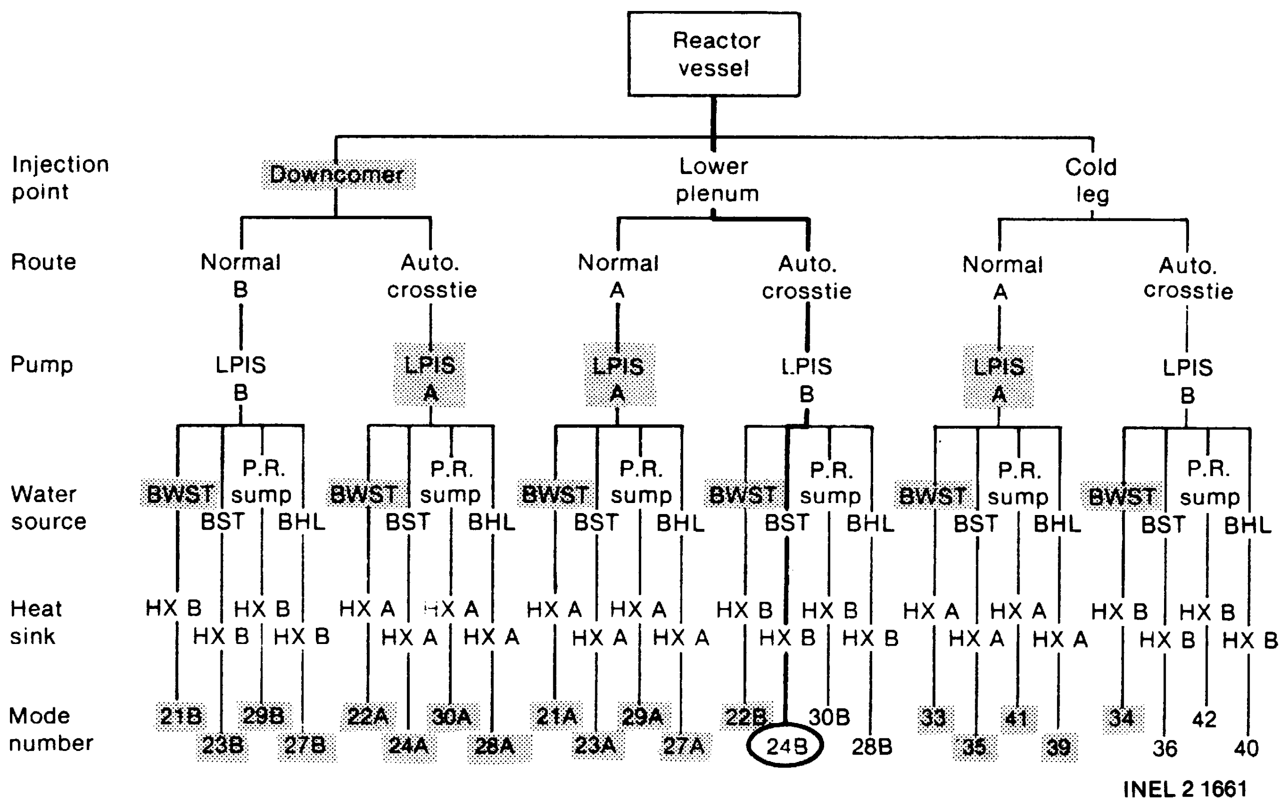

Figure 6. Response tree for LOFT LPIS.

environment for the reactor operator. A prime concern is to improve the efficiency of REACTOR's rule manipulation process so that a conclusion can be reached quickly without taxing the operator's patience. If simulation trials go well, we hope to apply REACTOR in an actual nuclear plant.

IV CONCLUSIONS

Application of a knowledge based expert system to nuclear reactor operations represents a significant new application of artificial intelligence methods. Although expert systems are beginning to demonstrate their value in a number of industrial settings, the nuclear application is unique in many ways. For instance, the nature of the decision process (on-line process control) is different from the usual expert system application. REACTOR will receive information directly from an operating plant. Decisions concerning plant operations must be made within adequate time to allow an effective action to be taken. Also, operation of a nuclear power plant requires the effective integration of a huge amount of information. Because of the safety requirements for reactor systems, the number of components to be monitored is larger than many other process control situations.

The safety implications of nuclear reactor operations also mandate very severe requirement for accuracy in an expert system. A nuclear reactor accident could disrupt the lives of a large number of people. Therefore, the decisions reached by an expert system must receive very careful review by the human operator. For the foreseeable future, the human operator will always have the final- responsibility for control room decisions.

Certain features of REACTOR may prove valuable to developers of expert systems in other fields. The integration of event-oriented and function-oriented diagnostic strategies provides a powerful combination for handling emergency situations. In many fault diagnosis problems, it is difficult to determine the exact cause of the problem. When this occurs, it is helpful to be able to use function-oriented techniques to deal with the situation. This approach could prove beneficial in other fields such as medical diagnosis.

The response tree seems to be a useful tool for representing knowledge in fault diagnosis tasks. By representing all the paths available to provide a function and then prioritizing each path, it is possible to embed a large number of IF-THEN rules in the structure of the response tree itself. This technique might also be useful for other expert system applications.

In summary, REACTOR is an effort to apply expert system technology to the operation of nuclear power plants. Although the development of REACTOR is not yet complete, it seems that expert systems could prove significant for helping nuclear reactor operators cope with the complexities of accidents. Further development and trials of REACTOR will be necessary to fulfill this potential.

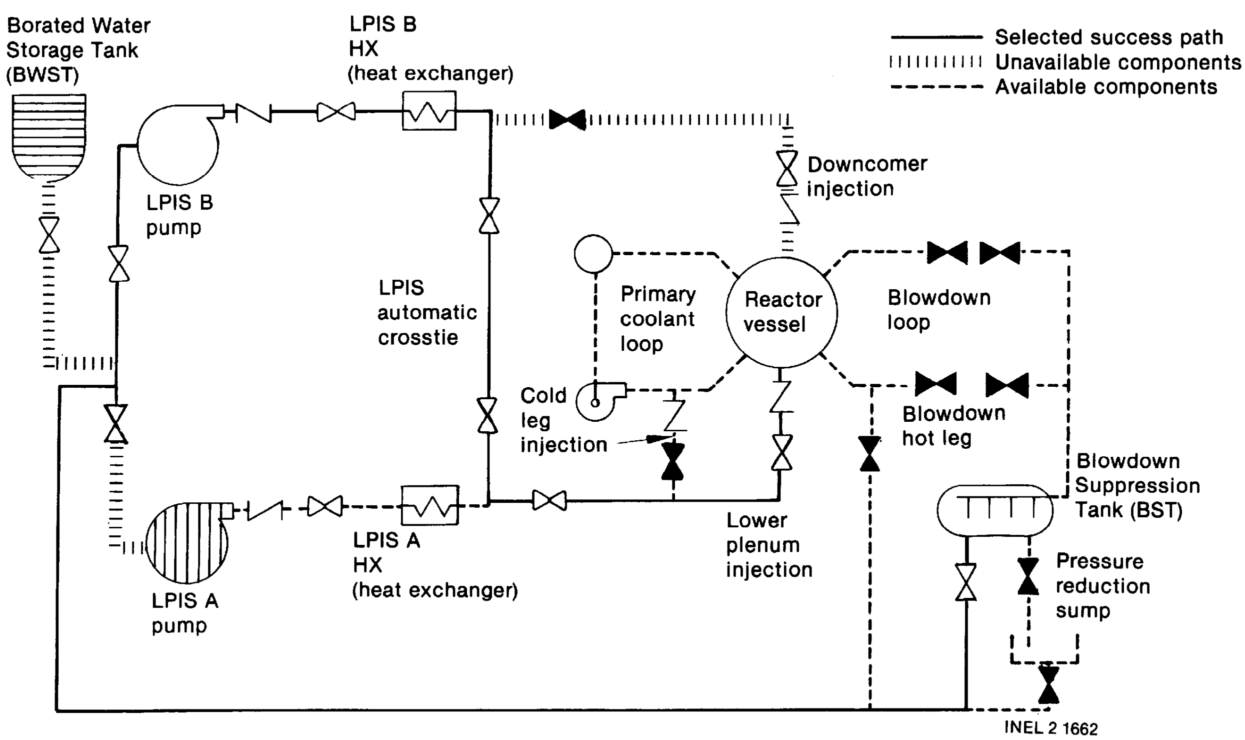

Figure 7. Display showing selected success path.

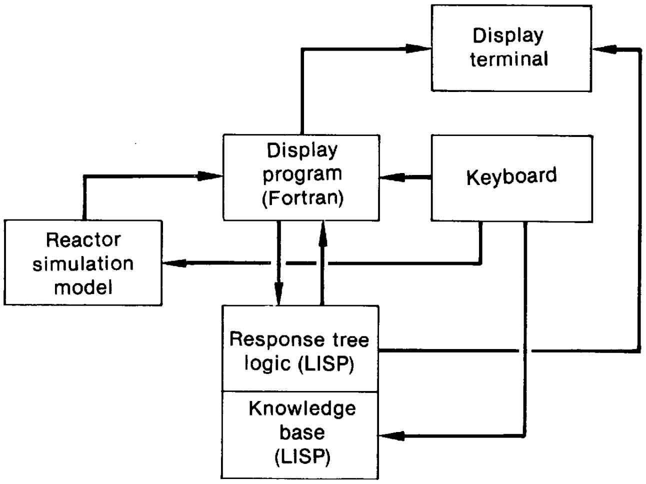

Figure 8. Structure of REACTOR.

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NOTICE

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