EXPRIME
AN EXPERT SYSTEM TO ANALYSE PRIMARY HEAT TRANSPORT SYSTEM ACCIDENTS

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ABSTRACT

In recent years a new branch of computer science has emerged, known as Artificial Intelligence. It represents a radical departure from standard procedural programming techniques currently in use. As such it has certain very interesting and powerfull properties that can be exploited to solve problems beyond the scope of standard programming methods.

The aim of the work currently being done by the authors is to exploit the new techniques available in the area of Artificial Intelligence to create an expert system to help operators determine the specific nature of a given Primary Heat Transport System (PHTS) accident. The expert system will also be capable of recommending the appropriate actions that should be taken.

The paper will have three parts. The first is an introduction to the field of Expert Systems. The second will be an examination of expert systems currently being developed in the nuclear industry and other potential applications. The third will be a discription of the expert system currently being developed by the authors to treat PHTS accidents.

EXPRIME
UN SYSTEME EXPERT D'ANALYSE D'ACCIDENTS DANS LE SYSTEME CALOPORTEUR PRIMAIRE

Ces dernieres annees l'intelligence artificielle est devenue une nouvelle branche de l'informatique. Elle represente une evolution radicale par rapport aux techniques de programmation actuellement utilisees. De ce fait elle possede des proprietes intrinseques tres efficaces pour la resolution de problemes hors de portee des methodes de programmation ordinaires.

L'objet du travail entrepris par les auteurs consiste a exploiter les nouvelles techniques disponibles grace a l'intelligence artificielle pour creer un systeme expert d'aide aux operateurs leur permettant de mieux cerner la nature d'un accident dans le systeme caloporteur primaire. Le systeme expert sera egalement capable d'emettre des recommandations sur les

actions correctrices a entreprende.

Ce rapport est divise en trois parties. La premiere presente les systemes experts. La seconde analyse les systemes actuellement developpes dans l'industrie nucleaire ainsi que quelques applications potentielles. La triosieme partie est une description du systeme expert en cours de developpement par les auteurs et dont le but est de traiter les accidents pouvant survenir dans le systeme caloporteur primaire.

1.0 INTRODUCTION

One of the most important aspects of the proper handling of a Loss of Coolant Accident (LOCA) in a nuclear reactor is how to best ensure that the reactor core is kept full and cool. This, quite simply put, means that the operator must make sure that sufficient Primary Heat Transport System (PHTS) inventory is available at all times. To carry out this task the operator has the use of both process and emergency systems.

This paper will discuss the possibility of using an expert system to help the operator diagnose PHTS accidents such that he will be able to make a more informed decision as to the best course of action to take. The paper will also examine some of the capabilities of an expert system that is currently being developed by the authors for this task.

In order to be able to discuss the implementation of an expert system in any field, an introduction to expert systems is first necessary. For this reason the paper has been broken down into three parts. The first is an introduction to the field of expert systems. The second is an examination of various types of expert systems and their current uses in both nuclear and non-nuclear fields. The third section is an examination of "EXPRIME" which is the expert system for PHTS accident analysis that is currently being developed by the authors.

2.0 INTRODUCTION TO EXPERT SYSTEMS

In the early 1950's a branch of computer science known as Artificial Inteligence began to attract some interest in both academic and research circles. It was originaly believed that computers could be made to duplicate most of the basic reasoning and information processing functions that humans characterise as intelligent behaviour. The basic idea was that due to their increadibly fast processing speeds, computers could simply be fed huge data bases and using basic comparison and combination techniques solve any problem that was put to them. This led to the creation of such early systems as the General Problem Solver (GPS). Unfortunately due to the large amount of time needed, even at high computer speeds, to exhaustively search the very large data bases involved GPS type systems never lived up to the early expectations made of them. This is in fact true of most of the branches of Artificial Intelligence research even today. The one notable exeption being expert systems.

2.1 WHAT ARE EXPERT SYSTEMS ?

Although, as has already been said, much of the work done in the area of Arificial Intelligence has not proven to be as sucessfull as originaly hoped it has produced some very usefull data base search techniques and some very powerfull programming languages that are better suited to the processing of ideas than numbers.

Expert systems are sophisticated computer programs that use these techniques and languages to solve problems that involve the manipulation of knowledge in a given domain, to make decisions and to solve problems for which experts are normally required.

2.2 BASIC EXPERT SYSTEM COMPONENTS

There are three main components to an expert system, these are the knowledge base, the inference engine, and the working memory.

2.2.1 Knowledge Base

The knowledge base of an expert system contains all the available information pertinent to the domain of application of the expert system. The information consists of facts about the system such (in our case a nuclear reactor) as operating limits on temperature, pressure and various other operational parameters. The knowledge base also contains heuristics which are personal rules of thumb that the experts use in guiding their examination of a given problem.

Both the facts and the heuristics are represented as production rules in the knowledge base. Production rules have the following form.

IF (CONDITION).....THEN (CONCLUSION)

It is possible for a production rule to have more than one condition and/or more than one conclusion. For cases where the conclusion is not completely certain the rules may have confidence factors associated with them.

IF (CONDITION)
THEN (CONCLUSION) (0.75)

Which means, if the condition(s) is true with 100% confidence the conclusion is only true 75% of the time.

2.2.2 Inference Engine

The inference engine is the control mechanism of the expert system. It manipulates the rules in the knowledge base to reach conclusions. It compares facts that are currently known about the system with rules in the knowledge base looking for a rule that incorporates this fact. Thus matching known facts and rules until a conclusion is reached. There are two main types of inference engines Backward chaining and Forward chaining.

Backward Chaining

Backward chaining inference engines start with an assumed conclusion and try to find a set of rules that connect the known facts to this conclusion. The inference engine searches the rules and tries to find on whose antecedents (or "if" part) matches the known facts and lead to the conclusion. If not all the antecedents are known directly they become the new goal to be satisfied in the inference process.

Forward Chaining

Forward chaining inference engines work by searching the rules until a rule is found whose antecedents match the known facts. The inference engine then activates this rule and adds its conclusion to the list of facts and deactivates other rules. This process is repeated until all the known facts are correlated and a final conclusion is reached. An inference engine very similar to this is the event-driven type. In which each succesive step is based on new data or on the results of previous steps. This inference engine is applicable to the analysis of transient data, particularly in real time analysis such as the task "EXPRIME" performs.

2.2.3 Working Memory

The working memory of an expert system is much like the memory of a human being. It keeps track of the current status of the problem and presents state and history of any important variables.

2.3 WHY CREATE AN EXPERT SYSTEM

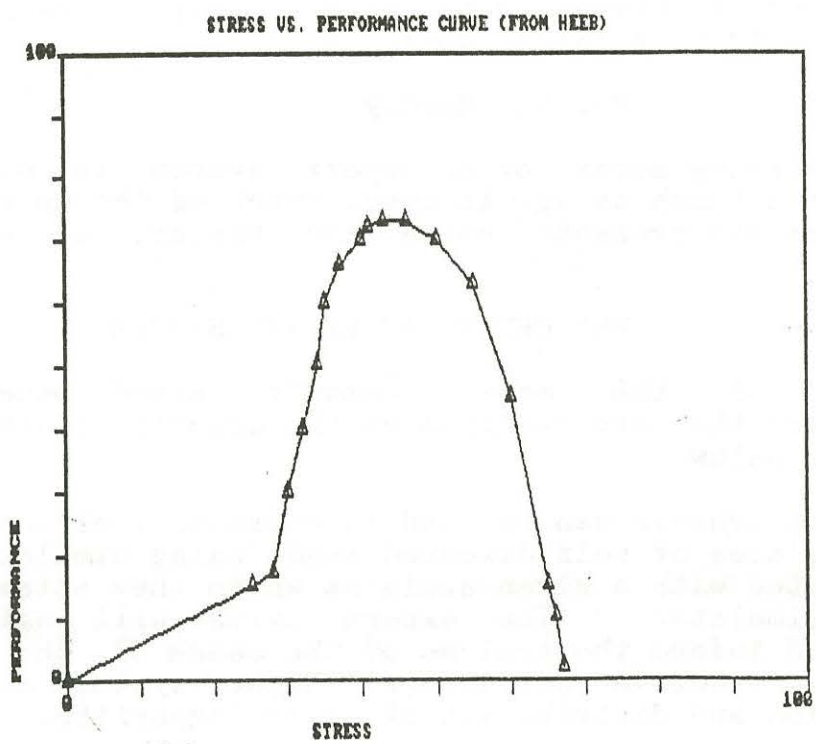
Some of the more commonly sited benefits to the implementers that are realized by the creation of expert systems are listed below.

Expert systems can be used in operator training. Their use is in the area of self directed study using simulators. Trainees are presented with a given accident which they attempt to handle on the simulator. The expert system will analyze the given actions and inform the trainee of the cause of the problem and the most effective solution(s). Expert systems also aid in the presentation and distribution of rare expertise. This means that as experts retire their knowledge will be retained for use by others in the field. A further advantage of having expert systems available to both trainees and operators is that they can provide case experience for given accidents. The process of creating an expert system also leads to the codification of knowledge previously known only as rules of thumb by a limited number of experts. Information overload under accident condition can be more effectively handled by operators, since expert systems can analyze the alarms and present only the most important ones to the operator. Expert systems can also be interfaced with simulator codes to do quick approximations that can provide usefull information for accident analysis.

While all of these reasons are valid, we believe that it is a severe omission on the part of most researchers to ignore the area of human response under accident conditions.

A great deal of work has been done in the area of human performance under stress. Tyhurst in 1951 made observations of people during a crisis and found that about 15 percent show organized, efficient behaviour. The majority, approximately 70 percent are still able to function with some effectiveness, but do show varing degrees of disorientation. The remaining 15 percent are completely disorganized, they either panic or simply freeze up. Regardless of the response, they are unable to function.

Another study by Hebb in 1972 shows roughly the same result. The figure below shows the level of performance versus the level of stress.



3.0 CURRENT AND POTENTIAL USES OF EXPERT SYSTEMS

Most of the research going on in the field of expert system technology is devoted to production rule (if ... then) type systems since they are percieved as being the most likely to yield results, at least in the short term.

Below we present (6) a list of some of the types of production rule expert systems currently being looked at and an explanation of the tasks which they perform.

Catagory	Problem Addressed
Intepretation	Inferring situation descriptions from sensor data
Prediction	Inferring likely consequences of given situations
Diagnosis	Inferring system malfuctions from observables
Planning	Designing actions
Monitoring	Comparing observables to operating constraints
Debugging	Prescribing remedies for malfuctions
Control	Interpreting, predicting, repairing and monitoring the behavior of the system

Interpretation systems infer situation descriptions from observable data. Such a system explains the observed data by assigning to it a symbolic meaning describing the situation or the state of the system accounting for the data. This system is essentially a table look up that has the ability to make a conclusion about the state of a process or piece of equipment then cross reference the conclusions using other indicators which should lead to the same conclusion. It can then offer a conclusion that has a probability factor associated with it.

Prediction systems infer likely outcomes to current or postulated situations. As in the interpretation systems, prediction systems can give numerical probability factors to all generated outcomes.

Diagnostic systems infer system malfunctions from observed data. There are two different techniques typically used in such systems to relate operational irregularities to observations, the first involves a simple table of associations between observations and their underlying cause. The other method uses knowledge of potential problem areas in design, operation or equipment to produce a list of malfunctions which are consistent with the observations.

Planning systems are generally used by the military to plan attack strategies. They could however be used to plan repair strategies so as to minimize exposure time in high radiation fields.

Monitoring systems perform much the same function as the computer system currently in use in CANDU REACTORS. However they use a knowledge based control structure as opposed to the algorithm control now in use.

Debugging systems offer solutions for malfunctions or courses of treatment of human diseases. These systems rely on planning, design data and prediction capabilities to generate recommendations for correcting the problem. Such systems use the expert knowledge at their disposal to generate a number of solutions to the current problem and then carry then out in the computer to determine the best solution.

Control systems are by far the most complex of all the expert systems now in use. Such systems adaptively govern the overall behavior of a system. To accomplish this the control systems must repeatedly interpret the data describing the situation, predict the future from this data, effect any changes needed to prevent any system constraints from being violated, diagnose the cause of any problems that arise and generate solutions to these problems. In short, they must embody all the skills of the other expert systems that were mentioned. Predictably, such systems are few and far between.

3.1 NON NUCLEAR APPLICATIONS

The following is an examination of some of the most well known expert systems in use today in some of the areas discussed above.

Interpretation

Dendral and Meta-Dendral

These two expert systems were developed by Stanford University and are used in the area of mass spectroscopy.

Dendral generates plausible chemical structures of organic molecules by analysing data obtained in the area of mass spectroscopy. Meta-Dendral looks for new rules for the behavior of fragments in mass spectroscopy by comparing all the facts used by Dendral in reaching a conclusion and searching for new correlations between the facts and the conclusion.

Diagnosis

Mycin

Mycin is a diagnosis and treatment system in the field of infectious blood diseases. It was developed by Shortliff at Stanford in the early 1970's. It is regarded as being one of the most successfull expert systems ever written and is in part responsible for the large interest in expert systems today. Mycin contains over 400 rules and uses a backward chaining inference engine. It was also the first expert system to implement a consistency checking routine. When tested against both medical experts and interns Mycin was found to perform as well or better than the human experts.

Control

Picon

Picon is a real-time plant control expert system. It operates on a parallel processing Lisp Machine. It has the potential to use up to 2000 rules. Some of its capabilities include giving recommendations and making diagnoses on plant conditions, economic optimization and emergency actions.

3.2 NUCLEAR APPLICATIONS

In the nuclear industry expert systems are being developed to assist operators in the handling of some of their more complex activities. These include starting up the reactor and handling accidents.

Two examples of expert systems being developed in the nuclear industry are the following.

An expert system being developed by Electricite de France (9) to analyze alarms during accidents and shut off any alarms that are nothing but a consequence of the accidents and not actually linked to it. The expert system has 2500 "if...then" type rules and uses zeroth order predicate calculus as an implementation

A production rule type expert system to assist operators in the startup of BWR being developed by Hitachi (7). The system has 55 rules covering constraints to the startup, corrective action for problems, the behaviour of Xenon transients and meta-knowledge for controlling the inference process.

These expert systems and others like them in the nuclear industry are of the diagnosis type. They represent a first step towards the development of a complex, overall plant control system, such as Picon, for the nuclear industry.

4.0 EXPRIME

"EXPRIME" is an experimental version of an expert system currently being written by the authors to assist operators in the diagnosis and handling of Loss of Coolant Accidents (LOCA). Its functions are to determine the nature of the accident (ie. Large or Small Break LOCA), determine the location of the break, determine whether or not there is adaquate cooling in the core and recommend actions, if any, that can be taken to optimize the effectiveness of the Emergency Coolant Injection System (ECIS).

"EXPRIME" is currently implemented on an IBM PC-AT with over 2 Mega-bytes of memory in Gold Hill Common LISP large memory format.

Some of the features of "EXPRIME" include an event driven diference engine capable of handling time varying data, and a set of simple steam tables that are used for quick calculations. Also included is a routine for predicting stagnation for accidents with Loss of Class IV power.

4.1 STRUCTURE OF EXPRIME

There are two schools of thought as to how best to treat accidents. These are known as Event-Based Procedures and Symptoms-Based Procedures.

Event-Based Procedure

Event-Based Procedures involve a set of specific actions the operator must follow for a specific accident. This naturally requires a correct diagnosis of the accident on the part of the operator prior to any action being taken.

Symptoms-Based Procedures

Symptoms-Based Procedures involve the use of a given set of actions dependant on the physical condition of the plant only. This type of procedure completely disregards the specific nature of the accident. The advantage of this type of procedure is that it will work for any accident regardless of the operators ability to diagnose the accident.

Two versions of "EXPRIME" currently exist, one which implements the Event-Based procedure for accident treatment and one which implements the symptoms based procedure.

The symptoms-based system is not an expert system in the true sense of the term since no inference structure is needed to implement it. This type of system is essentially a triggered data base that outputs the appropriate actions for each identified symptom. The only point in favour of making any further effort on the development of this version of "EXPRIME" is that it could be used as a backup if the event-based version is incapable of making a firm diagnosis.

The most promising version and the one that will be examined in depth is the event driven inference engine. This version of "EXPRIME" uses a working memory that keeps a constant record of the previous 30 minutes worth of the most important plant parameters and an alarm status table.

The Expert System cycles through the preliminary data aquisition section until a major alarm (eg. PHT pressure low) triggers the start of the inference process.

Once the inference process is started the working memory is frozen and only updated in bursts from a memory buffer. This is due to the fact that the host computer is incapable of parallel activities.

The inference engine uses the available information one piece at a time (alarms first) and looks for rules that have this piece of information in their "if" part, then uses the "then" part of the rule as an additional piece of information to continue the search for a conclusion if needed or simply identifies the accident. The following section gives a more detailed view of EXPRIME's Inference Engine.

4.2 EXPRIME'S INFERENCE ENGINE

Due to the large number of rules needed to adequately describe the behavior of a Nuclear Reactor Primary Heat Transport System under all possible accident conditions it was necessary to develop an efficient real time inference engine. Furthermore this inference engine was required to be able to handle transient data. These requirements lead us to adopt a forward chaining event-driven inference engine for "EXPRIME". Two additional features were added to this inference engine, the first being a confidence factor calculating algorithm, the second a consistency checker to allow for the transient nature of the data.

4.2.1 Event Driven Inference Engine

A forward chaining event-driven inference engine works in much the same way as a purely forward chaining inference engine. The main difference being that in an event-based inference engine each succesive step is based only on available data or on the results of previous steps. This differs from the pure forward chaining inference engine in that it will not set antecedents (the "if" part of an "if ...then" rule) as a sub-goal to be proved first. This requires a much more carefull ordering of the rules in an event-driven expert system but provides us with a much faster response time.

4.2.2 Confidence Factors

In most areas where human expertise is used conclusions are rarely certain. This is particularly true in the analysis of large systems where there are many factors interacting to influence the overall behavior of the system.

To account for this in an expert system, confidence factors are used. A confidence factor is a number that reflects the experts confidence in a conclusion if all the antecedents of the rule are true with 100% confidence.

ie. IF CONDITION A
AND B
AND C
THEN CONCLUSION D (0.8)

The 0.8 reflects the experts confidence in the rule.

In systems involving multiple rules confidence factors interact in the following manner.

Independent Checks Of The Same Conclusion

If we have more than one rule with a given conclusion and all these rules are found to be true it is reasonable to assume that our confidence in the conclusion can be higher than the largest of the independent confidence factors.

CONCLUSION D1 (0.8)
CONCLUSION D2 (.75)

The overall confidence factor is calculated in the following manner.

$$R = C / (1 - C) \qquad C = R / (R + 1)$$
$$R1 = 0.8 /(1 - 0.8) = 4$$
$$R2 = 0.75 /(1 - 0.75) = 3$$
$$R(total) = 3 * 4 = 12$$
$$C(total) = 12 / (12 + 1) = 0.923$$

That is to say that we have a confidence factor of 0.923 that conclusion D is true due to the independent confirmation of the conclusion by two different means.

Uncertainty Propagation

The final confidence factor of a rule assumes that all antecedents are known with complete confidence. If however the antecedents are the results of previous steps their confidence may be less than 1. To handle this accurately we use the following procedure.

IF CONDITION A (.75)
B (0.9)
C (0.6)
THEN CONCLUSION (0.8)

Rconc = 0.8 / (1 - 0.8) = 4
Ra = 0.75 / (1 - 0.75) = 3
Rb = 0.9 / (1 - 0.9) = 9
Rc = 0.6 / (1 - 0.6) = 1.5
Rfinal = Rconc * Ra/Rconc * Rb/Rconc * Rc/Rconc
Rfinal = 4 * 3/4 * 9/4 * 1.5/4 = 2.531
Cconc = Rfinal / (1 + Rfinal)
Cconc = 2.531 / (1 + 2.531) = .7168

This means that we have a confidence factor of 0.7168 due to the interaction of the uncertainties in the conditions and the conclusion.

4.2.3 Transient Data Analysis

Most expert systems that are currently being developed to analyse transient data use a consistency checking method that operates in the following manner:

STEP 1: Look at all operational parameters one at a time and use them as facts

STEP 2: Use the values of these parameters to reach a given conclusion

STEP 3: Check to see that the values of the operational parameters used have not changed by any significant amount

STEP 4: *: If they have changed go to the last occurence of a rule that was found to be true before the application of the now changed parameter and restart the inference process from this point

*: if they have not changed output the conclusion

It is claimed by that this method of analysis allows an expert system to analyse transient data and a valid conclusion to be reached.

We propose the following method as another way of handling transient data.

Consider a Secondary Side break within containment. Initialy we would have a fact of the form: PHTS PRESSURE LOW (due to over cooling). Some time later (assuming a loss of forced circulation) the primary side pressure would be high due to the loss of heat removal from the system. This would lead to a new fact of the form: PHTS PRESSURE HIGH and to the discarding of the previously known fact about the pressure being low.

Most expert systems currently designed to handle transient data using the consitency checking approach would simply restart the analysis from the last rule that was found to be true before the use of the changed fact.

The method implemented in "EXPRIME" is to use knowledge that the PHTS pressure was once low and is now high to create a new fact of the form: PHTS PRESSURE CHANGE LOW TO HIGH. "EXPRIME" then backtracks to the last occurence of a rule that was found to be true before the use of the changed factand continues the analysis using not only the fact that the PHTS pressure is high but that in was at one time low and is now high.

We feel that this method of transient analysis used in "EXPRIME" yields a more accurate result than the more commonly implemented consistency checking method. This is due to the fact that the transient, which is a property of a particular accident is not forgotten.

4.3 EXPRIME'S INFERENCE ENGINE

The following is an english translation of the major functions of the inference engine implemented in "EXPRIME".

```
1: Examine working memory for state of alarms
   Examine working memory for state of plant parameters
   Are there any alarms or problems with parameters ?

   NO: goto 1

   YES: start diagnosis procedure

   DIAGNOSIS

2: Look for rule containing alarm and/or parameter in question
   in its "IF" part
   Conclude the "THEN" part of the rule is true
   Add the conclusion to the list of known facts
   Calculate confidence factor
   Has accident been determined ?

   NO: goto 2

   YES: Has anything changed significantly ?

        NO: Give accident with confidence factor
            and recommended action
            stop

        YES: Create new fact reflecting the change
             goto 2
```

4.4 EXAMPLE OF EXPRIME AT WORK

The following is an english translation of some of the rules in "EXPRIME" and the method in which they interact during the solution of a problem. The complete set of rules includes confidence factors for conditions and conclusions and contains multiple condition and conclusion chains, which cannot all be written out in this paper.

The example treated deals with locating a large break LOCA and taking steps to optimize the effectivness of the ECI system. The first task will be to determine the location of the break, which for this example will be taken to be in the North-East Reactor Outlet Header. The next step will involve closing the ECI flow to the broken header.

Step 1: Determine if we have a LOCA.

```
(IF ((PHT PRESSURE LOW)
  OR (PRESSURIZER LEVEL LOW)
 AND (CONTAINMENT PRESSURE HIGH)
  OR (ACTIVITY IN CONTAINMENT))
THEN (LOCA))
```

Step 2: Determine size of LOCA.

```
(IF ((PHT FLOW LOW)
 OR  (HIGH NEUTRON POWER)
 OR  (NEURON LOG RATE HIGH))
THEN (LARGE LOCA)
ELSE (SMALL LOCA))
```

Step 3: Ensure ECI.

```
(IF ((ECI VALVES OPEN)
 AND (ECI PUMP RUNNING)
 AND (ECI FLOW > 1000 KG/S (HP) OR 500 KG/S (LP))
 THEN (ECI SYSTEM OK)
 ELSE (INFORM OPERATOR ECI NOT ESTABLISHED))
```

Step 4: Confirm break size from ECI pump characteristics.

```
(IF ((ECI PUMP PRESSURE < 3.0 MPA))
 THEN (LARGE LOCA)
 ELSE (SMALL LOCA))
```

We now wish to locate the break.

Step 5: Determination of LOOP

```
(IF ((PHTS PRESSURE IN NORTH LOOP > SOUTH LOOP))
 THEN (BREAK IN NORTH LOOP)
```

```
ELSE (BREAK IN SOUTH LOOP))
```

Step 6: Determine side of Reactor which was Break.

```
(IF ((FEEDER CABINET W TEMP. > FEEDER CABINET E TEMP.))
 THEN (BREAK IN WEST HEADER)
 ELSE (BREAK IN EAST HEADER))

(IF ((FEEDER CABINET W HUM. > FEEDER CABINET E  HUM.)
 THEN (BREAK IN WEST HEADER)
 ELSE (BREAK IN EAST HEADER))

(IF ((FEEDER CABINET W PRESS. > FEEDER CABINET E PRESS.))
 THEN (BREAK IN WEST HEADER)
 ELSE (BREAK IN EAST HEADER))
```

More than forty of these steps are required to assess with a high degree of confidence the side of the reactor that experiences a break and to display a recommendation to the operator which states to close the corresponding ECI valves.

Such a complicated information handling and decision making process, incorporating transient data cannot be done easily by an operator during emergency situations, but an expert system like "EXPRIME" can provide a very usefull diagnosis .

CONCLUSION

"EXPRIME" is currently fully developed in the conceptual stage. Additional programming has to be done in the inference engine to give a satisfactory diagnosis and in the near future "EXPRIME" will be assessed against a simulated LOCA. It is the authors' intention to use the basic frame work of "EXPRIME" and to expand it in an "all accident" diagnosis tool. The authors believe that such a tool can be implemented in all nuclear stations and training centers for diagnosis and operator action recommendations.

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