A MICROPROCESSOR-BASED, ON-LINE DECISION AID FOR RESOLVING CONFLICTING NUCLEAR REACTOR INSTRUMENTATION*

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Abstract

We describe one design for a microprocessor-based, on-line decision aid for identifying and resolving false, conflicting, or misleading instrument indications resulting from certain systems interactions for a pressurized water reactor. The system processes sensor signals from groups of instruments that track together under nominal transient and certain accident conditions, and alarms when they do not track together. We examine multiple-casuality systems interaction and formulate a trial grouping of variables that track together under specified conditions. A two-of-three type redundancy check of key variables provides alarm and indication of conflicting information when one signal suddenly tracks in opposition due to multiple casualty, instrument failure, and/or locally abnormal conditions. Since a vote count of two of three variables in conflict as inconclusive evidence, the system is not designed to provide tripping or corrective action, but improves the operator/instrument interface by providing additional and partially digested information.

1. Introduction

Nuclear power plants have a complex array of instrumentation designed to provide the operator with accurate information about essential plant conditions. The well-trained operator uses these instruments to operate the reactor under normal conditions and to react properly to accidents, but he may be less prepared to react upon receiving false, conflicting, or misleading information.

The vital importance of operator/instrument interfacing was clearly demonstrated during the accident at Three Mile Island-2 (TMI-2) on May 28, 1979. There, the operators received numerous false and conflicting bits of information from their instrumentation and, as a result of incorrectly resolving this information, took action which compounded the casualty. Operator training, appropriate instrumenting, and operator/instrument interfacing all proved to be inadequate.1 A breakdown of six major items contributed to the accident:

- water level indication in the reactor,
- electromagnetic relief valve (ERV) operation,
- auxiliary feedwater (AFW) flow indication,
- containment isolation,
- extended range instrumentation,
- computer readout.

But the severity of the accident was a direct result of incorrectly diagnosing reactor pressure vessel water level.

Within the first 15 min of the accident, the following major conflicting bits of information were present:

- the ERV console valve position indicator read closed but the ERV tail pipe temperature remained high,
- the AFW pump automatically turned on indicating flow to the steam generator but steam generator level was dropping rapidly,
- pressurizer water level indicated increasing but main coolant pressure was dropping rapidly,
- pressurizer water level was increasing but the high pressure backup injection system actuated,
- pressurizer water level was increasing but reactor containment pressure was increasing.

All but the second conflict explicitly related to reactor water level or pressure. Unfortunately, the operator was not completely aware of all of these conflicts and he resolved those conflicts he was aware of by assuming that pressurizer water level was correct and that conflicting information was false. Indeed, it was not until over two hours later that the real conditions of a small loss-of-coolant accident were identified. By that time, a substantial fraction of the core had been uncovered so that overheating of the zirconium clad and the evolution of hydrogen resulted.

The false pressurizer water level indication was a result of loop seals forming at low points of the primary system piping and a differential pressure into the pressurizer from the stuck-open ERV. Proposed solutions to such problems include direct instrumenting of the core water level. However, an important lesson from TMI-2 is the need to become aware of and to correctly resolve conflicting information by an on-line decision aid as a first, simple step toward reactor accident diagnostics.

Clearly, the cost of an on-line computer system to diagnose all plant variables and conditions and to decide on a proper course of action is presently prohibitive. However, there are alternative, intermediate steps that are reasonable in terms of cost and effort that can be immediately implemented. This paper discusses such an intermediate step that will not diagnose plant accidents, but will partially digest the instrument information presented to the operator in an effort to provide him with an awareness and resolution of conflicting information. We describe the design architecture for a microprocessor based, on-line decision aid for resolving which instruments, if any, are supplying false, conflicting, or misleading information as a result of certain systems interactions for a Pressurized Water Reactor (PWR). Two of three instruments supplying conflicting information would output an alarm and form a check to resolve the conflict. The system could potentially be extended to perform further diagnosis of the accident and recommend corrective actions.

Microprocessors are becoming increasingly important in a variety of nuclear control

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instrumentation. Their advantages compared to a full plant operations diagnostic minicomputer system include:

- miniaturization,
- reduced power consumption and dissipation,
- increased reliability,
- reduced cost.

The architecture of the standard Intel 8085 3-bus microprocessor system is simple, and the three characteristic buses are an 8-bit bidirectional data bus, an 8-bit monodirectional address bus, and the control bus. The 8085 chip is the central processing unit (CPU) including the arithmetic-logic unit (ALU), control unit (CU), and the clock crystal. It is a fourth-generation microprocessor and successor for small systems to the Intel 8080. It has special components such as the 8155 (RAM plus I/O) and the 8355 (ROM plus I/O) which provide memory, I/O, and demultiplexing of the data bus allowing a complete system to be built of just three chips. Finally, a power supply is required. All other large scale integration (LSI) components can be interfaced either directly to the buses or to this basic set. Analog-to-digital converters (ADC) are now available in a single chip for most applications. In short, a microprocessor system can easily be coupled to an analog-to-digital and digital-to-analog multichannel conversion assembly.

In Sec. 2, we consider normal power transients and specific reactor casualties to find conditions under which key plant variables track roughly together. We explore multiple casualty systems interactions and present an initial trial selection of instrument groupings.

In Sec. 3, we present the design architecture and sample software for resolving conflicting instrumentation information based on the two-of-three redundancy microprocessor hardware of Kimura et al. Since a vote count of two-of-three key variables does not ensure correctness, the system provides no tripping or corrective action, but constrains itself to providing additional and partially digested information for the operator as an aid to resolving conflicting information.

2. Grouping Reactor Variables

In this section, we present a trial grouping of reactor variables that tend to roughly track together during normal operating plant transients and during specific accident conditions. We also explore multiple-casualty systems interactions due to hidden dependencies.

We are not concerned with the detailed and complex interrelationships among plant variables because that would involve a complete reactor diagnostic minicomputer system, one that our proposed design system is intended to avoid. We are more concerned with a simple approach to partially digest simplified relationships between key variables in order to assist the reactor operator in detecting conflicting information which may result from certain system interactions. To accomplish this, it is sufficient to find unusual circumstances where key variables roughly track together and then to provide some parametric guidance (time delay and magnitude changes) in the trend analysis portion of the software effort (see Sec. 3) on which to base decisions. It is important to realize that the proposed system will provide no alarm for normal transients or single plant casualties, but only for more complicated situations.

The following review of normal and accident transient indications is not intended to be all-encompassing since there are significant variations among PWR plants. However, it is intended to be a programmatic approach for trial selection of variables that roughly track together.

Consider a normal (N) PWR plant transient (we will examine a power increase) for a constant average primary coolant temperature ($T_{av}$) system with the following initial conditions:

1. Reactor critical, self-sustaining, operating in the range of 15% power,
2. $T_{av}$ = nominal value,
3. $\Delta T = (T_{hot} - T_{cold})$ = nominal value,
4. $m_p$ (primary coolant mass flow rate) = slow speed pumps,
5. Pressurizer liquid level = nominal value,
6. $S_G$ (steam generator pressure) = nominal value,
7. $S_C$ (steam generator temperature) = saturation temperature for $S_G$,
8. Turbine condensers at vacuum = nominal value.

A ramp increase in electric load will now increase steam demand to the turbine. When the turbine throttle is opened by the governor system, steam flows to the main condensers which are at an initial vacuum. The large pressure differential and increased valve opening increases the mass flow rate of steam from the steam generators to the main condensers.

The steam generator is basically a tube-and-shell heat exchanger which maintains steam at saturation temperature and pressure. Thus, when the mass flow rate of steam to the main condensers increases, it reduces the partial pressure of steam inside the steam generator and allows water to "flash" to steam, and the temperature of the steam generator water is reduced. At the partial pressure drop of steam, a control device signals the steam generator water level control system to increase make-up feed water to keep an approximately constant level of water in the steam generator. This make-up feedwater is colder than the water already present, and thus it adds to a reduction of the temperature of the steam generator.

As the average temperature of this water declines, the temperature gradient between the primary coolant and the steam generator "secondary" water increases, thereby promoting better heat transfer. The lower average steam generator temperature draws more heat from the primary coolant and reduces the exit temperature of the primary coolant ($T_{cold}$) from the steam generator.

This is obvious from the relationships:

$$ \dot{Q}_p \text{ (heat rate primary)} = \dot{Q}_{SG} \text{ (heat rate secondary)},$$

$$ \dot{m}_p (T_{hot} - T_{cold}) = UA \left( T_{av} - T_{sat} \right),$$

and

$$ \dot{m}_p \Delta T = m_{SG} h_{SG}.$$

The saturation temperature of the steam generator ($T_{sat}$) is the first to drop. Thus, ($T_{av} - T_{sat}$) increases, resulting in $T_{cold}$ decreasing initially to maintain the balance. $T_{cold}$ has now been reduced several degrees.

This colder water returns to the reactor where, through action by the negative temperature coefficient, it increases reactor reactivity. A positive start-up rate for power will now
The rising power will raise the temperature of the coolant, and through the negative temperature coefficient, it will begin to cause negative reactivity. This will stop the power rise and eventually, after several oscillations, power will reach a new steady-state value which will be higher than its initial value (see Fig. 1).

If power doubled from its initial level, it follows from Eq. (2) that since $\dot{m}P_d$ does not change, then $(T_{\text{hot}} - T_{\text{cold}})$ must double. $T_{\text{AV}}$ would initially decrease as $T_{\text{cold}}$ decreased, but as reactor power increases, thereby increasing $T_{\text{hot}}$, $T_{\text{AV}}$ will return to its initial level.

Primary pressure and pressurizer level will vary during the transient; both resultant levels depend greatly upon the physical construction of the pressurizer piping and will thus vary from system to system. We will assume here, for a consistent argument, that pressurizer level will increase under this type of transient. Meanwhile, steam from the steam generator flows to the turbines. The used steam is converted to water in the main condenser and is pumped back to the steam generator. A simplified Rankine cycle diagram shown in Fig. 2 illustrates the process.

![Fig. 1. The variation of plant parameters during a power increase transient.](image1)

![Fig. 2. A simple Rankine representation of a power increase transient.](image2)

Cycle 1-5 is the initial condition. Cycle 6-10 is the cycle after the increase in power. The processes show that:

1. From 5 - 1 - 2 (10 - 6 - 7) heat is added at constant pressure. This is the heat addition that occurs in the steam generator.
2. From 2 - 3 (7 - 8) expansion process is done by accomplishing work. This is the temperature and pressure drop that occurs in driving the main turbines.
3. From 3 - 4 (8 - 9) the heat rejection process that occurs in the main condensers is condensed by the heat exchange process with a separate cold water source.
4. From 4 -5 (9 - 10) the compression process that results from the feed pumps pumping make-up feed water back to the steam generator.

The results of this power transient are:
1. lower steam generator pressure and temperature,
2. increased mass flow rate of steam from the steam generator,
3. increased mass flow rate of make-up feed water into steam generator,
4. higher power level,
5. larger $(T_{\text{hot}} - T_{\text{cold}})$,
6. lesser condenser vacuum,
7. increased pressurizer liquid level,
8. increased electrical generation output.

During a PWR normal (N) power plant transient, certain key variables track roughly together. These variables include electrical load, reactor power, $\Delta T$, steam mass flow rate, SG make-up water flow rate, and pressurizer liquid level. SG temperature, SG pressure, and condenser vacuum also track together. If reactor power were increasing, we would be suspicious if $\Delta T$ decreased. Likewise, we would not expect to see SG temperature increasing while SG pressure decreased; therefore, if we construct an alarm system that allows these instruments to track together, it will provide no alarm unless the added problems of systems interaction (such as instrument failure or a casualty during the transient) occur.

However, Fig. 1 shows that power increases in an oscillatory manner while $\Delta T$ increases monotonically. These parameter characteristics, complex and plant-specific issues, must be accounted for by limits of time constants and allowable magnitude changes which would be incorporated into the trend analysis portion of the microcomputers software package.

Next, consider the abnormal conditions of a reactor scram (S) where the plant responds to a step drop in power. The following immediate indications are typical:

- reactor scram alarm,
- rapid decrease in reactor power,
- rapid decrease in startup rate,
- rod position indication showing all rods on bottom,
- rapid decrease in $T_{\text{AV}}$,
- rapid decrease in pressurizer liquid level,
- rapid decrease in $\Delta T$,
- rapid decrease in primary coolant pressure.

We observe that during condition S, all events listed above track strictly together with large changes in magnitude and negligible time delay. It would be abnormal to observe a drop in reactor power but an increase in pressurizer liquid level for the single condition S.
During a loss of main coolant flow (F), the following indications are typical:
- Low flow alarm,
- Reactor scram and accompanying indications,
- Either a loss of primary coolant pump differential pressure or a shut indication from a main coolant cutout valve.

During the abnormal conditions of a reactor small primary leak (L) the following indications are typical:
- Primary pressure decrease,
- Pressurizer liquid level decrease,
- Reactor containment ambient temperature increase,
- Reactor containment pressure increase and possible blowout of rupture disk,
- Reactor containment sump water level increase,
- Pressurizer relief valve outlet temperature increase (if that is the leak source),
- Primary pressure and level alarms,
- Possible reactor scram and accompanying indications due to low pressure automatic protection.

For our present analysis, we do not include the initiation of high pressure backup injection pumps for condition L.

For over-pressurization (O) of the primary, we could find:
- High pressure alarm,
- Pressurizer level increase,
- Primary pressure increase,
- \( T_{av} \) increase.

For over-pressurization of the primary following a reactor scram (O and S), we would see the typical reactor scram indications followed by:
- High/low pressure alarm,
- Pressurizer liquid level either falling or rising,
- Primary coolant pressure increase,
- \( T_{av} \) increase/decrease.

The compound casualty of S and O leads to conflicting expectations. That is, the pressurizer level might track in opposition to variables it would normally parallel. It should begin to decrease at the start of S, but if the over-pressure resulted in condition O, the level would increase.

From the preceding review of key trends during normal or specific accident conditions, we suggest the trial grouping of reactor variables in Table 1. These variables will roughly track together during either a plant transient or a single casualty.

For more complicated situations, systems interactions can lead to conflicts. Then, when an instrument fails, abnormal local conditions (such as a fire), or compound casualties (like O and S) induce a conflict and the key variables will not track together due to systems interactions or hidden dependencies.

The problems of conflicting information arising from multiple casualties, instrument failure, and abnormal local instrument conditions during systems interaction can be mathematically formulated in the following manner:

Let \( G = \{g|g \text{ is a global transient or casualty}\}, \)

\( H = \{h|h \text{ is a local abnormality or failure}\}, \)

\( E = \{0, 1\} \) (event set)

and define maps,

\[ f: G \rightarrow E, \]

\[ k: H \rightarrow E, \]

which map the global and local conditions into the event set. In other words, if casualty \( g_1 \in G \)
has occurred then \( f(g_1) = 1 \), otherwise it is \( g \).

Next, consider

\[ c: f \times f \rightarrow E \]

which maps multiple casualty systems interactions into the event set and

\[ c: f \times k \rightarrow E \]

which maps systems interactions resulting from locally abnormal conditions (or failures) during a global transient (or casualty) into the event set.

The map \( c \) is mod 2 "and" logic according to

\[ \begin{array}{ccc}
0 & 0 & 1 \\
1 & 0 & 1 \\
\end{array} \]

Returning to our earlier considerations, let \( G_1 = \{N, S, F, L, O\} \) be a subset of \( G \). The set \( G_1 \) is open to discussion since \( G_1 \) is by no means complete, but merely illustrative. Let \( H_1 \)

\[ = \{\text{instrument failure, locally abnormal conditions for instrument}\} \]

be a subset of \( H \). Then,

<table>
<thead>
<tr>
<th>TABLE 1. Trial grouping of reactor variables.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j=1 )</td>
</tr>
<tr>
<td>( i=1^a ) Reactor power</td>
</tr>
<tr>
<td>( i=2^a ) Reactor power</td>
</tr>
<tr>
<td>( i=3^b ) Reactor power</td>
</tr>
<tr>
<td>( i=4 ) Primary coolant pressure (loop 1)</td>
</tr>
<tr>
<td>( i=5 ) Primary coolant pumps</td>
</tr>
<tr>
<td>( i=6 ) Reactor containment water level</td>
</tr>
<tr>
<td>( i=7 ) Emergency high pressure injection pumps</td>
</tr>
<tr>
<td>( i=8 ) Turbine condenser vacuum</td>
</tr>
<tr>
<td>( i=9 ) ERV position indication</td>
</tr>
<tr>
<td>( i=10 ) Steam generator level</td>
</tr>
<tr>
<td>( i=11 ) Reactor power</td>
</tr>
<tr>
<td>( i=12 ) Reactor power</td>
</tr>
</tbody>
</table>

\(^a\) Small changes in reactor power due to operator use of control rods (other than scram) are excluded by trend analysis parameter settings.

\(^b\) Charging into the primary with charging pumps could initiate this alarm unless trend analysis parameters are set large enough to exclude this possibility.
c: \( f(G_1) \times f(G_1) \rightarrow \{0, 1\} \) and
c: \( f(G_1) \times k(G_1) \rightarrow \{0, 1\}. \)

Ideally, we might desire
\( c = 1 \) if any two conditions in \( G_1 \times G_1 \)
(with the exception of \( A \times A = A \) types) occurred or one condition in \( G_1 \)
occurred and any instrument failed (or was subject to locally abnormal conditions like a small fire), and
\( c = 0 \) otherwise.

However, we only guarantee that
\( c = 1 \) if certain two conditions in \( G_1 \times G_1 \)
occurred or if one condition in \( G_1 \)
occurred and certain instrument failed (or were subject to locally abnormal conditions), and
\( c = 0 \) otherwise.

When the plant undergoes normal transients, single casualties, or a single instrument fails, 
\( c = 0 \) we rely on the exiting plant design and operator training to cope with the problem. When multiple casualties (a plant transient and a single casualty) or a single casualty coupled with an instrument failure occurs \( c = 1 \) we expect conflicting instrumentation information and we would like an alarm to signal us that a conflict exists and, if possible, some way to resolve the conflict. In our review of transients and casualties, we found some key variables that tracked together. We wish now to make a judicious selection of variables, such that three of them that track together under transient and certain casualty conditions that result from system interactions, will give the operator clues to resolve any conflicts (see Table 1). Then, when the operator receives a conflict alarm \( c = 1 \) he not only becomes aware of the possibility of a multiple casualty, but has immediate clues. For example, the multiple casualty \( (O \text{ and } S) \) will have pressurizer liquid level \( (P_{LL}) \) in conflict with variables it normally tracks with because the reactor protection system will provide a step drop in power causing \( P_{LL} \) to drop and the over-pressure initiating event (causing \( O \)) will cause \( P_{LL} \) to rise rapidly. An alarm system that provided one alarm, indicating \( P_{LL} \) was in conflict with reactor power and \( AS \), would alert the operator of the conflict. A second alarm indicating that \( P_{LL} \) was in conflict with primary coolant pressure would resolve the conflict as an \( S \) and an instrument failure of \( P_{LL} \). The absence of the second alarm would indicate multiple casualty. A simple subroutine for classifying and sorting in a software package tied into the alarm system could have accomplished this task and simply notified the operator of the conclusion.

Our goal is alarm activation whenever \( c = 1 \) to make the operator aware of the especially selected conflicting information and to provide a prearranged indication to resolve the conflict. In the next section, we present a microprocessor system that will alarm under conditions for \( c = 1 \). The selection of variables from Table 1 that track together along with a sort-and-classification software package could then help the operator

\*When an instrument fails under plant steady-state conditions, it usually fails to "safe" range and would not in general provide conflicting information.

3. System Architecture

Figure 3 presents an overview block diagram of the architecture of the system. Three groups of instruments \( (X_{11}, X_{12}, X_{13}) \) are processed by subsystems \((j = 1, 2, 3)\), each of which includes a data acquisition module (Fig. 4) and a microcomputer unit (Fig. 5) that follows, with modifications, the hardware design of Kimura et al.\(^3\) Each subsystem microcomputer receives its own group of sensor readings \((i = 1 \ldots n)\) which have been scanned by the multiplexer (MUX), sampled, and read by the ADC. The subsystem microcomputer takes the sensor reading for each instrument, in turn, and adds it to its own data

![Fig. 3. An overview of the architecture of the system design.](image)

![Fig. 4. The data acquisition unit and ADC.](image)
The signal relations and timing chart using an 8255 for a subsystem microcomputer (A) transferring data to the MM is shown in Kimura et al. and is applicable here. The triplets \( Y_{11}, Y_{12}, Y_{13} \) are variables attached that normally track together. The idiosyncrasies of their tracking during transits are accounted for in the trend analysis subroutine which adjusts for each parameter.

The microcomputers in the three subsystems are required to acquire new data and perform a trend analysis for each instrument to determine if that instrument's parameter is \( Z_{ij} = 1, 0, \) or \(-1\). A sample program flow diagram is present in Fig. 6. The MM will receive one instrument trend value \( Z_{ij} \) from each of the microcomputers and form a

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**Fig. 6.** Program flowchart for each subsystem microcomputer.
if \( Z_{11} = Z_{12} = Z_{13} \) is False, then \( c_1 = 1 \) (there is a conflict and action is taken accordingly).

If multiple triplets indicate conflicts, the MM will sort and classify common parameters for further diagnostic analysis such as deciding if a multiple casualty has occurred and which it might be. Figure 7 gives a program flowchart for the MM. Note that it is a minor complication for us to extend the flowcharts in Figs. 6 and 7 to account for instruments that monitor common variables for redundancy.

4. The TMI-2 Example

Consider the TMI-2 conditions listed in Table 2. The MM would immediately find three triplets indicating conflicts and give an alarm and output indicating that the corresponding parameters were tracking in opposition. It would then be up to the operator to digest this information and conduct further diagnostics, but this information immediately focuses on the questionable pressurizer liquid level. With an extensive listing of instruments and sort-and-classifying subroutines, the helpfulness of this system should be apparent.

5. Conclusions

We have described a design for a microprocessor based, on-line decision aid that could resolve which instruments, if any, are providing false, conflicting, or misleading information during certain systems interactions. We examined multiple-casualty systems interaction and formulated a trial grouping of variables that track together under specified conditions. The microprocessor system follows Kimura et al. and would determine, by a two-of-three vote, when instruments which normally track together, suddenly track in opposition. An alarm and indication would identify the conflict for which the operator should take further action. Such a system would be inexpensive, highly reliable, and provide significant improvement in operator/instrument interfacing by presenting key, partially digested information to the operator.

Acknowledgment

It is a pleasure to acknowledge the valuable criticism and helpful suggestions of Dr. C. Smith and J. Lim.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Indication</th>
<th>( Z_{ij} ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>decreasing</td>
<td>( Z_{31} = -1 )</td>
</tr>
<tr>
<td>Primary coolant ( \Delta T )</td>
<td>decreasing</td>
<td>( Z_{32} = -1 )</td>
</tr>
<tr>
<td>Pressurizer water level</td>
<td>increasing</td>
<td>( Z_{33} = +1 )</td>
</tr>
<tr>
<td>Primary coolant pressure (loop 1)</td>
<td>decreasing</td>
<td>( Z_{41} = -1 )</td>
</tr>
<tr>
<td>Primary coolant pressure (loop 2)</td>
<td>decreasing</td>
<td>( Z_{42} = -1 )</td>
</tr>
<tr>
<td>Pressurizer liquid level</td>
<td>increasing</td>
<td>( Z_{43} = +1 )</td>
</tr>
<tr>
<td>ERV position</td>
<td>shut</td>
<td>( Z_{91} = -1 )</td>
</tr>
<tr>
<td>ERV tailpipe temperature</td>
<td>increasing</td>
<td>( Z_{92} = +1 )</td>
</tr>
<tr>
<td>Pressurizer high level alarm</td>
<td>on</td>
<td>( Z_{93} = +1 )</td>
</tr>
</tbody>
</table>
References


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