Abnormal transient operating procedures for nuclear power plants

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The aims, objectives and methodology involved in producing abnormal transient operating procedures for nuclear power plants were discussed in detail at the American Power Conference in April, 1980.* Abnormal Transient Operating Guidelines now exist in draft form for Arkansas Power and Light, and it is possible to detail a truly symptom-oriented approach to transient management. Using this approach, the operator does not have to immediately diagnose the initiating casualty and locate the event-specific procedure for that casualty. Instead, the operator can pick up and use one simple procedure for all transients starting with a reactor trip. This paper describes the approach and provides several examples of the simplified decision making process now available to the operator. Also discussed is one possible approach to implementing these new guidelines into the existing procedure structure.

Background

The traditional approach to transient and accident control has been to develop many "emergency" procedures, each based on a postulated event such as loss of main feedwater. The operator is then required to study this event and memorize its symptoms and immediate actions. If a loss of feedwater occurs, he is expected to recognize it, perform the appropriate immediate actions, and then use the event-oriented loss-of-feedwater procedure for determining follow-up actions. This approach has several inherent drawbacks:

1. At time zero, the operator must correctly diagnose the initiating event. He does this mentally, based on training or prior experience. After taking several actions, depending on this instant evaluation, he then refers to the event-oriented procedure that fits his diagnosis. If he were to treat a small steam line break inside the reactor building, but actually had a small loss of coolant accident (LOCA) inside the building, he would be tracking through the wrong procedure. He would eventually recognize this misinterpretation; however, by then he would be well into the transient and possibly confused.
2. Procedures must be written to cover every conceivable initiating event. If the operator correctly diagnoses a loss of nonnuclear instrumentation power and no procedure covers that event, his actions will be based only on experience.
3. If more than one event contributes to the transient, the operator will find himself working two or more procedures *at the same time.* For instance, if a main steam safety valve failed to reseat following the loss of main feedwater, the operator would have to use the loss of feedwater

*"Engineering basis for operator control of nuclear power stations in abnormal operations — closing the loop," E. A. Womack, J. J. Kelly, and N. S. Elliott, American Power Conference, Chicago, Illinois, April 21-23, 1980 (Babcock & Wilcox BR-1151).

procedure and small-steam-line-break procedure (if available). These procedures may conflict and he would have to decide a priority between them — with no convenient method of shifting between the two procedures. Writing a procedure to combine these two events is possible; however, if just a few more failures are considered (e.g., the power-operated relief valve or spray valve remains open), the number of combinations of failures, along with possible initiating events, quickly increases. Even if writing the appropriate procedures was attempted, the operator's ability to pick the correct procedure would certainly diminish.

4. Because of these limitations, most operators are likely to use no specific procedure. They will use training, experience, intuition, etc., to bring the plant under control. They will then choose what they think is the closest procedure to what is happening and confirm their actions or see if they overlooked anything.

To correct these deficiencies, it is necessary to step back from the traditional approach and examine what the operator is attempting to do during reactor posttrip abnormal transient control. He can best protect the health and safety of the public by guarding the integrity of the core. To do this he must ensure the continuous removal of decay heat from the fission products to the ultimate heat sink. By adjusting the priorities and concentrating efforts on maintaining proper heat transfer along this path, he can protect the core and minimize radioactive release. To give the operator this capability, a concept of symptom-oriented (as opposed to event-oriented) procedures was investigated. The symptoms are based on upsets in heat transfer from the core to the coolant and from the coolant to the steam generators. The symptom-oriented procedures thus focus on core cooling first and on event identification second. The result of this investigation is the Abnormal Transient Operating Guidelines (ATOG).

Expected plant response

To produce a symptom-oriented procedure, B&W developed a thorough understanding of expected plant responses during many varied abnormal transients. These transients included classic singular initiating events as well as additional single and multiple component failures. The procedure was developed through the following steps (usually in parallel):

1. Existing plant casualty procedures were investigated for common symptoms. Few single alarms or parameters were found to uniquely identify a transient. Similarly, some parameters were common to *all* transients. One event found throughout the study was a reactor trip. Consequently, it was used as the key for entering the abnormal guidelines procedure.
2. Event trees for various initiating events* and consequential failures were developed. These included various multiple failures (including operator error), and therefore covered a large number of possible scenarios. Event trees were studied to find repetitive patterns and common end points. The study showed that although many failures can occur, the symptoms of unbalanced heat transfer that result from these failures followed a few common patterns or trends.
3. Actual operating transients were investigated, again looking for patterns. This time the emphasis was on parameter trends and the time available for operator action.
4. Where necessary, computer simulations were run to complete the baseline and fill in gaps in understanding plant response. Because the output was intended for use in developing operating guidelines, realistic input was used (as opposed to bounding safety analysis assumptions).

This investigation's conclusion was that the operator can track the removal of decay heat from the core to the ultimate heat sink by monitoring just a few symptoms which reflect the "health" of the thermodynamic process around the reactor coolant system and its coupling to the secondary side.

Symptoms identified

The three symptoms of primary interest to the pressurized water reactor (PWR) operator are adequate subcooling of the primary system inventory, inadequate primary-to-secondary heat transfer, and excessive primary-to-secondary heat transfer. These symptoms are important for the following reasons:

1. Adequate primary inventory subcooling. If the operator knows the primary fluid is in a liquid state, he is assured that it is available and capable of removing heat from the core and transferring it to the steam generators. If subcooling is lost, these issues are in doubt, and he is therefore directed to make every effort to regain subcooling.

*Included as initiating events were loss of main feedwater, loss of offsite power, excessive main feedwater, small steam line break, and steam generator tube rupture.

2. Inadequate primary-to-secondary heat transfer. This symptom addresses the heat transfer coupling across the steam generators. It describes the ability of the system to keep the flow of energy moving from the reactor coolant system to the ultimate heat sink. The operator monitors the relationship between the reactor coolant cold leg temperature and steam generator secondary side saturation temperature. Following a reactor trip, these two values should be nearly equal under good heat transfer conditions. If this coupling is broken, the procedure outlines appropriate corrective actions to restore it.
3. Excessive primary-to-secondary heat transfer. In this case, the symptom is indicative of a secondary side malfunction (e.g., loss of steam pressure control or steam generator overfill). The heat transfer is again unbalanced and the operator's attention is directed toward generic actions to restore this balance.

By tracking these basic symptoms the operator can quickly focus on problems without checking a large number of parameters. At the same time, by their nature the symptoms allow rapid elimination of problem sources and continue to emphasize core protection. Additionally, the symptoms are so basic that the procedure inherently covers many more initiating events than those first studied. This happens because initiating events cause equipment to fail, and equipment failures affect these symptoms. As the operator follows the procedure to treat the symptom he will probably identify and correct the cause.

ATOG display

The information required to identify and track these symptoms is already available in power plant control rooms. It simply consists of reactor coolant system hot and cold leg temperatures, reactor coolant system pressure, steam generator pressure, and access to steam tables. The problem is how these variables can be best displayed to give the operator a simple and logical method of monitoring the symptoms of interest. The solution developed in the ATOG is shown in Figure 1, which is basically a pressure-temperature (P-T) display with a saturation curve included. The area above and to the left of this curve is the subcooled region. The area below and to the right is the superheated region. Reactor coolant system hot leg temperature (T_{hot}) and cold leg temperature (T_{cold}) are input to this display and plotted as functions of reactor coolant system pressure. Steam generator pressure

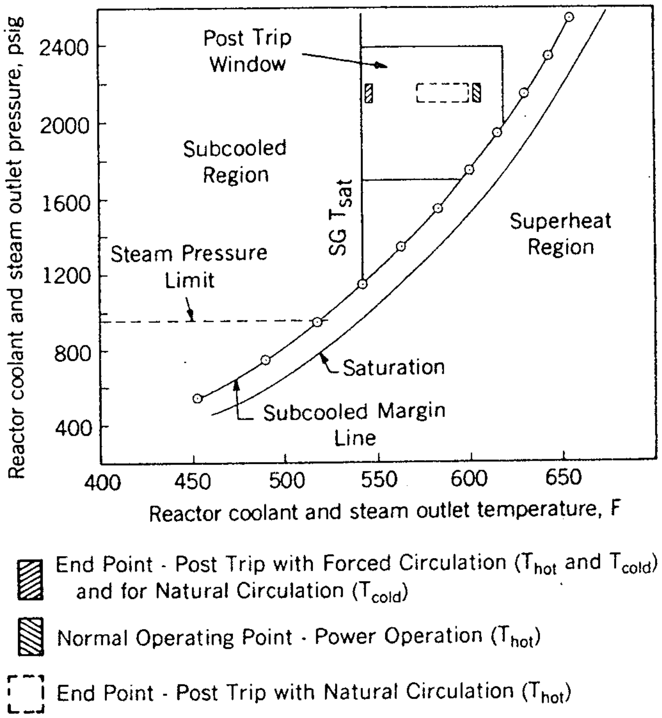

Figure 1 Basic pressure-temperature (P-T) display

is also input. The saturation temperature for this input pressure is displayed as a vertical line. The subcooled margin line accounts for potential instrumentation inaccuracies with the objective of assuring subcooling above that line.

A typical plant response to a reactor trip is shown in Figure 2. For simplicity, only reactor

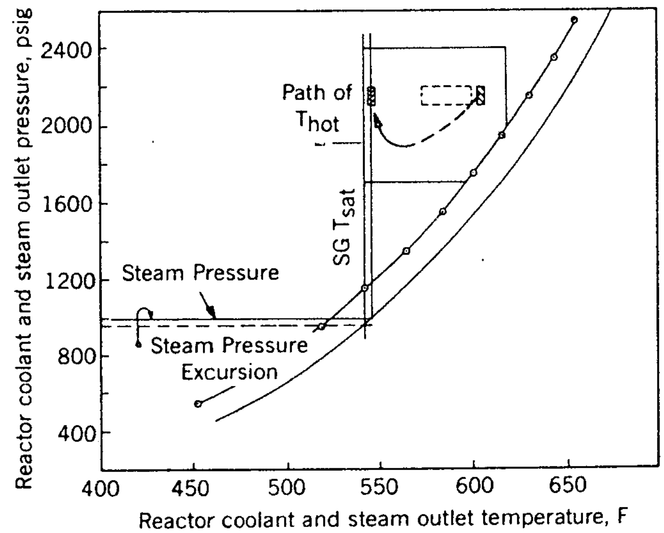

Figure 2 Typical posttrip response

coolant hot leg temperature is plotted. With the reactor coolant pumps running (forced circulation) and the comparatively small amount of energy being added to the coolant by decay heat, the cold leg temperature is also expected to settle out close to this hot leg temperature. Additionally, because the ΔT across the steam generator tubes is small, both of these temperatures should approach the saturation temperature of the secondary side of the steam generator (SG T_{sat}). The Figure also shows steam pressure moving from its pretrip value up to the steam safety valve setpoint and back to its

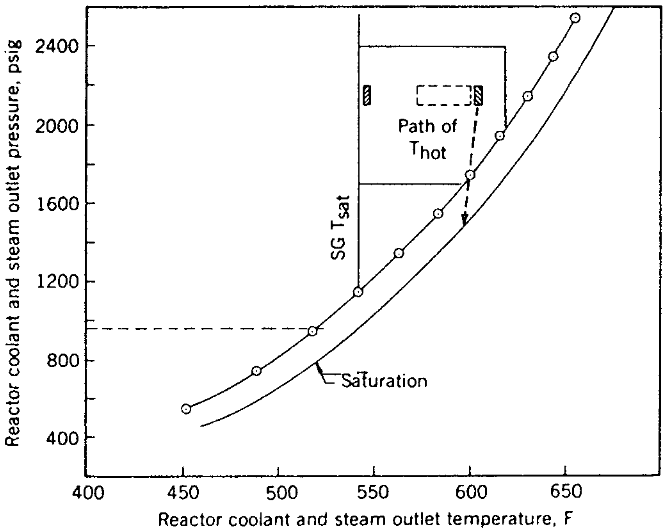

Figure 3A Inadequate subcooling margin: T_{hot} is not progressing toward its target value; in fact, it has rapidly dropped through the subcooled margin line. This condition is diagnosed as loss of adequate primary inventory subcooling, or simply "inadequate subcooling margin," and the procedure is written with directions to take care of inadequate subcooling margin.

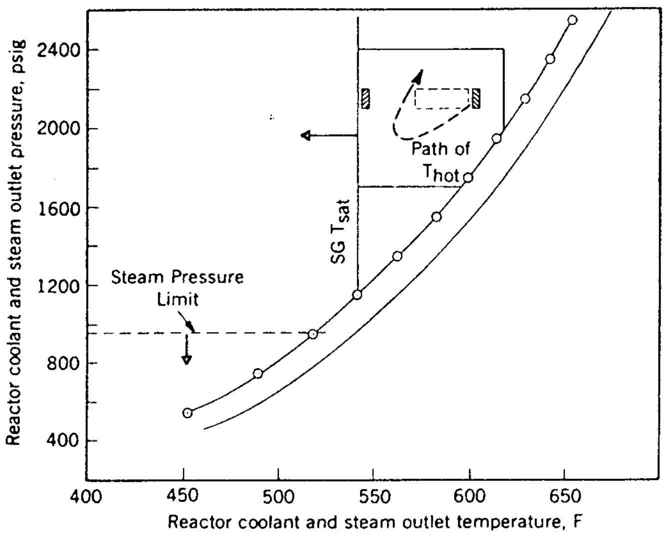

Figure 3B Loss of primary-to-secondary heat transfer: T_{hot} is increasing as SG T_{sat} is decreasing. A ΔT between the two is growing larger. The secondary is no longer removing heat and has lost coupling with the primary. This condition is diagnosed and treated as loss of (inadequate) primary-to-secondary heat transfer.

posttrip value. As long as T_{hot}, T_{cold}, and SG T_{sat} remain within a "posttrip window," the plant is responding normally.

With this type of display, the symptoms of interest are highlighted and brought into focus for the operator. Consider the example in Figure 3.

Combinations of these symptoms are also easily

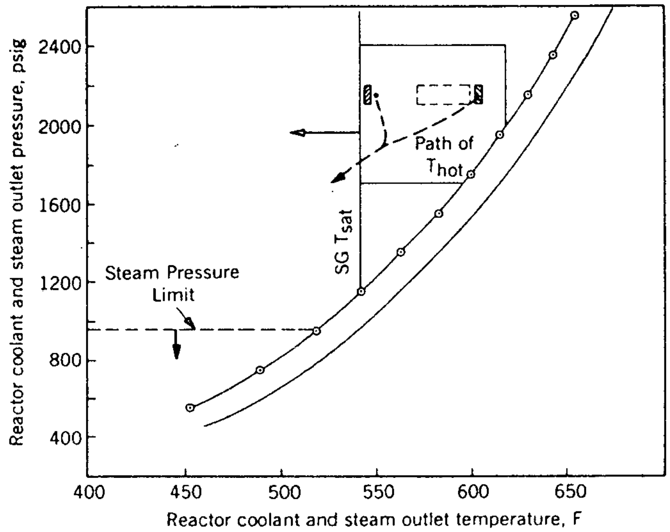

Figure 3C Excessive primary-to-secondary heat transfer: SG T_{sat} has decreased below its established limit. T_{hot} and T_{cold} have reached equal values but both have gone out of the posttrip window following SG T_{sat}. This condition is diagnosed and treated as excessive primary-to-secondary heat transfer.

recognized. Consider the example in Figure 4, taken from the first twenty minutes of the TMI-2 transient.

As shown by these examples, the symptoms of interest can be combined simply and displayed on a cathode ray tube. With a relatively few number of input variables, the operator can monitor the real-time progression of the transient. If one such display is used for each reactor coolant system loop (because of possible asymmetric loop conditions), the operator has a continuous, complete record of the entire event. This record allows initial diagnosis, positive feedback on corrective actions, and early detection of subsequent malfunctions.

Other display arrangements of basically the same fundamental parameters have been developed with similar effectiveness, still relying on basic patterns of parametric change to indicate an overall plant bill of health.

ATOG organization

Once the symptoms are identified and a method of monitoring those symptoms developed, the next step is to reduce this information into something

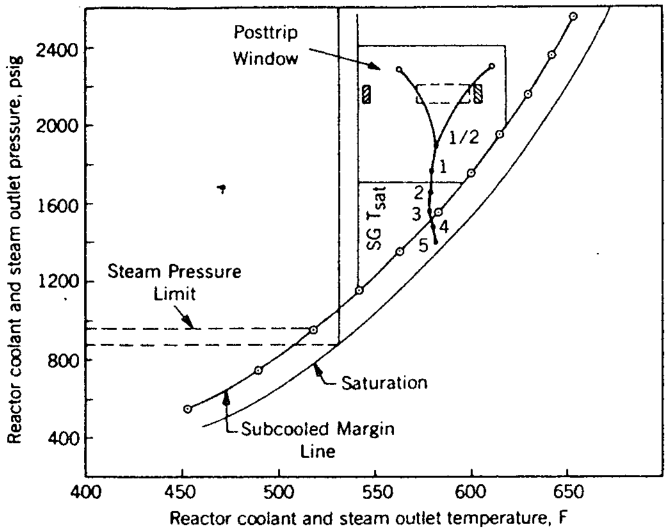

Figure 4A 0 to 5 minutes:
At time zero the reactor has tripped on loss of feedwater. At ½ minute T_{hot} and T_{cold} are essentially the same temperature. At 2½ minutes the ESFAS pressure setpoint is reached and high pressure injection (HPI) is automatically started. At 3½ minutes subcooling margin is lost, and at 4½ minutes the operator stops HPI. By the time 5 minutes have elapsed the RCS is beginning to heat up. Secondary pressure and temperature are below limits. The primary-to-secondary ΔT is ~50 F.

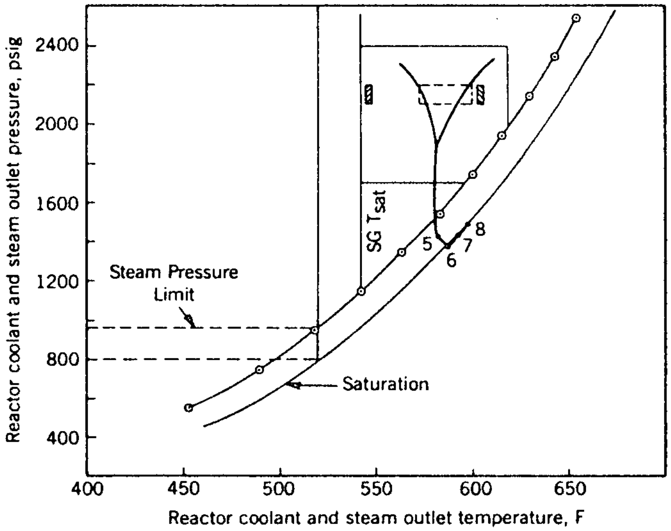

Figure 4B 5 to 8 minutes:
The primary continues to heat up along the saturation line while secondary temperature and pressure drop. At 8 minutes the primary-to-secondary ΔT ~80 degrees. Also, auxiliary feedwater is first directed to the steam generators.

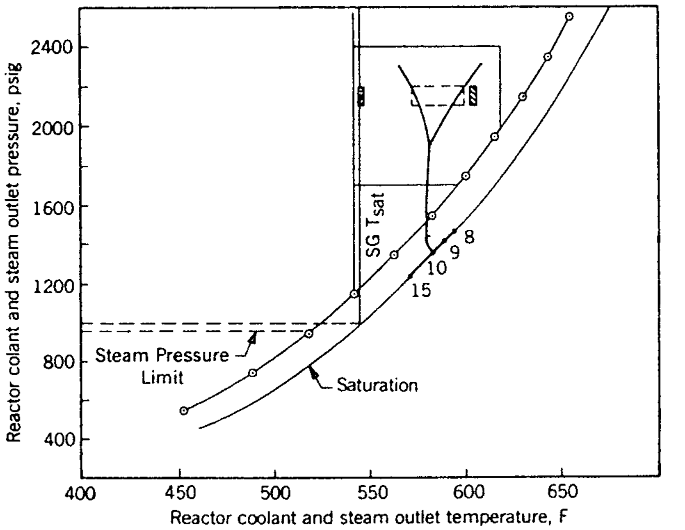

Figure 4C 8 to 15 minutes:
Steam pressure and temperature have recovered to their normal posttrip values. A substantial cooling of the primary is also in progress.

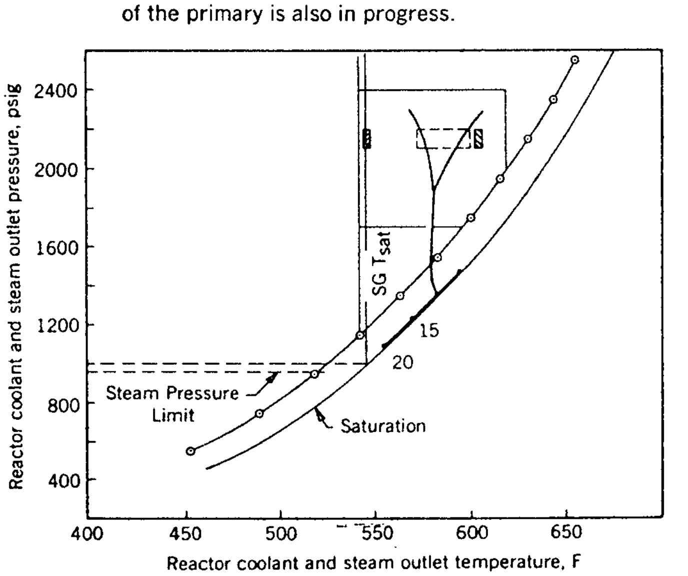

Figure 4D 15 to 20 minutes:
Primary-to-secondary heat transfer (coupling) is now almost completely restored. T_{hot} and T_{cold} are approaching their normal posttrip values. However, the inadequate subcooling margin is evident.

useful to the operator. The Abnormal Transient Operating Guidelines consist of two parts. The first part is procedural guidance to be used in the control room during transients. The second part, a much larger volume, is a training aid explaining the design bases for, and the use of, the procedures.

Figure 5 outlines the organization of Part I. The immediate actions are common to every reactor trip and must be performed regardless of the cause. The vital system status verification is a short checklist used to determine a baseline for possible operator actions. This checklist considers instrumentation power supplies, engineered safety features activation system (ESFAS) status, steam line break protection system status, etc. Included in this checklist is a requirement to monitor the ATOG display. If everything is normal, the plant has

Section I
Immediate Actions

Section II
Vital system status verification

Section III
A. Treatment of lack of adequate subcooling margin
B. Treatment of lack of primary-to-secondary heat transfer
C. Treatment of too much primary-to-secondary heat transfer

Cooldown procedures
- Large LOCA
- Normal
- Saturated RCS
- HPI cooling
- Solid water cooldown

Figure 5 ATOG — organization of Part I

responded as designed and come to a steady post-trip condition. No further action is required. However, if the operator diagnoses an imbalance in one of the basic symptoms, he is directed to the appropriate section for follow-up actions. These sections treat the symptoms and do not require the operator to determine the cause. It is expected, however, that as he treats the symptoms he will find the original problem.

Treating the symptoms will allow returning the plant to a stable condition. This stable condition could very well be abnormal compared to what the operator normally sees. Accordingly, various cooldown procedures are provided to give him guidance on long-term recovery from these possible conditions.

Figure 6 outlines the organization of Part II. Intended to give the operator a thorough understanding of Part I, it conveys the writer's intent as to *why* various steps are taken in Part I. It also describes, using many graphic examples, the expected plant response information gathered during the guideline development stage. Part II has been written to aid the operator's training and is important to the guidelines because an intelligent, capable operator is a basic part of the plant operating structure in which the guidelines are built (i.e., the guidelines try to optimize the operator's effectiveness instead of minimizing his impact).

Volume 1
Fundamentals of reactor control for abnormal transients
A. Heat transfer
B. Use of P-T diagram
C. Abnormal transient diagnosis and mitigation
D. Backup cooling methods
E. Best methods of equipment operation
F. Stability determination

Volume 2
Appendices — selected transients
A. Excessive feedwater
B. Loss of feedwater
C. Steam generator tube rupture
D. Loss of off-site power
E. Small steam line break
F. LOCA

Figure 6 ATOG — organization of Part II

Guideline validation

Once written, the potential guidelines were tested on a PWR simulator by imposing multiple casualties and using the guidelines to recover. Guideline credibility was also established by back checking the guidelines against event tree paths and benchmarking event tree paths and computer simulations against actual plant transients. The event trees were also reviewed by the utility operators to take advantage of their plant experience. The draft guidelines were sent to the plant site for walk-through drills to test their applicability. Feedback from the operator to the plant designer served to greatly reduce communication errors and increase confidence in the final guidelines.

An important final step in validation involves implementing the guidelines into the plant procedures system. This implementation tests the guidelines' scope and appropriateness since they must be a workable part of the overall plant procedures system or their worth diminishes. Existing posttrip procedures must be checked against the guidelines to determine the following:

1. Necessary actions outside the development program scope but needed for a posttrip procedure in the same time frame. This assures that, although everything may not be considered, the adoption of ATOG does not decrease in any area the adequacy of procedures from the previous level. Some actions in the previous procedures may be found good but not *necessary,* and either be deleted or relegated to a lower level of instruction. The goal is to maximize simplicity.
2. Actions that should be included in an instruction for longer term action. Current posttrip procedures include many necessary follow-up actions that are not appropriate for ATOG, but must be included somewhere. Three actions, identification of these items, determination of the form in which they should be given, and optimization of the interface between the form in

which they are given and the ATOG, are necessary to make ATOG a workable part of the overall plant procedure system. Again, the goal is to maximize simplicity.

3. Any posttrip procedures not accommodated by ATOG, but which must remain intact. One goal of ATOG is to eliminate these procedures, but that goal has not yet been proven consistently attainable. Any such procedures identified must be entered in a manner compatible with ATOG implementation.

Although plant procedures vary from plant to plant, preliminary work indicates that portions of all of the procedures, such as the following, may be replaced by the ATOG:

- Reactor-turbine trip
- Degraded electrical power
- Loss of coolant/RC pressure
- Steam supply system rupture
- Loss of steam generator feedwater
- Steam generator tube rupture
- Loss of reactor cooling flow - RCP trip

Summary

By using the Abnormal Transient Operating Guidelines, the operator can enhance plant safety by monitoring reactor posttrip parameters for only a small number of symptoms and taking corrective action as directed by the procedure. The guidelines allow him to use one simple procedure for *all* transients which start with a reactor trip. The unique feature of this approach is that it provides a common starting point, independent of initiating event, and leads the operator through a step-by-step procedure to regain stable plant conditions without having to identify either the cause of the transient or any additional posttrip malfunctions.