ANALYSIS OF FEEDWATER TRANSIENT SEQUENCES IN B&W NUCLEAR STEAM SUPPLY SYSTEMS

C. Abbott, J. Bickel & W. E. Kastenberg
ACRS Fellows

I. INTRODUCTION

This study uses event tree analysis, and existing WASH-1400 methodology and data to determine various sequence probabilities for three different events which have occurred in plants with a B&W Nuclear Steam Supply System. The events evaluated are the March 29, 1979 Accident at Three Mile Island (TMI), the March 30, 1978 Loss of Instrument Power Transient at Rancho Seco (RS) and the September 24, 1977 Depressurization Transient at Davis Besse (DB). The sequence of events at RS and DB are given in Appendix A. The events are generically classified as loss of main feedwater. The TMI and DB events are similar in that the sequence of events (i.e., the separate plant and operator actions) are comparable up to the point of the operator manually blocking the power operated relief valve (PORV). The RS event is similar only in that the initiating event resulted in a loss of main feedwater. The plant and operator actions, however, are different from TMI and DB.

In the first part of this memo, a heuristic analysis of feedwater transients in B&W plants prior to TMI is given. This is followed by an analysis using the data, event trees and sequences contained in WASH-1400 for the S2 small break LOCA (break diameter $\leq$2") and for the T-transient.* It must be recognized, however, that WASH-1400 utilzes event sequences characteristic of the Westinghouse Nuclear Steam Supply System and its associated protective and engineered safeguard systems. In the last part of the study, we develop a feedwater transient

---

* A glossary of abbreviations is given in Table I (page 3).

8012020804

event tree sequence unique to B&W plants valid prior to April 1979. This tree is applicable to B&W plants where the PORV is designed to lift prior to RPS trip during a feedwater transient.

TABLE I

GLOSSARY OF TERMS

AFWS - Auxiliary Feedwater System

CHRS - Containment Heat Removal System

CSIS - Containment Spray Injection System

CSRS - Containment Spray Recirculation System

CVCS - Chemical Volume Control System

ECI - Emergency Coolant Injection

ECR - Emergency Coolant Recirculation

EP - Electric Power

DB - Davis Besse

ICS - Integrated Control System

HPIS - High Pressue Injection System

LOCA - Loss of Coolant Accident

NNI-Y - non-nuclear instrumentation power bus Y. (power supply for instruments not associated with the determining of the fission rate in the core)

PCS - Power Conversion System

PORV - Power (or pilot) operated relief valve

Psi - Pounds per square inch

P_X - probability of failure for system X. (e.g., P_k = probability the RPS system fails to insert the reactor's control rods)

PWR - Pressurized Water Reactors

RCS - Reactor Coolant System

RHRS - Residual Heat Removal System

RPS - Reactor Protective System

RS - Rancho Seco

S2 - small break LOCA event tree of WASH-1400 for a PWR

SFRCS - Steam Feedwater Rupture Control System

SHA - Sodium Hydroxide Addition

SR - Safety Relief

SSR - Secondary Steam Relief

T - Transient Event Tree of WASH-1400 for a PWR

TE - Transient Event

TMI - Three Mile Island

VO - Valve Opens

VR - Valve Recloses

WASH-1400 - The Reactor Safety Study NUREG-75/014.

II. HEURISTIC ANALYSIS OF B&W FEEDWATER TRANSIENTS

As stated above, the sequence of events at Davis Besse (DB) and Rancho Seco (RS) are given in Appendix A. The Three Mile Island (TMI) accident is similar to the DB transient up to the last event where the stuck open PORV is isolated at DB but not at TMI. As discussed later in this development, the time frames are however, somewhat different.

Examination of the sequences given in Appendix A yields the following heuristic analysis:

1. The events for TMI and DB are determined by: a) the frequency of feedwater transients in PWRs ~ 3 per reactor year, b) the fact that in B&W plants prior to April 1979, a feedwater transient causes the PORV to open independent of AFWS operation, and c) failure of the PORV to close (3×10^{-2} per demand). Hence this family of transients would be initiated on the order of 9×10^{-2} per reactor year.

2. The eventual outcome of this sequence depends upon a) whether or not the PORV is gagged at the time of transient initiation (50% of the time it is), b) operator action in not interrupting the HPIS, and c) isolating the PORV if it fails to close.

3. For DB the PORV was not gagged, the operator interrupted the HPIS and did isolate the PORV. In order to estimate the frequency of the outcome, the probability of these three events must be obtained. A telephone survey of B&W plants by the authors revealed that the PORV is gagged 50% of the

time. The operator action is more difficult to obtain. WASH-1400 (Appendix III) states that the probability of operator failure under stress is:

0.9 - 5 minutes after a large LOCA

0.1 - 30 minutes after a large LOCA

0.01 - several hours later

The average error rate, in a high stress situation is given as 0.2 to 0.3.

In addition, if P is the probability of operator error, and the number of people present is n, then P^n is given as the probability of a collective error. In practice, the final decision rests with the shift supervisor so that n can vary between 1 and 3 depending on his influence. (See Appendix B)

One problem (among others) in using this data is that it is not clear that the operator made an error in defeating the HPIS. That is, the procedure followed called for interruption of HPIS with high level indicated in the pressurizer. In that case, it may have been the procedure that was in error, and the operators failed to recognize it.

Using a probability of 0.5 for the chance of a gagged PORV, $(0.3)^3 = 0.027$ for defeating the HPIS after several minutes, and using $1-(0.1)^3 = .999$ for successfully blocking the PORV at 20 minutes yields a frequency for DB

$$DB = (9x10^{-2})(0.5)(0.027)(0.999) = 1.2x10^{-3}$$

4. At TMI, the PORV was not gagged, the operator interrupted the HPIS and the PORV was not isolated. Since the decay heat load was greater at TMI than DB, the failure to block the PORV occurred sooner. The operator

should have recognized that the PORV had stuck open by the time the quench tank rupture disk blew (about 15 minutes into the transient). This yields an estimate of the error probability of $(.5)^3$. Hence at TMI

$$TMI = (9x10^{-2})\ (0.5)(0.027)(.125) = 1.5x10^{-4}$$

5. For Rancho Seco (RS), the initiating event (loss of non-nuclear instrumentation) was estimated to be $8.6x10^{-3}$ per reactor year*. Since this loss initiated the feedwater transient, this value is used, rather than the 3 per reactor year used for DB and TMI.

   Since the PORV was gagged (0.5), the operators throttled the HPIS (0.027) and the code safety valves opened and closed as required (1.0), the frequency of this event is estimated as

   $$RS = (8.6x10^{-3})(0.5)(0.027) = 1.2x10^{-4}$$

   In the next section, an attempt is made to map these events on the WASH-1400 event trees.

---

*/ Because of the difficulty in estimating the specific failure of the non-nuclear instrumentation (NNI-Y) power supply in the absence of a detailed fault tree analysis, the failure rate for low power, solid state devices was used. It should be noted that the final result is very sensitive to this failure rate and should be viewed as representing the family of NNI failures.

III. WASH-1400 EVENT TREES

In this section, we have attempted to trace the Davis-Besse (DB), Rancho-Seco (RS) and Three Mile Island (TMI) events on the WASH-1400 Transient (T) and Small Break LOCA (S2) event trees shown in Figures 1 and 2. Mapping the sequences occurring at DB and RS on the WASH-1400 T tree without any modification yields sequence TM, which does not result in core melt, and was subsequently omitted from the dominant risk sequences in WASH-1400. Mapping TMI on the T tree yields: (a) sequence TMLQU if no credit is given for the return of the Auxiliary Feedwater System (AFWS) or TMU if credit is given for AFWS. Both paths do not give credit for actuation of the High Pressure Injection System (HPIS). With HPIS actuation, the corresponding paths are TM and TMLQ (See Figure 1). Several problems arise when trying to evaluate these events in terms of this event tree. For the DB and RS events, sequence TM does not differentiate between the failure of the PORV to close at DB and the initially gagged PORV at RS. Second, the sequence is for all transient initiated events and hence does not identify the initial loss of non-nuclear instrumentation (power bus NNI-Y) induced by human action which resulted in the feedwater transient and in the loss of indicators during the transient at RS. Lastly, for DB and TMI, the tree fails to include the fact that the PORV will lift regardless of the availability of the auxillary feedwater supply in B&W plants, and, therefore, neglects the possibility that the PORV fails to close.

For the DB and RS events, the frequency of sequence TM for all feedwater transients would be given by:

$$P_{TM} = P_T \ (1-P_K) \ P_M \ (1-P_Q) \ (1-P_U) \ (1-P_W).$$

Based on WASH 1400 data, P_T = 3 feedwater transients per reactor year, $P_M = 1$ (failure to recover the main feedwater system within minutes) and assuming $(1-P_i) = 1$ we obtain

P_{TM} = 3 per reactor year.

For TMI, the appropriate sequence (taking into account the return of the AFWS) is TMU with

$$P_{TMU} = P_T\ (1-P_K)\ P_M\ (1-P_Q)\ P_U$$

Hence $P_{TMU} = 3 \times P_U$ per reactor year where P_U is the unavailability of the HPIS. Since HPIS was available, but the operators interrupted its operation, P_U is chosen as $(0.3)^3$ which is in the range of WASH-1400 numbers for operator error. Hence for this sequence

$$P_{TMU} = 8.1 \times 10^{-2} \text{ per reactor year.}$$

Again, this tree neglects failure of the PORV to close.

In WASH-1400, it is suggested that transients, for which the PORV fails to close, should be treated as a small break LOCA, and the event tree S2 be used (Figure 2). Since the LOCA is terminated at both DB and RS, (the PORV is finally blocked at DB and the code safety valve reseats at RS), these events become sequence S_2 with a frequency of 3 per year.

Mapping the TMI event on the small break LOCA tree yields sequence S_2D. The initiating frequency S2 is given by

S2 = 3 feedwater transients/year x 10^{-2} failure to close/demand *

= 3 x 10^{-2} S2 events/yr.

Using a HPIS unavailability of $(0.3)^3$ due to operator error, TMI becomes

$$P_{TMI} = 8.1 \times 10^{-4}\text{/year}$$

Failure to block the PORV is not included in the tree and the PORV failure to close on demand number comes from Appendix V, page V-38 of WASH-1400.

---

* WASH-1400 states this number has an error factor of 10.

For the particular feedwater transient at Rancho Seco, the probability of loss of non-nuclear instrumentation (which led to loss of feedwater) and the probability that the loss was attributable to human error should be obtained.

Data from WASH-1400 on loss of non-nuclear instrumentation is about 8.6 x 10^{-3}/reactor year. Hence the Rancho Seco initiating event may be on the order of 8.6 x 10^{-3}/reactor year.

IV. APPLICATION OF A B&W EVENT TREE TO TMI, DB AND RS

A unique event tree was developed for feedwater transients in B&W plants which is different from those used in WASH-1400. The differences between the WASH-1400 - PWR and the B&W PWR were described in Section III.

The sequence of events at TMI is well known and not presented here. The events follow along sequence #5 on the attached event tree and are self-explanatory (Figure 3). The sequence of events for Davis Besse follows sequence #6 on the event tree. The sequence of events for Rancho Seco follows sequence #14 on the event tree.

The probabilities and failure rate data shown below were obtained from WASH-1400 except for those marked with * and **. The uncertainty in P_Q, and P_Q were also obtained from B&W data. The uncertainty in the other probabilities are difficult to obtain because they depend on human errors, operating procedures, etc., and have not been ascertained. Hence, the final results could have large error bounds.

The probabilities for the significant events in the event tree are:

P_T - 3 per reactor year (WASH-1400, Appendix V, pg. V-34)

* $P_P = .5$

** $P_{Q'} = 3 \times 10_{-2}$ $(\pm 1 \times 10^{-2})$

$P_Q = 3 \times 10^{-2}$ $(\pm 1 \times 10^{-2})$

$P_{U'} = (.3)^3$ (WASH-1400, Appendix III, page III-60)

$P_{Q''} = (.5)^3$ " " " " " " (for TMI)

$P_{Q''} = (.1)^3$ " " " " " " (for DB)

For TMI the probability is as follows:

$$P_{TMI} = P_T \times P_U \times (P_Q) \times (P_{U'}) \times (P_{Q''})$$
$$= 3 \times .5 \times 3 \times 10^{-2} \times (.3)^3 (.5)^3$$
$$= 1.5 \times 10^{-4}/\text{year}$$

For DB the probability is as follows:

$$P_{DB} = P_T \times P_P \times P_Q \times (P_{U'}) \times (1-P_{Q''})$$
$$= 3 \times .5 \times (3 \times 10^{-2}) \times (0.3) \times (1-(.1)^3)$$
$$= 1.2 \times 10^{-3}/\text{year}$$

For the Rancho Seco event, the probability of the loss of an instrument bus leading to a feedwater transient must be used for P_T. Using WASH-1400 data, the failure rate of low power solid state devices is:

1×10^{-6}/hr or 8.6×10^{-3} per year.

---

* The P_P value was obtained from a telephone survey of B&W plants and their estimate of the frequency of defeating the PORV by blocking or gagging.

** Obtained from B&W

The probability of the RS family of events is then estimated as

$$P_{RS} = P_{NNI} \times P_P \times P_{U'}$$
$$= 8.6 \times 10^{-3} \times .5 \times (.3)^3$$
$$= 1.2 \times 10^{-4} \text{ per reactor year.}$$

These results are summarized as follows:.

TABLE II.

	WASH-1400		B&W
	T	S_2	Feedwater Transient
TMI	8.1×10^{-2}	8.1×10^{-4}	1.5×10^{-4}
DB	3	*	1.2×10^{-3}
RS	8.6×10^{-3}	*	1.2×10^{-4}

It is important to recognize that the largest uncertainty is in characterization of operator action. WASH-1400 states that if P is the probability of operator error, then P^n is the probability of error if the number of personnel in the control room is n. Because of the supervisory nature of the shift supervisor, the probability may be between P and P^n. This report uses .3 for HPIS unavailability as an average for the initial one-half hour for all three sequences. Failure to block the PORV is given a probability at .5 at fifteen minutes and .1 at thirty minutes. This report does not evaluate in detail the resultant error in the calculations because of a lack of data on operator action. The values chosen are considered to be within the ranges of WASH-1400, and consistent with the methodology.

---

*Does not apply.

V. CONCLUSIONS

After mapping the TMI, DB and RS events on the WASH-1400 Transient and Small Break LOCA trees, constructing an event tree for B&W Feedwater Transients, and employing the WASH-1400 data, the following is concluded:

1. As shown in Table II, the values obtained from a B&W transient tree differ from those obtained from the T and S_2 event trees in WASH-1400 because the latter trees do not include the necessary features as discussed above.

   As noted in Section II, the WASH-1400 event trees cannot be used since the PORV lifts during a feedwater transient. This clearly shows that the strict use of these event trees to other PWRs yield erroneous results. This should be obvious because the trees in WASH-1400 are unique to the Surry Plant which is a Westinghouse PWR.

   The values obtained above could have been obtained prior to the event sequences discussed because the data, knowledge of the transients and methodology were known. The only requirement to complete a similar study would have been development of a unique event tree for B&W plants.

2. The consequences of these sequences of events depend upon the exposure history of the core. At DB, the plant was operating at low power with fresh fuel. At TMI, the plant was operating at full power well into the fuel cycle. The time allowed to block the PORV and for re-initiating HPSI before the core is uncovered was different in each case. These time differences are reflected in the characterization of operator action.

3. The NRC will construct event and fault trees for individual plants under the Integrated Reliability Evaluation Program (IREP). The individual licensees, however, could easily perform similar studies using available failure rate data and developing a unique event tree for their respective plants. This would immediately focus upon needed areas of improvement in operations and provide an independent check to IREP.

APPENDIX A

Sequence of Events

The sequence of events for Davis Besse is:

- T - A spurious initiation of Steam Feedwater Rupture Control System (SFRCS) isolates the steam generators and starts the auxiliary feedwater pumps.
- P - The pressure rise in the primary system causes the Power Operated Relief Valve (PORV) to open.
- K - The control room operator manually trips the re: .or because the pressurizer level is outside (high) of the operating range.
- L - Both auxiliary feedwater pumps start but only one feeds a generator due to binding in the throttle linkage in the other pump's turbine control system.
- P;Q- Code safety valves do not lif' as the PORV is relieving reactor coolant pressure.
- Q - The PORV "simmers" due to a missing relay in the closing circuit and after nine cycles it sticks open.
- U - Safety Features Actuation System (SFAS) initiation on low RCS pressure starts the HPI pumps.
- U'- The operator cycles the HPI pumps to maintain pressurizer level.
- Q"- The operators recognize that the PORV is stuck open and shut the block valve.

The sequence of events for Rancho Seco is:

- T - The loss of one of the two non-nuclear instrumentation fuses (NNI-Y) causes the Integrated Control System (ICS) to sense a loss of BTU output and isolates the feedwater system.

P - The primary system pressure rise would have caused the PORV to open but it was gagged shut.

K - The reactor trips on high RCS pressure.

L - The operator manually initiates main feedwater after realizing the NNI-Y failure has blocked the initiation of the auxiliary feedwater system (the auxiliary feedwater pumps initiates automatically on SFAS actuation later on in the transient.)

P - The increased RCS pressure causes one of the two code safety valves to open at a pressure less than maximum setpoint of 2500 psi. The subsequent decrease in RCS pressure causes a SFAS initiation (HPI and AFWS start).

Q'- The power safety valves reseat.

U'- NNI-Y is restored. The operators recognize an excessive cooldown ($> 100^{\circ}$ F/hr) has resulted. They throttle HPI and auxiliary feed flow to reduce rate of cooldown.

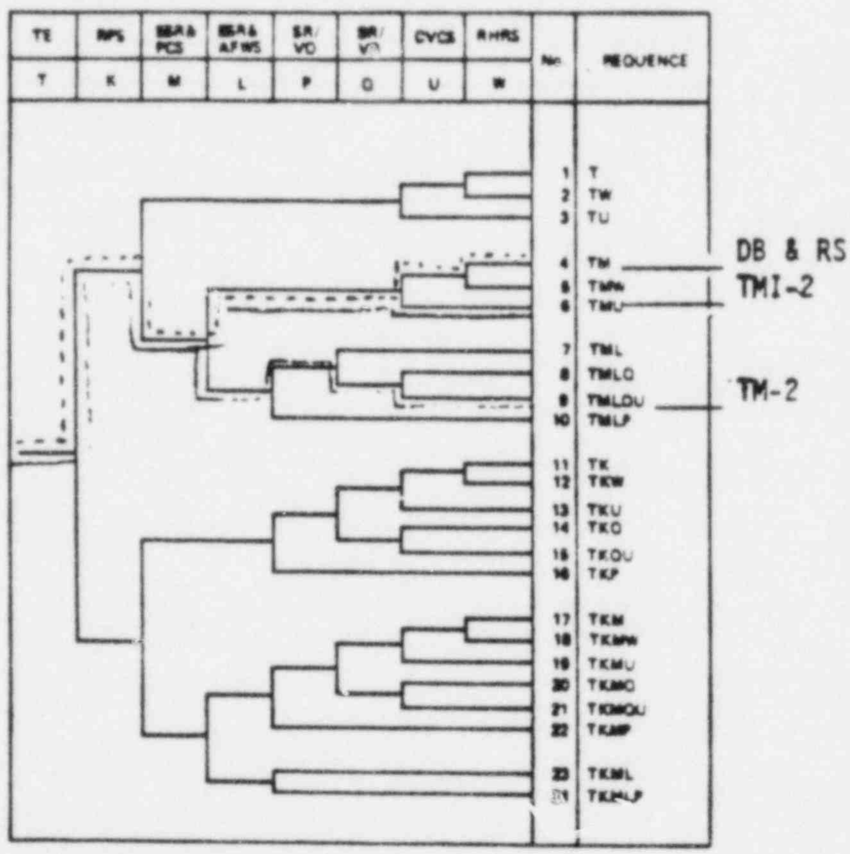

FIGURE I 4-14 PWR Transient Event Tree

FIGURE 1

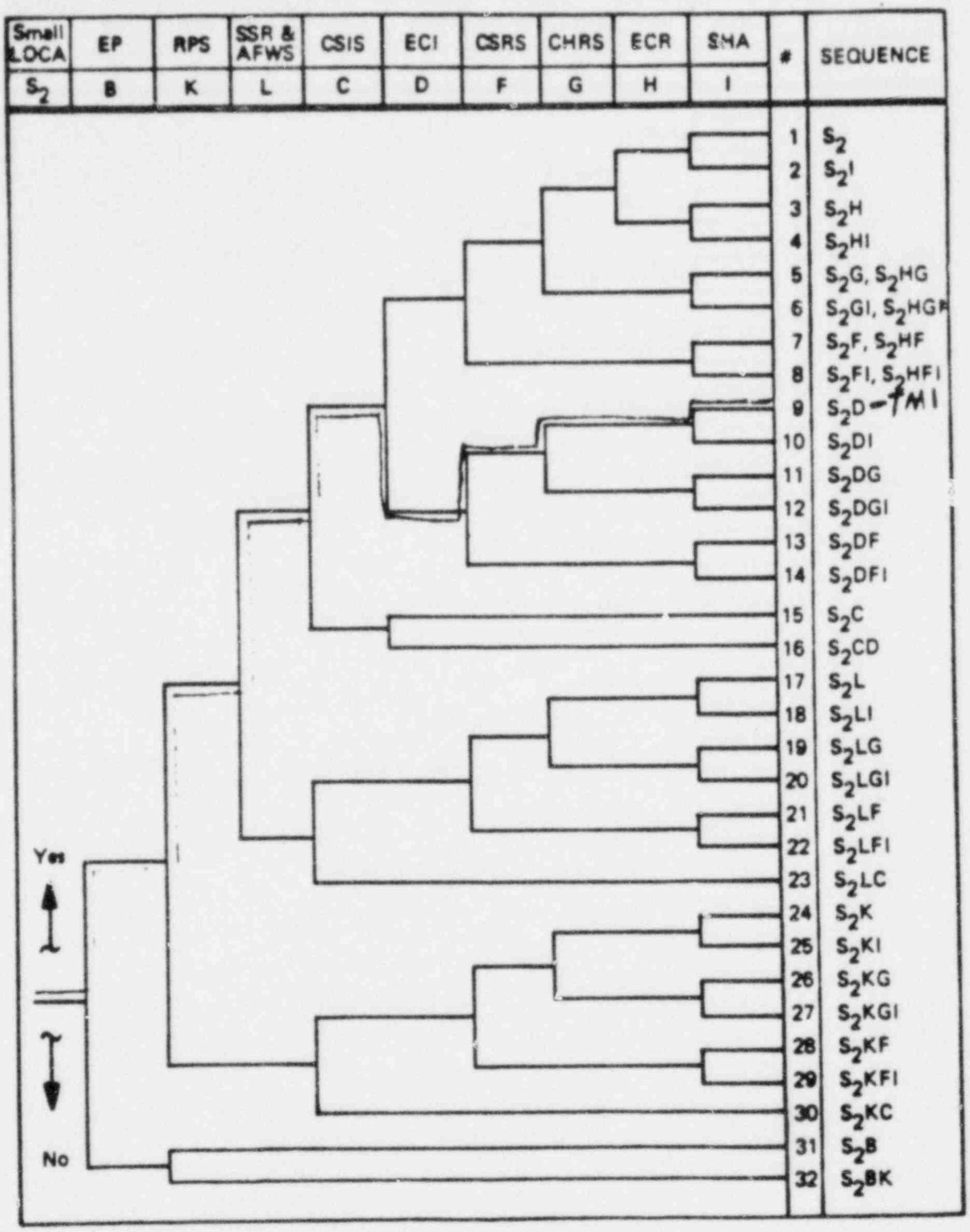

FIGURE I 4-4 PWR Small LOCA (S2, 1/2-2 inch diameter) in RCS

FIGURE 2

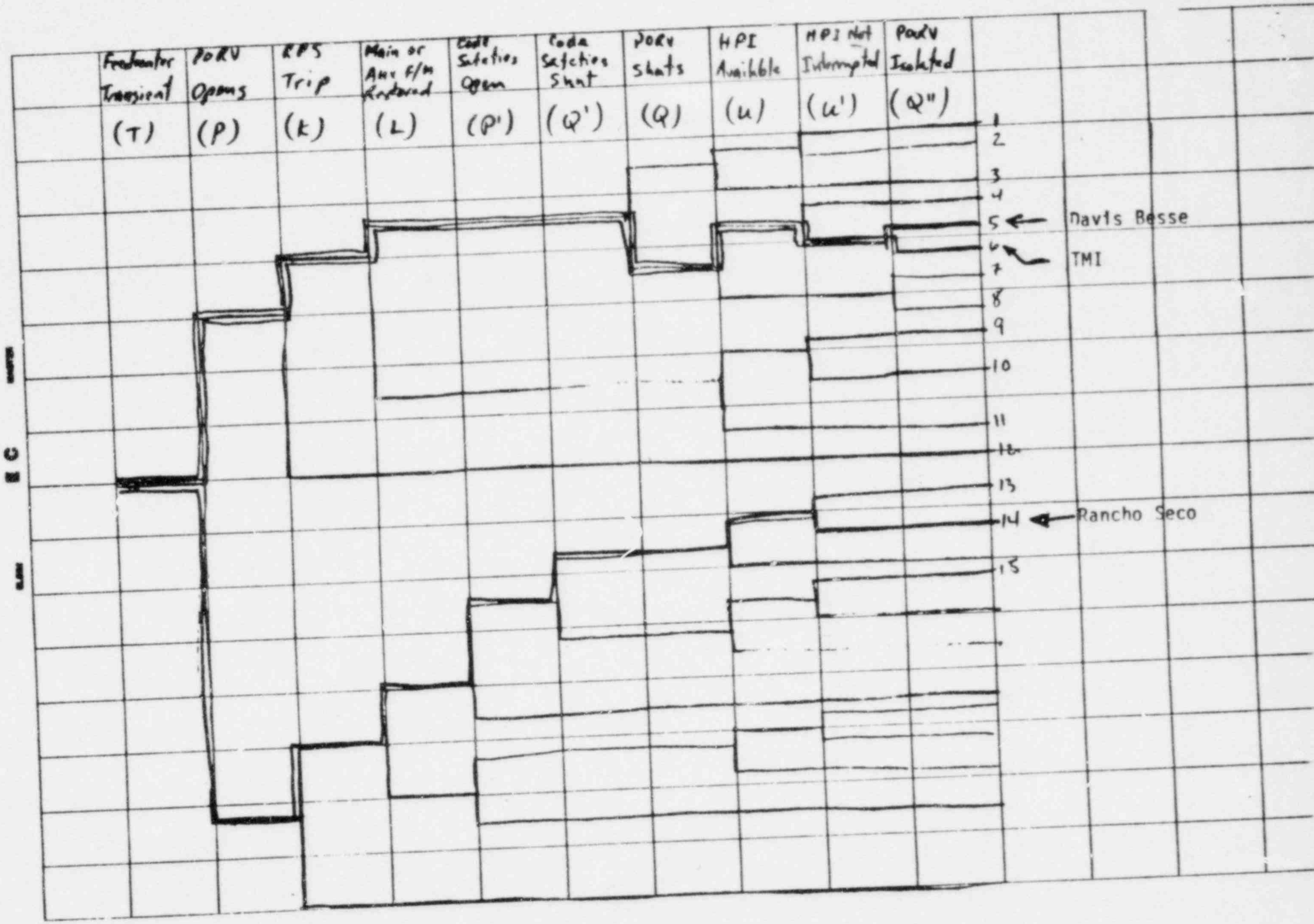

FIGURE 3. B&W FEEDWATER TRANSIENT EVENT TREE

APPENDIX B
OPERATOR ERROR

The rationale for characterization of operator error in WASH-1400 can be demonstrated as follows. Let p_f be the probability of operator failure and let p_s be the probability of operator success. Then

$$p_s + p_f = 1 \tag{1}$$

as it should. Suppose there are n operators in the control room. Let P_f be the probability the n operators make a "collective" error. In WASH-1400, P_f is given by

$$P_f = (p_f)^n \tag{2}$$

Since probability must be conserved, the probability that the n operators make a "collective" success, denoted P_s is

$$P_s = P_f = 1-(p_f)^n \tag{3}$$

To understand the implications of such an approach consider the following:

let $p_f = 0.1$ (individual failure), n=3.

It follows that:

$p_s = 1-0.1 \quad = 0.900$ (individual success)

$P_f = (0.1)^3 \quad = 0.001$ (collective failure)

$P_s = 1-(0.1)^3 \quad = 0.999$ (collective success)

The possible operator actions are:

$p_f\,p_f\,p_f = (0.1)^3 = .001$

$p_f\,p_f\,p_s = (0.1)^2\,(0.9) = .009$

$p_f\,p_s\,p_f = (0.1)(0.9)(0.1) = .009$

$p_f\,p_s\,p_s = (0.1)(0.9)^2 = .081$

$p_s\,p_f\,p_f = (0.8)(0.1)^2 = .009$

$p_s\,p_s\,p_f = (0.9)^2\,(0.1) = .081$

$p_s\,p_f\,p_s = (0.9)(0.1)(0.9) = .081$

$p_s\,p_s\,p_s = (0.9)^3 = .729$

1.000

Hence, WASH-1400 can be interpreted as follows:

a) For a "collective" failure, all n operators must be in error.

b) For a "collective" success, at least one operator must take correct action.

With this interpretation, $P_s \neq p_s^n$ i.e. all operators are correct.

As stated in the report, the shift supervisor should have the final word ... however, to be consistent with the WASH-1400 approach

$$P_f = p_f^n \text{ and } P_s = 1-(p_f)^n$$

is used, with the interpretation given above.