AEOD/E93-01

ENGINEERING EVALUATION REPORT

HUMAN FACTORS ASPECTS OF BOILING WATER REACTOR REACTIVITY MANAGEMENT EVENTS DURING POWER OPERATIONS

FEBRUARY 1993

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AEOD ENGINEERING EVALUATION

Unit:	Multiple	Report No.:	AEOD/E93-01
Docket No:	Multiple	Date:	February 22, 1993
Licensee:	Multiple	AEOD Contact:	J. Kauffman
NSSS/AE:	Multiple		
Event Dates:	Multiple		

SUBJECT: **HUMAN FACTORS ASPECTS OF BOILING WATER REACTOR REACTIVITY MANAGEMENT EVENTS DURING POWER OPERATIONS**

SUMMARY

Reactivity control is an essential element of reactor safety. The LaSalle power oscillation event and related generic communications in 1988 increased the industry's sensitivity and awareness of the importance of reactivity control. Events at Quad Cities and at Monticello in late 1990 and 1991 indicated that reactivity control was still a challenge to operators and that additional feedback of the lessons learned from evaluation of operating experience might lead to improved operator performance.

The study objectives were to: (1) identify reactivity events that resulted in automatic reactor trips in Modes 1 and 2 from mid-1988 to the present, (2) assess the safety significance of the events, (3) identify and evaluate the contributing factors and root causes, (4) develop lessons learned that may be fedback to industry to improve performance, and (5) identify industry trends in this area and potential outlier plants.

DISCUSSION

1.0 INTRODUCTION

There are several significant operational differences between a nuclear power plant and a fossil plant. Two of the most important and fundamental differences are the need for reactor decay heat removal and reactivity control. Boiling water reactor (BWR) reactivity control is dependent on many variables including control rod positions, recirculation flow, feedwater (FW) flow and temperature, reactor pressure (RP) and temperature, void content, fission product and burnable poisons, power level, and flux distribution. Hence, reactivity in a BWR is complex, and may be cognitively challenging to operators.

The fundamental goal of this study is to identify and feedback human performance information that might enhance operator control of reactivity in the future. In particular,

the study identifies and feeds back the contributors to these events and the corrective actions that plants have taken.

This report documents the review of operational events from mid-1988 to present that involved reactivity events leading to BWR reactor trips from Modes 1 and 2. These events were identified by searching databases, including licensee event reports (LERs) coded in the Sequence Coding and Search System (SCSS), and LERs contained in the Nuclear Documents System text search system. Events with equipment malfunctions, such as a turbine control valve or main steam isolation valve closure, that led to a reactor trip without time for operator response prior to the trip were not included in this report. Manual scrams were not included.

2.0 REVIEW OF OPERATIONAL EVENTS

2.1 Big Rock Point

On May 13, 1992, the plant was starting up after a refueling outage (Reference 1). The operators experienced difficulty in opening the turbine stop valve (TSV) during testing. The turbine bypass valve (BPV) was opened to reduce the differential pressure across the TSV. The BPV was then given a partial close signal as the TSV opened. The reactor scrammed on short reactor period (high rate of flux increase) due to a changing void concentration resulting from pressure perturbations.

The licensee attributed the event to opening the BPV to reduce RP at low power levels. This lowered reactor power to below one percent, which enabled short period scram protection. Operators did not recognize the sensitivity of the nuclear instrumentation below one percent power. There was a lack of written precautions or warnings regarding operation of the BPV in this power range, and undersized steam flow pilot holes internal to the TSV caused difficulty opening the TSV.

Licensee corrective actions included revision of general operating procedures to enhance precautions and limitations related to low power operations, addition of a caution statement at appropriate points in related system operating procedures to control use of the turbine BPV at low power and provide additional direction as to when and how the BPV is tested during startup, and training of the operators on the specifics of the event.

2.2 Nine Mile Point Unit 1

On July 18, 1991, the unit was being shut down when an unanticipated RP decrease occurred (Reference 2). The operators initially diagnosed a pressure regulator malfunction, but later concluded that steam loads and steam leakage were greater than steam generation. Hence, the operating crew decided to isolate main steam line drains to reduce steam loads. The reactor scrammed on Intermediate Range Monitor (IRM)

Hi during or shortly after isolating the main steam line drains, likely due to a flux spike caused by a decreased void concentration resulting from pressure perturbations.

The licensee did not determine the cause of the trip. Possible causes were a neutron flux spike caused by pressure perturbations resulting from isolating the main steam line drains, or spurious spiking of the IRMs due to induced noise. A contributing factor to the pressure regulator malfunction misdiagnosis was open indication for a BPV, when the BPV was actually closed (the position indication switch had a history of sticking).

Licensee corrective actions included repair of steam leaks, posting an operator aid for the BPV indicator, additional procedural cautions and guidance for manipulating auxiliary steam loads during plant shutdown, and a lessons learned transmittal to inform all operating crews of the event.

2.3 Nine Mile Point Unit 1

On April 18, 1992, the plant was operating near full power (Reference 3). About 3 minutes prior to the scram, the mechanical pressure regulator (MPR) took control from the electronic pressure regulator (EPR). An operator observed that RP was stable and the EPR servo stroke was decreasing from 94 percent to 88 percent. To correct the perceived EPR failure, the operator turned off the EPR and attempted to control pressure manually with the MPR. RP started dropping and the operator stopped reducing pressure with the MPR. RP dropped to a low of 994 psig. Then RP rapidly increased, causing voids to collapse and neutron flux to increase to the flow-biased average power range monitor (APRM) scram setpoint.

The licensee attributed the cause to the failure of the MPR servo motor position indicator. This failure caused an operator on a prior shift to reposition the MPR which allowed the MPR to take control of RP from the EPR. The failed servo motor position indicator made it difficult for the operator to control pressure using the MPR. The licensee's investigation concluded that dirt may have inhibited movement (in both directions) of the MPR balance beam, causing incorrect response of the MPR to changes in RP.

Licensee corrective actions included troubleshooting and repair of equipment problems related to the event.

2.4 Monticello

On February 11, 1991, a reactor startup was in progress (Reference 4). With the IRMs on range 7 and the reactor critical, a control rod was withdrawn a single notch. Flux increased rapidly and an IRM Hi Hi scram was received before the operator could up range the IRMs.

The licensee attributed the cause of the event to flux redistribution effects. Flux redistribution resulted in local effects that caused the IRMs to respond as if the overall reactivity were much greater. The flux redistribution was not accounted for in the operator guidance provided by the nuclear engineers.

Licensee corrective actions included reduction of flux redistribution effects by changing the control rod withdrawal sequence, and establishing controls to alert operators to rod withdrawals that might result in a large IRM response due to flux redistribution effects.

2.5 Monticello

On June 6, 1991, a reactor startup was terminated and a reactor shutdown was commenced to repair a leaking safety relief valve (SRV) (Reference 5). The reactor began to depressurize because decay heat (DH) was insufficient to supply all auxiliary loads. As the reactor depressurized, the reactor coolant temperature decreased, adding positive reactivity. As long as the operator continued to insert control rods, the reactor was maintained subcritical. The operator stopped inserting control rods to review plant conditions and the reactor scrammed about a minute later due to IRM Hi Hi.

The licensee attributed the cause of the event to cognitive error in failing to recognize the actual plant conditions. Numerous contributing causes were identified including a sense of urgency due to potential SRV failure, transition from startup to shutdown procedures, customary crew briefings did not occur, and responsibilities were not clearly assigned, all of which led to one reactor operator being left with responsibility for control rod insertion and monitoring of other panels. The crew had a misperception (because of prior successful shutdowns with high DH) that moderator cooldown was of minimal concern while in the IRM heating range with pressure above 650 psig, and the crew did not recognize that the absence of sufficient DH early in core life would result in significant cooldown rates with normal auxiliary steam loads in service. Operating procedures lacked specific guidance for controlling cooldown with low DH, and the use of recorders as tool for recognizing trends of reactivity during significant reactor transitions had not been emphasized.

Licensee corrective actions included emphasizing to shift supervisory personnel that their primary focus should be on command and control to ensure that responsibility has been clearly assigned for all activities necessary for safe plant operation, changing plant administrative controls to clarify the duties of control room personnel especially during power changes, changing operating procedures to secure steam loads to avoid excessive cooldowns under low DH conditions, and requiring all control rods be inserted or receiving guidance from the nuclear engineer prior to establishing a cooldown rate.

This event was the subject of an AEOD Human Factors Study Report (Reference 6) and NRC Information Notice IN 92-39 "Unplanned Return to Criticality During Reactor Shutdown."

2.6 Quad Cities Unit 2

On October 27, 1990, the reactor was being returned to normal operation following the discontinuation of a turbine torsional test (Reference 7). While reducing RP to return the electro-hydraulic control system to normal, the reactor operator did not realize the reactor had gone subcritical. As pressure decreased below 800 psig, the reactor operator began withdrawing control rods to increase RP. The rod withdrawals resulted in a short period and an IRM Hi Hi scram.

The licensee attributed the primary cause of the event to personnel error. The licensed reactor operator focused on controlling RP and did not realize that the reactor was subcritical. The reactor operator did not use the reactor physics knowledge expected of a licensed operator and did not follow all required procedure steps. The licensee identified a number of contributing causes including insufficient management oversight of hot standby operations, ineffective communications including ineffective turnover or logging of an earlier shift's experience, a delayed shift briefing, insufficient training, and the limited onsite review of the special test procedure used for the turbine torsional test.

Licensee corrective actions included specific training for controlling RP under different operating conditions, providing augmented management oversight for hot standby operation, and procedure revisions associated with the shutdown procedure and the administrative control process for special test procedures.

This event was the subject of an AEOD Human Factors Study Report (Reference 8) and NRC Information Notice IN 91-04 "Reactor Scram Following Control Rod Withdrawal Associated with Low Power Turbine Testing."

2.7 Vermont Yankee

On July 3, 1988, a reactor shutdown was commenced to repair a steam leak (Reference 9). About 30 minutes after the turbine was taken offline, the operators observed a pressure decrease. Operators then used various modes of the mechanical hydraulic control (MHC) system to attempt to control pressure. MHC operated erratically in all modes. Attempts to control pressure by positioning BPVs resulted in large valve position changes and subsequent RP and level oscillations. During a high level oscillation, the operating FW pump tripped. A standby FW pump was started, but the resulting injection of relatively cold water caused a rapid neutron flux increase which resulted in a high IRM flux scram.

The licensee attributed the cold water injection to plant procedures that did not address response to low RP when not in the "Run" mode, and cognitive error in that the use of any MHC pressure regulating mode during the depressurization would serve to further reduce pressure. The suspected root cause of the event was a malfunction of the MHC system due to dirt or grit lodging in oil system pressure control valves.

Licensee corrective actions included a review of shutdown and transient procedures for possible improved guidance for pressure control problems, training on these improvements, and addition of a caution tag to the control switch for the BPV opening jack to preclude its use in similar situations (unless the reactor is shutdown or use of the jack is required by plant emergency procedures).

2.8 James A. Fitzpatrick

On November 12, 1989, a reactor scram occurred during a scheduled surveillance test of the SRVs (Reference 10). In preparation for the test, power was about 10 percent and RP was about 575 psig. The first SRV was opened and then closed. Upon closing the SRV, the reactor scrammed due to a pressure transient which resulted in a high flux APRM (15 percent) trip.

The licensee attributed the event to the surveillance test not providing instruction concerning an appropriate margin to the APRM trip, nor did it provide a caution to the operator concerning the possible pressure transient and need for an appropriate margin. There was an element of human error in that the operators did not anticipate the magnitude of the pressure and flux transient relative to the margin to the scram setpoint.

The licensee corrective action was a procedure revision so that SRV testing will be performed at 940 psig with the mode switch in "Run." This change provided greater margin to the scram setpoint.

2.9 James A. Fitzpatrick

On December 15, 1990, a reactor start up was in progress (Reference 11). Reactor water level began decreasing when the FW low flow control valve would not stroke full open. This resulted in a need to use the reactor feed pump (RFP) discharge valve to control water level. After several controlled jogs in the open direction of the RFP discharge valve, the increase in FW injection flow resulted in a high APRM (15 percent) neutron flux scram.

The licensee attributed the cause of the event to the failure of the reactor FW low flow control valve due to a failure of a diaphragm in the air operator and air leakage from the operator stem packing gland.

Licensee corrective actions included valve repair, revision of the startup and shutdown procedures to verify that the low flow control valve operates smoothly throughout its full stroke, and addition of procedure cautions to restrict steam flow to limit the demand open signal for the low flow control valve to less than 70 percent.

2.10 Fermi Unit 2

On May 8, 1988, the reactor was in startup at six percent. A high pressure coolant injection system (HPCI) automatic actuation surveillance was required to be performed (Reference 12). The scope of the surveillance was to verify that upon receipt of an actuation signal the HPCI test return line isolates as designed.

As required by procedure, the HPCI pump discharge inboard isolation valve (IV) was opened to test the interlock associated with the HPCI pump test line outboard IV. The outboard IV is designed to close when the inboard IV is opened. Since the surveillance did not require the HPCI pump to be running, the HPCI test return line provided a low resistance path for FW flow to the condensate storage tank, during the time that the test line outboard IV was closing. Reactor water level decreased and a low level alarm was received. Operators closed the inboard IV in response to the low level alarm, which restored FW flow to the vessel. The operator actions to compensate for the low reactor water level, however, resulted in a rapid injection of colder FW and an IRM high flux scram.

The licensee attributed the cause of the scram to conducting a surveillance test during startup that was intended to be performed in cold shutdown or refueling. The procedure did not contain precautions to prohibit performance of the surveillance in other plant modes.

Licensee corrective actions included adding a precaution to the applicable surveillance procedures and issuing required reading stressing the importance of shift briefings prior to performing similar plant evolutions.

2.11 Limerick Unit 1

On April 9, 1988, a controlled shutdown using individual rod insertions was in progress (Reference 13). With reactor power steadily decreasing, the reactor operator had stopped inserting control rods in an effort to control the cooldown rate. IRMs began trending upward due to the positive reactivity insertion from the decreasing moderator temperature. Reactor power increased from 27 on IRM range 2 to the high alarm of 108 on range 2. The reactor operator (RO) reacted to the alarm but did not uprange IRMs in time to prevent the IRM Hi Hi scram, 6 seconds after the alarm.

The licensee attributed the event to cognitive personnel error in that the RO did not adequately anticipate the reactivity effects of moderator cooldown and did not properly monitor the IRMs.

Licensee corrective actions included cautioning the RO to be constantly aware of conditions which effect core reactivity, revising the shutdown procedure to caution about the effects of moderator cooldown, emphasizing during continuing training the need to constantly monitor process indications when in a transient condition, and lowering the IRM alarm setpoint to allow additional time for operator response prior to a scram.

2.12 Edwin I. Hatch Unit 2

On February 24, 1991, a startup was in progress with the reactor critical below one percent power (Reference 14). A nuclear heatup was in progress at 280 psig. Water level began to decrease when a BPV opened to control RP. In response to the level decrease, FW was rapidly injected to the vessel causing neutron flux to increase to the scram setpoint (about 12 percent).

The licensee attributed the event to personnel error in that operators failed to maintain the BPV pressure control setpoint about RP as required by procedure. In addition, operators failed to recognize that the BPV was open. Contributing to the event was the closure of a valve in the FW long-cycle return to condenser flow path. The valve indicated open, but it had failed closed. This caused condensate booster pump discharge pressure to be higher than expected (approximately 600 psig versus the normal 300 psig). Operators failed to recognize the higher than normal condensate system pressure and greater than expected FW flow to the vessel.

Licensee corrective actions included counseling of the involved personnel and replacement of the failed valve positioner.

2.13 Nine Mile Point Unit 2

On June 28, 1988, a reactor startup was in progress with the reactor at nine percent power and 850 psig (Reference 15). Operations personnel discovered that the temperature increase of one moisture separator reheater was lagging the other. Operators misinterpreted a procedure caution that requires the temperature difference between the two steam separator reheaters to be less than 50 °F. In order to equalize the temperatures, the operator throttled open a low load steam inlet valve. This caused increased steam loads and reactor power at low RP. This caused reactor water level and pressure to decrease initially. In the final 20 seconds prior to the scram, FW flow, reactor level, and RP were all increasing causing reactor power to rise. The reactor scrammed on an APRM upscale trip (15 percent).

The licensee attributed the event to operator error in that operators failed to recognize that the procedure caution was only applicable when the turbine was in service, and so should not have been opening the reheat steam valves. In addition, the operators should have been sensitive to the effect on power and the reduced margin that existed to the APRM scram setpoint. Secondary causes were a training deficiency and a procedural deficiency.

Licensee corrective actions included changes to the startup procedure to assure that the reheater steam supply valves are closed until the turbine has reached 15 percent to 19 percent load, and simulator demonstrations to stress to operators the effects of changing steam loads on system stability during startup.

2.14 Nine Mile Point Unit 2

On October 18, 1988, a reactor shutdown using control rods was in progress with reactor power below one percent at 525 psig (Reference 16). Operations personnel were removing steam loads to gain improved control of the cooldown rate, and reactor water cleanup reject flow had been increased to restore normal system flow. The above actions, in parallel to the high cooldown rate, caused reactor water level to decrease about 1.5 inches. The FW system responded to the lower indicated level by increasing FW flow. The introduction of the relatively cold (84 °F) FW resulted in a significant increase in core inlet subcooling and positive reactivity insertion. In response to a source range monitor short period alarm, the RO took immediate action to uprange the IRMs, but the reactor tripped due to high upscale IRM trips.

The licensee attributed the event to inadequate control and coordination of activities associated with the shutdown on the part of the control room personnel. In particular, the chief shift operator did not properly control the multiple activities affecting reactor power during the shutdown process, there was inadequate communication among the control room operators performing the activities such that each was not aware of the others' activities, and the senior reactor operators did not properly oversee control activities during this time period. In addition, a contributing factor was inadequate direction in the shutdown procedure as to when to secure steam loads during the shutdown.

Licensee corrective actions included actions to address the above; plus all crews were instructed that only one activity affecting reactivity be performed at any one time, and operators were instructed to pay increased attention to the effects at low power resulting from changes in RP or changes in FW flow or temperature.

2.15 Perry

On June 5, 1988, the reactor was operating at about 80 percent power (Reference 17). Operators were periodically adjusting recirculation flow to maintain power constant due to changes in Xenon concentration.

During one such adjustment, an operator inadvertently depressed the "auto" pushbutton on the recirculation system flux controller, shifting the flux controller in automatic. Due to the deviation between actual and demanded flux, the recirculation flow control valves were automatically opened. This resulted in increased recirculation flow and a high APRM (118 percent) flux scram.

The licensee attributed the event to personnel error in that the operator did not exercise sufficient care to avoid contact with the pushbutton. The "auto" pushbutton was located directly behind the setpoint adjustment slide switch and in the direct line of motion of the operator's hand when making an adjustment to the control setting.

Licensee corrective actions included disabling the automatic mode (the system was not intended to be used) until the system could be properly tuned, disciplining the involved operator, and including the event in requalification training.

2.16 Perry

On June 16, 1988, the reactor was operating at 100 percent power (Reference 18). Troubleshooting of a recirculation system automatic flux controller circuit card was in progress when a spurious spike in recirculation flow demand caused increased core flow and an upscale neutron flux trip. The spike occurred when the circuit card was reinstalled.

The licensee attributed the event to reinsertion of the automatic flux control card into the recirculation flow control circuitry which induced a noise spike into the control loop circuitry. A technical manual and design drawing review by engineers, both prior to and following the event did not reveal the potential for this transient. However, contact with the manufacturer confirmed that reinsertion of the card may cause grounding which could induce a noise spike. Subsequent troubleshooting confirmed this hypothesis.

Licensee corrective actions included initiation of steps to ensure that the hydraulic power units to the flow control valves will be locked to prevent unexpected transients when removing or installing circuit boards in the recirculation flow control system during power operation.

2.17 River Bend

On February 20, 1989, a reactor startup was in progress with the reactor critical in the IRM range (Reference 19). The startup was at the point where additional steam loads were being added. Between each addition of a new steam load, water level was allowed to stabilize. Following the opening of the fourth 3-inch drain, the level dipped further than for the previous drain opening. Because of reactor level and power reductions, additional steam voids formed in the core and power began to decrease. The reactor operator continued withdrawing control rods to maintain RP. The IRM upscale trip occurred when the startup FW regulator valved opened rapidly, causing a rapid increase in FW flow and a rapid positive reactivity addition.

The licensee attributed the event to a startup FW regulator valve that had numerous air leaks and led to its slow, sluggish response, and consequent rapid opening.
Licensee corrective actions included repairing the valve and changing the startup procedure to require having a steam BPV open at approximately 50 percent prior to placing steam drains in service.

3.0 LESSONS LEARNED

3.1 Licensee Corrective Actions

Many causes were identified for the physical causes of reactivity insertion events and many corrective actions were taken to correct or prevent recurrence. Because the corrective actions generally focus on the causes, the corrective actions are presented below as "lessons learned" that may be useful for other licensees to consider.

3.1.1 Pressure Transient and Cooldown Events

For pressure transient and cooldown events, some licensee human performance corrective actions were:

- improved procedure guidance, precautions, and limitations for pressure control during low power operations, in particular, improved guidance for:
  - control of BPVs at low power
  - addition and removal of steam loads at low power
  - securing steam loads to avoid excessive cooldowns under low DH conditions
  - requiring all control rods be inserted or nuclear engineer guidance prior to establishing a cooldown rate
- improved control room command, control, and communications, in particular:
  - clarification of the duties of control room personnel especially during power changes
  - emphasizing the importance of clear assignment of responsibilities for all activities necessary for safe plant operation
  - augmenting management oversight for hot standby operation
  - instructing crews that only one activity affecting reactivity be performed at a time
- efforts to improve training, in particular training on:
  - controlling RP under different operating conditions

- the need to constantly monitor process indications when in a transient condition

- nuclear instrumentation response

– improved guidance and controls for testing, in particular changing:

    - the administrative control process for special test procedures

    - SRV testing so that it will be performed at 940 psig with the mode switch in "Run"

– improved human-machine interface, in particular:

    - adding a caution tag for the BPV opening jack control switch to preclude its use in a depressurization event (unless shutdown or as directed by emergency procedures)

    - lowering the IRM alarm setpoint to allow additional time for operator response prior to a scram

3.1.2 Cold Feedwater or Rapid Feedwater Injection Events

For cold FW or rapid FW injection events (in addition to the relevant actions from the pressure transient events above), some licensee human performance corrective actions were:

– improved guidance for testing, in particular:

    - providing precautions to perform some surveillances only when in cold shutdown or refueling

– improved procedure guidance, in particular:

    - verifying during startup and shutdown that the low flow control FW valve operates smoothly throughout its full stroke

    - administratively restricting steam flow during startup and shutdown such that the demand open signal for the FW low flow control valves does not exceed 70 percent

3.1.3 Recirculation Flow Transients

For recirculation flow transient events, some licensee human performance corrective actions were:

- disabling the automatic mode of recirculation flow control to prevent inadvertent automatic operation

- administrative controls to lock the hydraulic power units to the recirculation flow control valves to prevent unexpected transients when removing or installing circuit boards in the recirculation flow control system during power operation

3.1.4 Control Rod Withdrawal Events

For control rod withdrawal events, some licensee human performance corrective actions were:

- reduction of flux redistribution effects by changing the control rod withdrawal sequence

- establishing controls to alert operators to rod withdrawals that might result in a large IRM response due to flux redistribution effects

3.2 Operator Knowledge

Operator knowledge weaknesses contributed to impromptu operator actions that were inappropriate in responding to events involving equipment failure.

Operator knowledge weaknesses contributed to inappropriate operator actions during startups and shutdowns that resulted in reactivity insertion events.

Operator knowledge weaknesses were demonstrated in diverse areas.

3.2.1 Pressure Control

Operator knowledge weaknesses involving pressure control included:

- not understanding the sensitivity of pressure changes (including valve testing and addition/or removal of steam loads) on reactor power

- not recognizing that a depressurization and cooldown (and positive reactivity insertion) would result from normal steam loads at low DH levels

- not recognizing a cooldown and positive reactivity insertion following receipt of low pressure alarms

- using a pressure regulator to (erroneously) open BPVs in an attempt to raise RP

3.2.2 Reactivity Control

Operator knowledge weaknesses involving reactivity control included:

- not understanding observed nuclear instrumentation response
- not monitoring appropriate instrumentation during reactor startups and shutdowns
- withdrawing control rods in an attempt to control pressure rather than power (reactivity or period)

3.2.3 General Knowledge

Operator general knowledge weaknesses included:

- not ensuring adequate margin to scram setpoint prior to performing SRV testing
- performing surveillance tests in wrong mode
- not understanding operating characteristics (normal parameters) of the FW and condensate systems

4.0 FINDINGS AND CONCLUSIONS

Based on the review of operating experience, the following findings and associated conclusions are provided:

From 1988 to 1989 there was a perceptible drop in the number of BWR reactivity events. From 1989 to present there was no discernible trend. No plant was identified as an outlier.

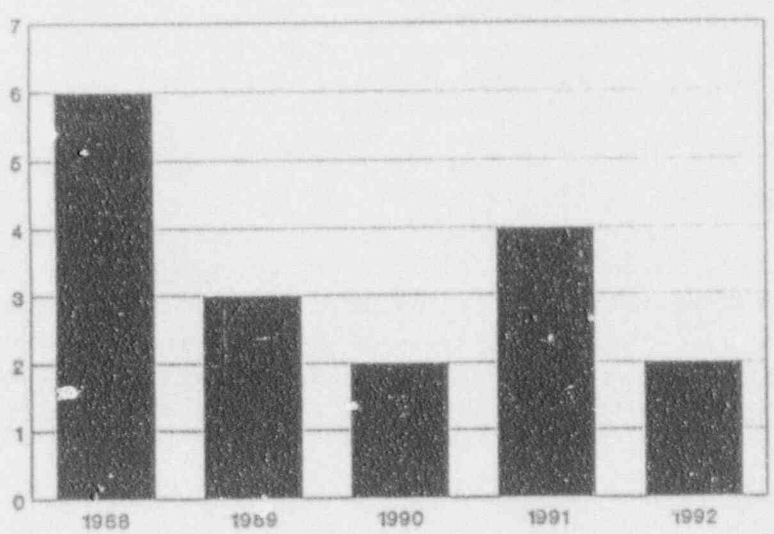

Figure 1 BWR Reactivity Events

The events were of low safety significance. The reactor automatic protective equipment functioned to shut down the reactor in all cases.

Over half of the reactivity events occurred during startup, and about 30 percent occurred during plant shutdowns. Only 18 percent occurred during steady state operation at high power.

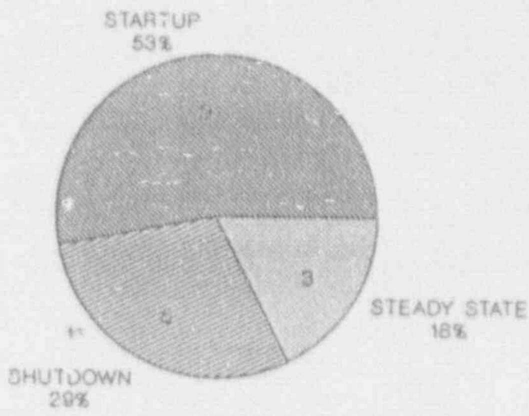

Figure 2 BWR Reactivity Events
by Activity

Every event had human factors aspects, while less than half of the events involved equipment failure.

The human performance weaknesses were in: (1) procedures, (2) operator knowledge, (3) command, control and communications, (4) human-machine interface, and (5) impromptu operator actions.

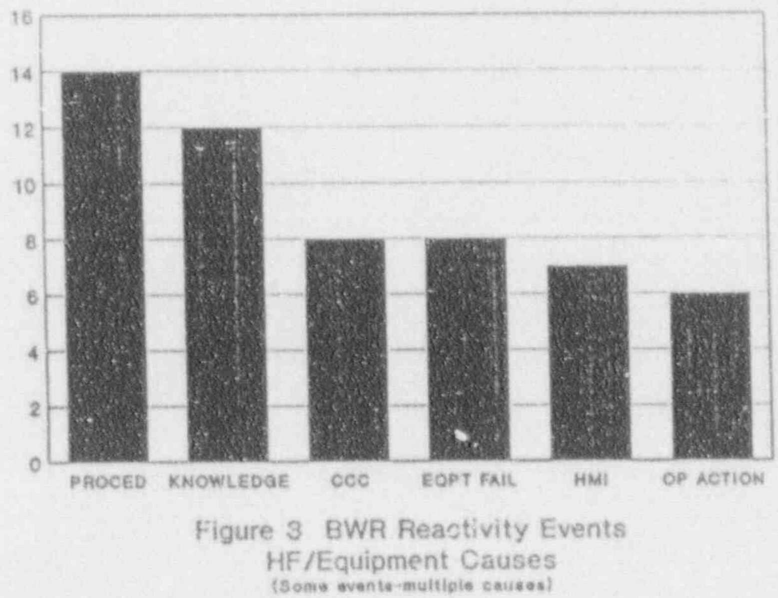

Figure 3 BWR Reactivity Events
HF/Equipment Causes
(Some events-multiple causes)

The equipment failures involved FW or condensate system valves (3), pressure regulators (2), TSV and BPV position indication, and a SRV.

The physical causes of reactivity insertion events were: (1) pressure transients, (2) cold FW injection, (3) plant cooldown, (4) recirculation flow increase, and (5) control rod withdrawal.

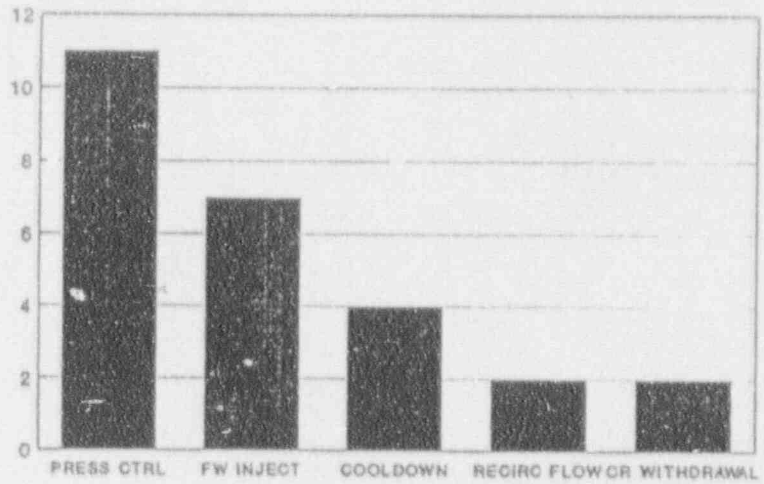

Figure 4 BWR Reactivity Insertion
Physical Causes
(Some events-multiple causes)

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