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Evaluation of Events Involving Unplanned Boron Dilutions in Nuclear Power Plants

Prepared by E. W. Hagen

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Prepared for
U.S. Nuclear Regulatory Commission

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FOREWORD

The Nuclear Safety Information Center (NSIC), which was established in March 1963 at Oak Ridge National Laboratory, is sponsored by the U.S. Nuclear Regulatory Commission's Office for Analysis and Evaluation of Operational Data. Support for the technical progress review *Nuclear Safety* (see last page of this report) is provided by both the Breeder Reactor and Light-Water Reactor Safety Programs of the Department of Energy. NSIC is a focal point for the collection, storage, evaluation, and dissemination of operational safety information to aid those concerned with the analysis, design, and operation of nuclear facilities. The Center prepares reports and bibliographies as listed on the inside covers of this document. NSIC has developed a system of keywords to index the information it catalogs. The title, author, installation, abstract, and keywords for each document reviewed are recorded at the central computing facility in Oak Ridge.

Computer programs have been developed that enable NSIC to (1) prepare monthly reports with indexed summaries of Licensee Event Reports, (2) make retrospective searches of the stored references, and (3) produce topical indexed bibliographies. In addition, the Center Staff is available for consultation, and the document literature at NSIC offices is available for examination. NSIC reports (i.e., those with ORNL/NSIC and ORNL/NUREG/NSIC numbers) may be purchased from the National Technical Information Service (see inside front cover). All of the above services are available free of charge to U.S. Government organizations as well as their direct contractors. Persons interested in any of the services offered by NSIC should address inquiries to:

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PREFACE

The Nuclear Regulatory Commission (NRC) Division of Safety Technology in the Office of Nuclear Reactor Regulation assigned the project entitled *Special Studies of Reactor Operating Experience* to the Nuclear Safety Information Center (NSIC) in the early part of FY-1981. The object of this project was to identify safety significant implications of current nuclear power plant operating experience by special studies of the following specific subsystems: compressed air and backup nitrogen, service water, decay heat removal, and boron dilution.

About two to three man-months of engineering assessment was devoted to each of the studies. The information used was basically that found in NSIC's files. The documents containing this information are available to the public in the NRC Public Document Room, 1717 H Street, Washington, DC 20555. The scope of the project did not include visits to the plants or meetings with inspectors of the NRC Office of Inspection and Enforcement.

Project personnel for the studies were

NRC Cognizant Manager	M. L. Ernst
NRC Technical Manager	R. J. Colmar
NRC Cognizant Branch Chief	W. Minners
ORNL Program Director	A. L. Lotts
ORNL Program Manager	W. B. Cottrell
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EVALUATION OF EVENTS INVOLVING UNPLANNED BORON DILUTIONS IN NUCLEAR POWER PLANTS

E. W. Hagen

ABSTRACT

This report reviews and evaluates events concerned with the inadvertent dilution of boron concentrations to the reactor coolant system for pressurized-water-cooled thermal reactors in commercial service. The safety concern is the unplanned addition of reactivity. The information was collected from operating experiences, licensee event reports, system designs in safety analysis reports, and regulatory documents. The results are collated and analyzed for significance and impact on power plant safety performance.

Several operating experience events were selected for analysis because they meet the criteria for safety significance. However, no boron dilution incidents resulted in a reactivity excursion or transient that scrammed a unit, nor was a reactor protection system challenged by any of the events. The most common cause for unplanned boron dilutions was human error, of which one was a common-mode/common-cause failure. For each recorded event, the operator had sufficient time to diagnose and correct the cause of the inadvertent dilution before the shutdown safety margin was lost or seriously challenged.

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1. INTRODUCTION

The Safety Program Evaluation Branch (SPEB) in the Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation (NRR) has the responsibility for evaluating reactor operating experience to detect events or trends that may be of safety significance to nuclear reactors so that these results may be factored into the licensing process. The SPEB commissioned this study of operating experiences involving the inadvertent dilution of boron concentration, particularly those experiences, occurring in the reactor coolant system (RCS) for pressurized-water-cooled thermal reactors (PWRs), that were outside the plant

Technical Specifications but including as well those within the Technical Specifications. The safety concern is the unplanned addition of reactivity. The purpose of this review was to identify and place in perspective any possible significant implications for reactor safety.

Computerized reference files of the Nuclear Safety Information Center (NSIC) [containing more than 24,500 Licensee Event Report (LER) descriptions plus abstracts of thousands of other operational and licensing documents] were systematically searched for those events associated with boron dilutions and impairment of boric acid delivery to the RCS. The computer selected and retrieved 555 references for 79 units in 49 plants from mid-1969 or unit initial operation (whichever was first) through early 1981. LERs by the electric power generating utilities were the major source of information for this study. However, other sources were also reviewed for information. The generic or vendor Safety Analysis Reports (SARs) were used to obtain background information, design, and operating philosophies. NRC guides, notices, and letters were reviewed for regulatory direction. The operating experiences were systematically compiled, categorized, and evaluated. This study analyzes the events involving inadvertent dilution of the RCS and of the boric acid supplies available to the RCS. The LERs used in this study are summarized in the Appendix.

Because boric acid is used as a reactivity control in PWR's, this study begins with a brief discourse on boric acid application; then the safety-related operating experiences are reviewed (i.e., those instances where less than the desired amount of boron was present in the RCS for that unit's operational mode). These instances constituted unwanted and unplanned boron dilution and thus the insertion of unanticipated reactivity. The safety relevance is noted, and a discussion of observaions and comments follows. Conclusions and recommendations conclude this study.

Boron, an absorber of thermal neutrons, is used to control excess reactivity. Controlled boron concentration in the RCS is used (1) to obtain optimum positioning of control element assemblies; (2) to compensate for reactivity changes associated with major changes in reactor coolant temperature between cold shutdown and hot full-power operation, fuel burnup, and burnable poisons buildup of fission products in the fuel; (3) to compensate for xenon variations; and (4) to provide a shutdown margin for maintenance and refueling operation. Boron concentration adjustment is a manual operation under strict administrative controls with procedures setting limits for the rate and duration of changes. Changes are made in the reactor coolant boron concentration for the following conditions:

1. Reactor startup — boron concentration must be decreased from shutdown concentration before taking the reactor to criticality.

2. Load change — boron concentration must be either increased or decreased to compensate for the xenon transient following a change in load.

3. Fuel burnup — boron concentration must be decreased to compensate for fuel burnup and the buildup of fission products in the fuel.

4. Cold shutdown — boron concentration must be increased to the cold shutdown concentration. Thus, boron in the form of the BO_3 ion in the reactor coolant controls reactivity.

The operator determines, by the use of nomographs or the in-plant computer, the desired boron concentration for the desired operating mode of the plant. He then either adds boric acid solution or primary water to the RCS as needed. These changes are made to the RCS through a process of feed and bleed using the chemical and volume control system (CVCS). Boron concentration in the RCS can be decreased (diluted) either by controlled addition of unborated makeup water with a corresponding removal of reactor coolant or by using the deborating ion exchangers. Controlled dilution has a purpose, that is, a preselected quantity of primary water is added at a preselected rate. Uncontrolled boron dilution is defined as the decrease in the RCS boron concentration caused by the inadvertent addition of unborated water. Uncontrolled boron dilution could result from equipment failure or human error.

Typically, the Final Safety Analysis Reports (FSARs) carry a statement, applicable only to the RCS makeup systems, that inadvertent or unplanned dilution of the reactor coolant due to the addition of unborated water can be terminated by (1) isolating the makeup water system, (2) stopping either the makeup water pumps or the charging pumps, or (3) closing the charging system isolation valves. A charging pump must be running in addition to a makeup water pump for boron dilution to take place. However, a review of the operating experiences associated with inadvertent or unplanned boron dilution in this report found that 81% of these events were not consistent with this FSAR statement. The SARs also state that the maximum possible rate of boron dilution is limited by design such that the operator has sufficient time to identify and terminate a boron dilution incident prior to serious loss of shutdown margin. Experience reports show this to be usually or conditionally true.

2. DESCRIPTION OF SYSTEM CONTROL

A boric acid blend system is provided to permit the operator to match the boron concentration of the reactor coolant makeup water to that in the RCS during normal charging of the RCS. The makeup and purification system normally has one pump in operation, which supplies makeup to the RCS and the required seal flow to the reactor coolant pumps. For makeup water to be added to the RCS at pressure, at least one charging pump must be running in addition to a primary makeup water pump. Boric acid solutions can be supplied to the charging pump from (1) the boric acid (makeup storage) tank (BAT), (2) the refueling water storage tank (RWST), and (3) the volume control tank (VCT) and to the RCS from the boron injection tank (BIT) (Fig. 1).

Information on the status of the reactor coolant makeup is continuously available to the operator. Lights are provided on the control board to indicate the operating condition of the pumps in the CVCS. Alarms are activated to warn the operator if boric acid or demineralized water flow rates deviate from preset values as a result of system malfunction. The signals initiating these alarms will also cause the closure of control valves, thus terminating the addition of boric acid to the RCS. Thus, the CVCS is designed to limit, even under various postulated failure modes, the potential rate of dilution to a value that, after indication through alarms and instrumentation, provides the operator sufficient time to correct the situation in a safe and orderly manner.

The controlled rate of addition of unborated makeup water to the RCS when it is not at pressure is limited by the capacity of the primary water makeup pumps. With the RCS at pressure, the maximum delivery rate is limited by the control valve. The highest rate of dilution can be handled by the automatic control system, which inserts rods to maintain the power level and the RCS system temperature. Control rod insertion to the predetermined limit will cause the feed block valve to close, terminating the addition of deborated water. If the reactor is under

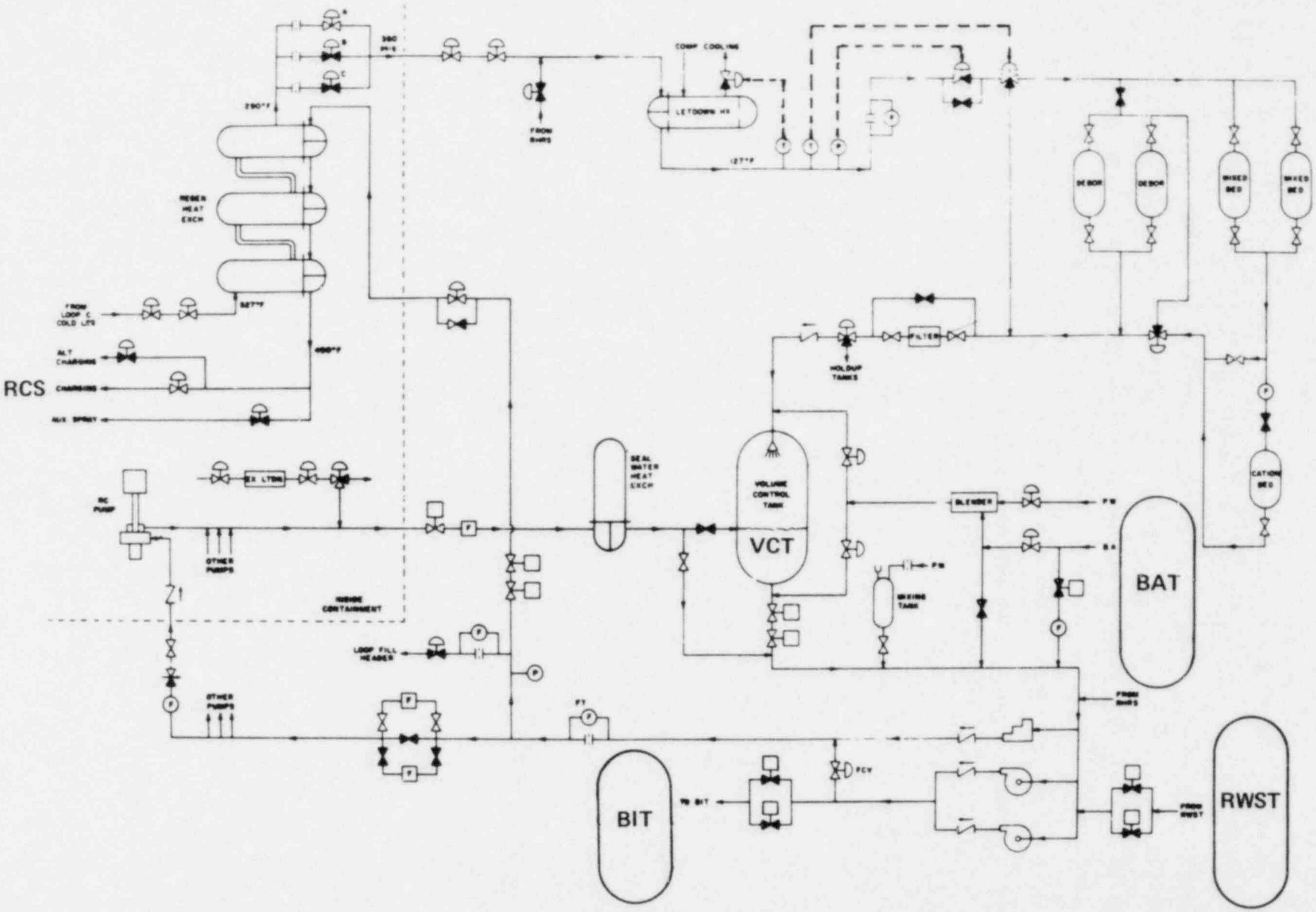

Fig. 1. Typical chemical and volume control system.

3. TECHNICAL SPECIFICATIONS

Technical Specifications define plant variables, operating conditions, surveillance requirements, and administrative controls that are considered necessary to ensure the health and safety of the public. The scope of these specifications is set forth in the *Code of Federal Regulations*, Title 10, Section 50.36 (Ref. 1). Typical Technical Specifications concerned with the boric acid system are similar to the following:

1. When fuel is in the reactor there shall be at least one flow path to the core for boric acid injection.
2. The reactor shall not be critical unless the following chemical and volume control system conditions are met.
   a. Two boric acid transfer pumps shall be operable.
   b. The boric acid tanks together shall contain a total minimum of (*) gallons of (*) weight percent boric acid solution at a temperature of at least (*)°F.
   c. System piping instrumentation, controls, and valves shall be operable to the extent of establishing one flow path from the boric acid tanks and one flow path from the refueling water storage tank to the RCS.
   d. Two channels of heat tracing shall be operable for the boric acid tank flow paths.
3. During power operation, the requirements of No. 2 may be modified to allow any one of the following conditions to exist at any one time. If the system is not restored to meet the requirements of No. 2 within the time period specified, the reactor shall be placed in the hot shutdown condition in (*) hours utilizing normal operating procedures. If the requirements of No. 2 are not satisfied within an additional (*) hours, a cold shutdown shall be initiated utilizing normal operating procedures.

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*Plant specific condition or parameter.

a. One out of two boric acid transfer pumps may be out of service provided that the pump is restored to operable status within 24 h.

b. One boric acid tank may be out of service provided a minimum of (*) gallons of (*) weight percent boric acid solution at a temperature of at least (*)°F is contained in the operable tank.

c. One channel of heat tracing may be out of service for (*) hours.

4. The quantity of boric acid in storage from either the boric acid tanks or the RWST shall be sufficient to borate the reactor coolant in order to reach cold shutdown at any time during core life.

Each time a Technical Specification is violated, that utility is required to submit to the NRC an LER describing the event, its cause, and the corrective action taken.[2] During the period under review, unplanned dilution of the RCS was reported 26 times and dilution of tanks containing solutions of boric acid occurred 58 times. From 1978 through 1980, 55 individual heat tracing failures occurred. Unit power reductions were recorded 18 times to comply with Technical Specifications: 2 for heat tracing failures, 2 for unplanned RCS dilution during power operation, and 14 for holding or storage tank dilutions.

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*Plant specific condition or parameter.

Table 2. Number of unplanned RCS dilutions by year

Year	Number of dilutions		
	RCS	SLCS[a]	Storage tanks
1969	1	0	0
1970	0	0	0
1971	0	0	0
1972	0	0	1
1973	1	2	3
1974	5	3	10
1975	2	0	13
1976	2	0	9
1977	4	0	4
1978	3	0	1
1979	2	0	0
1980	6	0	5
1981	0	0	6

[a]Standby liquid control system.

way for the NRC's NRR Division of Risk Analysis as a part of the Light-Water-Reactor Systems Survey.) The other two equipment failures were caused by leaking tubes or faulty maintenance seals in steam generators.

Other less frequent disturbances to the boric acid system concerned the interruption of electric power to pumps and some valves and failures of the heat tracing on some lines. These were all immediately recognized and fixed. Of the 55 reported heat tracing interruptions from 1978 through 1980, only in three reported instances was redundancy of heat tracing lost; in one of these a shutdown was required, and in another a power reduction was necessary. During the period November 1974 to February 1977, a number of cracking incidents were experienced in safety-related stainless steel piping systems, one of which involved cracks in piping containing stagnant or essentially stagnant borated water. This potential failure was recognized by the NRC in their bulletin No. 79-17 (Ref. 3). In 1980, another NRC letter informed of RCS dilution problems during steam generator decontamination.[4] A recent study by NRC Office of Analysis and Evaluation of Operational Data reaffirmed that problems caused by cold-weather freezing of instrumentation lines (boron for one) are still being reported despite the Inspection and Enforcement Bulletin of September 27, 1979 (Ref. 5).

Human error. Twenty-one inadvertent boron dilution events of the RCS were attributed to human errors (i.e., 80% of the boron dilution events). Six of these involved steam generator maintenance such as (a) omission of procedural steps (not plugging sectioned tubes), (b) miscalculations (the amount of excess boron needed for tube header washing and the decision as to when to open a manway for maintenance action), and (c) execution of prescribed actions but choosing either an inadequate seal plug during a maintenance action or the incorrect use of tools (accidentally slicing or nicking other tubes during the process of removing or sectioning specific tubes). Nine other events were concerned with operating procedures and were caused by misinterpretations, omissions, or inadequate surveillance. Six other events were associated with the general problem of commission (e.g., when executing a prescribed course of action, the operator selected the wrong controls or valves).

Table 3. Low concentration of boric acid in tanks (reduced below Technical Specifications)

Unit	Docket No./LER No.	Date	Reactor power level (%)	Refueling water storage tank	Boron injection tank and core flood tank	Standby liquid control system storage tank	Boric acid storage tank	Boric acid mix tank	Cause	Remarks
Ft. Calhoun 1	285/76-23	8/4/76	98[a]	X					Equipment	Valve leakage increased level
Trojan	344/76-33	5/13/76	42[a]		X				Operator	Makeup due to routine sampling
Pilgrim	293/	10/10/74				X			Operator	Opened water valve instead of air sparging valve
Turkey Point 4	251/	9/23/74					X		Maintenance	Flush and isolation valves left partially open
Sequoyah 1	327/81-037[b]	4/10/81	0	X					Chemical operator	Failure to follow sampling procedures
North Anna 2	339/81-021	3/2/81	100		X				Equipment	Leaky check valve
Beaver Valley 1	334/80-091R	1/29/81	0		X				Operator	Insufficient mixing before sampling
Surry 2	281/80-013	9/12/80	0				X		Operator	Sampling procedures not followed
Oconee 2	270/80-005	7/2/80	0[a]		X					Improper mixing prior to sampling during filling
Oconee 1	269/80-017	7/11/80	73				X		Maintenance	Pump removed from service (68/IVS)
Salem 1	272/76-31/3L[b]	1/28/77	0		X					Inadvertent safety injection reduced concentration
Salem 1	272/76-26/3L	1/14/77	17		X					Inadvertent safety injection reduced concentration
Robinson 2	261/76-3	2/9/76			X				Equipment	Check valve leak
Cook 1	315/75-59	9/22/75	80		X					Boron crystallization due to heater failure
Cook 1	315/75-61	9/29/75	81		X					Flow blockage due to heat loss
Palisades	255/75-22	9/22/75	40		X					Poor mixing when tank was topped off
Surry 1	280/75-14	8/12/75	0[a]		X					Inleakage through check valves
Surry 2	281/75-14	8/8/75	100[a]		X				Equipment	Inlet valve leakage
Surry	280/75-81	8/12/75	0[a]		X					Check valve leakage
Zion 2	304/74-59	6/25/75					X			Primary water added to tank
Rancho Seco	312/75-9	5/13/75	c				X		Operator	Tank not refilled after use and before critical operation
Indian Point 2	247/	5/5/75	c	X	X					Low level from filling BIT
Zion 2	304/75-17	4/11/75	84				X		Operator	Makeup not of proper concentration
Zion 2	304/75-6	2/5/75					X			Valve leakage
Ginna	244/74-16	9/30/74			X					Valve leakage
Oconee 1	269/74-12	8/22/74			X					Unknown
Zion 1	295/74-40	9/4/74	42				X			Unknown, possible dilution through recirculation
Zion 2	304/74-55	9/3/74	4				X			Valve leakage
Zion 1	295/74-32	8/8/74	c				X			Improper valve lineup, procedures
Oconee 2	269/	7/29/74	80[a]				X			Demineralizer valve leakage
Surry 2	281/	7/12/74	50		X					Leaking valves
Turkey Point 4	251/[b]	7/5/74	c		X					Minor inleakage and insufficient recirculation
Turkey Point 3	250/	4/19/74			X					Unknown, possibly due to injection testing
Peach Bottom 2	277/74-4	2/27/74				X				Testing procedure
Cooper	298/74-2	2/7/74	0			X				Faulty chemical analysis
Point Beach 1	266/	11/3/73					X		Operator	Failure to sample transfer
Maine Yankee	309/73-6	11/6/73		X						Results from testing
Turkey Point 4	251/73-11	9/73			X					Primary water leak into suction of boric acid pump
Monticello	263/	6/4/73	c			X				Procedures for water addition
Dresden 3	249/	1/9/73				X				Demineralizer water valve and air sparging valves open
Maine Yankee	309/	12/15/72								Check valve leakage
Maine Yankee	309/80-017	9/19/80	65	X						Improper sampling procedure
Trojan	344/80-016	8/18/80	3				X		Operator	Procedures not followed
North Anna 1	338/78-13	4/25/78	0	X						Poor sampling
Zion 2	304/77-14	4/29/77	50		X					Back leakage through valves
Zion 2	304/77-15	4/29/77	48		X					Back leakage through valves
Salem 1	272/76-01	9/3/76	0				X			Charging pump discharge valve leaking
Ft. Calhoun 1	285/76-23	8/4/76	98[a]		X					Valve leaking
Turkey Point 4	250/76-4	6/25/76	100		X					Inleakage through isolation valve
Turkey Point 3	251/76-4	6/25/76	100		X					Inleakage through isolation valve
Turkey Point 4	251/76-5	6/25/76	100		X					Inleakage through isolation valve
Cook 1	315/76-26	6/15/76	75		X		X			Dilution from flushing lines
Indian Point 2	247/75-2	12/12/75	80[a]				X		Operator	Sampling inaccuracies and excessive flushing water
Turkey Point 4	251/	1/30/75	100[a]				X			Dilution during flushing
Beaver Valley 1	334/81-034	5/7/81	0				X			Procedural deficiency
Cook 1	315/81-001	2/13/81	100		X		X			Unknown
Surry 2	281/81-006	2/13/81	100		X					Leakage through check valve

[a] Forced reduction in power.

[b] Repeated events.

[c] Not given.

5. EVENTS OF POTENTIAL SIGNIFICANCE

The significance of all the reported events relating to unplanned boron dilution was evaluated, and the events were listed as to their safety relevance. The top six events are briefly described. These events resulted from either a common-mode failure, a control system failure that degraded a safety system operation, or a recurring single failure.

Human factor deficiencies in tagging, labeling, and both operational and administrative procedures appear to be the causative factors for the recurrent events. There were seven recurring, single failure events, four of which constituted 27% of all unplanned RCS boron dilution incidents.

Human errors were the causative factors in 81% of the RCS dilution incidents and in 46 of the unplanned dilutions of the boron concentrations in the holding and storage tanks (see Chap. 4).

1. At Oconee 1, a common-mode failure in boron analysis occurred during physics testing.[9] A sodium hydroxide solution used for titration in the determination of boron concentration in the RCS had been improperly evaluated as to normality. Therefore, for 3 d, during zero-power physics testing, the boron concentration determinations for the RCS were in error, and criticality was attained at other than the extrapolated value. The normality of the sodium hydroxide changed over a period of several months due to an absorption of carbon dioxide. This incident was an example of a common-mode failure. "Although the absolute boron concentrations were not accurately known, plant performance was accurately predicted and controlled using relative concentrations."[9]

The following four-step procedure[9] was inaugurated to prevent recurrence: (1) Fresh batches of standard sodium hydroxide solutions are to be prepared weekly for use in titrating boron samples. Quantities are to be kept small so that new solutions must be prepared. (2) A boron standard is checked in duplicate twice each day. (3) Each sample is run in duplicate twice each day. (4) Each sample is run in duplicate on a boron titrator. (5) A meter for measuring boron concentrations is used to provide an independent check of lab results.

prevent recurrence, (1) the operating personnel were informed of the event and its cause, (2) additional leak rates or tests were to be performed when the unit was in cold shutdown, and (3) the shutdown margin due to boron concentrations was to be recorded in graphic form so that trends would be obvious in the future. However, 5 months later at Unit 2, makeup water isolation valves were inadvertently left open and an unplanned RCS dilution incident occurred. The unit was in cold shutdown. Prevention of recurrence involved verifying .alve position prior to testing and depressurizing the isolation valve seal water supply tank whenever the unit is in cold shutdown.

6. CONCLUSIONS AND RECOMMENDATIONS

Accident analyses in the FSARs are quite different from the problems discovered in reviewing the actual operating experiences. The analytical exercise provides (1) for the verification of the initial design, (2) for its control concepts, and (3) for design-basis accidents; but feedback from the field via review of operating experiences does not appear to find its way back into the designs for the later plants. The same design philosophies seem to prevail in the recently licensed plants as did when the vintage plants were designed. Because the systems and their control are simple and conventional, the procedure of replication maintains the status quo. However, 81% of the operating experiences for unplanned dilutions of the RCS were other than those postulated in the design analyses in the PWR FSARs that were reviewed. Reviewers of SARs are principally concerned with the functioning of the systems as per the design criteria and safety philosophies. In the opinion of the author, operations, maintenance, and plant availability apparently are given only superficial consideration, if they receive any at all. (This opinion is based on the author's reviews of questions and answers made to plant SARs.) For example, there were five inadvertent dilution events of the standby liquid control system for BWRs, but all were within the period January 1973 to October 1974. Apparently, some lessons were learned at BWRs.

Human errors were the causative factors in 80% of the unplanned RCS dilution incidents and in 46% of the inadvertent dilutions of the boron concentrations in holding and storage tanks (BAT, BIT, RWST, and boric acid refueling tank). The errors were caused by incomplete or faulty procedures, selection of wrong controls or equipment, miscalculations, improper sampling, incorrect use of tools, and misapplication of equipment. Equipment failures were random and of the kind expected during normal service life. All of this is not unique to the nuclear industry, its modus operandi, or its regulations; but the situation can be improved.

On the average over the past 8 years, there have been 3 unplanned dilutions of the RCS per year, for a rate of about 0.05 such events per

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13. Oconee Nuclear Plant, Unit 1, *Improper Boration for Transient Xenon*, Abnormal Occurrence Report 269/74-6, Mar. 28, 1974.

14. Zion Nuclear Plant, Unit 1, *Unplanned Dilution Occurs at Zion 1*, Licensee Event Report 76-62, Oct. 15, 1976.

Appendix

SUMMARIES OF BORON DILUTION INCIDENTS

This appendix consists of summaries of occurrences involving inadvertent boron dilution in the RCS and in boron solution holding tanks during refueling, cold shutdown, hot standby, and critical operation. Summarized information is taken from the respective LERs (docket numbers, LER numbers, and dates are in parentheses).

Refueling

1. St. Lucie Plant, Unit 1 (335/79-15, June 7, 1979)

Two tubes in one steam generator (SG) were unknowingly cut during a SG modification. When the SG secondary side was serviced for operation, feedwater passed through the damaged tubes and into the RCS. This dilution of the RCS boron concentration (1698 ppm) was detected by surveillance inspection. "No core alterations or positive reactivity changes occurred and more than adequate shutdown margin was always maintained." Proper concentration (1720 ppm) was restored in 135 min.

2. Point Beach Nuclear Plant, Unit 1 (266/79-19, November 21, 1979)

Two tubes that had sections removed from the hot-leg side were not plugged on the cold-leg side. During filling of the SG secondary side, secondary-to-primary leakage occurred from one tube into the primary outlet nozzle. Filling was stopped, but the secondary-to-primary leakage continued for another hour due to siphoning over the U-levels. "At no time did the reactor deviate from the refueling subcriticality conditions." Proper concentration (1800 ppm) was restored from a low of 1733 ppm in 4 h.

3. Trojan Nuclear Plant (344/80-10, June 27, 1980)

A miscalculation was made regarding the amount of excess boric acid required to offset the demineralized water used in high-pressure washing of the SG tube sheets. "There was no effect on safety because core alterations had been completed." Concentration had dropped to 1902 ppm from the Technical Specification minimum of 2000 ppm.

Cold Shutdown

4. Indian Point Station, Unit 1 (3/---, June 5, 1969)

Unborated water reached the core through a previously detected SG leak during a hydrostatic test of the RCS. Coolant pumps were not running; therefore, mixing through the core was poor. The shutdown margin decreased from 3.1 to 1.5%.

5. Ginna Nuclear Power Plant (244/74-1, January 28, 1973)

When the SG manway cover was removed, an in-rush of air unbalanced the pressure on water in the tubes. Some of this water drained into the RCS and caused a 3% change in reactivity. "The reactor was always subcritical."

6. Surry Power Station, Unit 1 (280/75-01, February 24, 1975)

Over a 4-d period, too great a flow of primary-grade water to the blender produced a boron concentration of 1312 ppm, which diluted the RCS to 1842 ppm from the required 2000 ppm. A temporary loss of power to the flow controller caused the controller to switch to manual operation. The control valve was fully open at that time and thus remained fully open. The manual mode status light was burned out and therefore could not alert the operator. Discovery was made by routine chemistry sampling. "Had the dilution continued indefinitely, the reactor coolant boron concentration would have leveled off at 1312 ppm. This concentration would have maintained the required shutdown margin."

7. Ginna Nuclear Power Plant (244/75-06, March 25, 1975)

A deborating demineralizer instead of a cation demineralizer was valved onstream. This error in the procedures caused the RCS boron concentration to be unintentionally reduced from 2068 to 1975 ppm.

8. Surry Power Station, Unit 2 (281/76-03, July 30, 1976)

Leakage from three tubes that had been cut during the removal of a section of the seventh tube support plate on the secondary side of the SG diluted the boron concentration in the RSC from 2356 to 1836 ppm. This resulted in a shutdown margin of 11.6% as compared with a required minimum of 1%.

9. Zion Nuclear Plant, Unit 1 (295/76-62, October 15, 1976)

Isolation water entered the RCS through a normally closed makeup water valve and in 17 h reduced the boron concentration from 1081 to 964 ppm. "This posed no safety problem because the reactor was at all times shut down by the required margin."

10. Crystal River Nuclear Plant, Unit 3 (302/77-12, February 16, 1977)

Placing the mixed-bed demineralizer into service during RCS cleanup instead of the cation bed caused a 230 ppm reduction in the boron concentration. "Shutdown margin was maintained at least 8.51% $\Delta K/K$, assuming the highest worth control rod withdrawn, 11% $\Delta K/K$ with highest worth rod inserted."

11. Zion Nuclear Plant, Unit 2 (304/77-9, March 24, 1977)

Incorrectly positioned (open) seal water system isolation valves caused the RCS level to increase 3 ft in 3 h and the boron concentration to decrease from 2182 to 2090 ppm. "The boron concentration was at all times above the refueling concentration of 1888 ppm, and so there were no safety implications."

12. Calvert Cliffs Nuclear Power Plant, Unit 1 (317/78-9, February 2, 1978)

The RCS had been drained down to about 12 in. above the bottom of the hot leg to allow for an inspection of the SG. Due to the slow mixing of the stagnant coolant in the hot and cold legs with coolant in the vessel, the RCS boron concentration slowly decreased from 1720 to 1660 ppm.

13. Surry Power Station, Unit 2 (281/78-12, April 6, 1978)

A failed flow controller caused the primary-grade water valve to overfeed during blend operation. The boron concentration in the RCS decreased from 1372 to 1259 ppm in 13 h. The failure also affected the primary-grade water flow deviation. "Had the event proceeded undetected for an extended period of time, the reactor would never have been less than about 2.3% shut down."

14. Millstone Nuclear Power Station (336/78-5, May 4, 1978)

A partially open bypass valve for the primary makeup water flow control valve allowed the RCS boron concentration to be diluted from 2068 to 1634 ppm. This happened three times on consecutive days, but on two of them the unplanned dilution was masked by planned dilutions. While the bypass valve was thought to be locked closed, it actually was locked three-quarters of a turn open. This resulted from a visual check of valve position rather than a physical verification. "The required shutdown margin of greater than 1% $\Delta K/K$ was maintained during the dilution."

15. Surry Power Station, Unit 1 (280/---, May 12, 1980)

Inadvertent boration of the RCS occurred when a mixed-bed demineralizer was placed in service without verifying that boron concentration of the effluent was equalized with that of the RCS.

16. Oconee Nuclear Plant, Unit 2 (270/80-03, June 5, 1980)

The chemistry records for the deborating demineralizer had not been kept up to date. When the demineralizer, which was thought to be boron saturated, was placed into service, the RCS boron concentration changed from 1895 to 1539 ppm in about 2 h. "A margin of 296 ppm existed above that necessary to maintain the 1% $\Delta K/K$ required shutdown margin."

17. San Onofre Nuclear Generating Station, Unit 1 (260/80-29, July 21, 1980)

Leaky inflatable plugs used to isolate an SG during channel head decontamination resulted in the RCS boron concentration changing from 3357 to 2957 ppm. The inadvertent dilution occurred during a time when containment integrity was not established. "However, at no time did boron concentration decrease below 2400 ppm, which represents a K_{eff} of 0.90."

18. San Onofre Nuclear Generating Station, Unit 1 (206/80-34, September 17, 1980)

While an SG tube removal was being performed, unexpected water in the secondary side flowed by a nonwatertight plug in the nozzle and entered the RCS. The water had leaked past a block valve downstream of the feedwater regulator valve. A maximum dilution of 35 ppm occurred. "At no time since refueling has the RCS boron concentration dropped below 2400 ppm, which represents a 10% shutdown margin."

Hot Shutdown/Standby

19. Oconee Nuclear Plant, Unit 1 (269/---, July 17, 1973)

During zero-power testing, the predicted boron concentration for criticality was 1334 ppm. However, indications were that criticality would be reached at about 1000 ppm. The normality of the sodium hydroxide solution used for the boric acid titration was incorrect, and this condition had existed for 4 d. The errors in the boron analysis were systematic (common-mode failure). "Although the absolute boron concentrations were not accurately known, plant performance was accurately predicted and controlled using relative concentrations."

20. Surry Power Station, Unit 2 (281/---, November 26, 1977)

The RCS was diluted to 873 from 950 ppm due to a misinterpretation of the dilution nomograph. "The reactor was at all times more than 2% shut down."

21. Crystal River Nuclear Plant, Unit 3 (302/77-8, February 9, 1977)

A makeup and purification demineralizer was inadvertently placed into service while the unit was recovering from a trip. RCS boron concentration was diluted about 50 ppm. "Shutdown margin remained greater than 4% $\Delta K/K$."

22. Zion Nuclear Plant, Unit 2 (304/---, May 16, 1974)

The reactor was made critical with one control rod bank below the low-low insertion limit due to an incorrect RCS boron sampling technique. The boron concentration used for the estimated criticality calculation was reported as 1108 ppm when actually it was 1053 ppm. "This incident did not degrade, hamper, or jeopardize the safety of the plant."

23. Point Beach Nuclear Plant, Unit 1 (266/---, June 8, 1974)

The controls for the boric acid blender permitted the output concentration to be 20% less than the desired value, which resulted in a boron concentration of 1435 ppm instead of the expected 1470 ppm in the RCS. "Throughout this occurrence a shutdown margin in excess of 4% ΔK/K existed. At all times the reactor was sufficiently subcritical to protect the core from all potential reactivity accidents."

Critical Operation

24. Indian Point Station, Unit 2 (247/A04-2-6, February 8, 1974)

Criticality was achieved with the control rods about 27 steps below the insertion level for criticality. The boron concentration was 1125 ppm. "With the assumption that one rod is stuck in its fully withdrawn position, the boron concentration in the RCS was still more than sufficient to shut the reactor down."

25. Oconee Nuclear Plant, Unit 1 (269/74-6, March 28, 1974)

A series of power level changes left the unit operating at 90% of full power. However, continued control rod insertion to compensate for xenon burnup would have resulted in the violation of the control-rod-withdrawal Technical Specification limitation. Therefore, boration was begun to keep the control rods within the insertion limits. Shortly afterwards, a review of the situation revealed that xenon had not been at equilibrium, and the addition of boron was contrary to Technical Specifications. The power level was immediately reduced to below 80% full power. "The principal cause of the occurrence was misevaluation of transient xenon reactivity changes following a series of changes in power level. A contributing case to the occurrence was misunderstanding of the intent of Technical Specification 3.5.2.5-d, which prohibits changes in boron concentration above 80 percent full power to compensate for transient xenon but allows boration to compensate for reactivity effects other than transient xenon at any time."

26. St. Lucie Plant, Unit 1 (335/80-71, January 1, 1981)

While blending boric acid to slightly dilute the RCS, a relief in the line to the blending valve failed. This returned the boric acid to the boric acid makeup tank instead of diluting it and sending it into the VCT. This resulted in the dilution of the RCS because pure water reached the RCS. The plant is designed to safely accommodate this transient, but the event is potentially significant because of the misleading indication given. Because the relief valve is downstream from the boric acid flow element, the operators had indication of a normal blend to the VCT. The small amount of acid involved (a few gallons) and the large boric acid tank size (8000 gal) did not cause a noticeable change in tank level. Increasing power was the first indication of the transient, and the cause was not readily apparent. Because dilution via the VCT is a slow process, the transient had been in progress for several minutes before there was any indication of dilution.

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16. ABSTRACT *(200 words or less)*

This report reviews and evaluates events concerned with the inadvertent dilution of boron concentrations to the reactor coolant system for pressurized-water-cooled thermal reactors in commercial service. The safety concern is the unplanned addition of reactivity. The information was collected from operating experiences, licensee event reports, system designs in safety analysis reports, and regulatory documents. The results are collated and analyzed for significance and impact on power plant safety performance.

Several operating experience events were selected for analysis because they meet the criteria for safety significance. However, no boron dilution incidents resulted in a reactivity excursion or transient that scrammed a unit, nor was a reactor protection system challenged by any of the events. The most common cause for unplanned boron dilutions was human error, of which one was a common-mode/common-cause failure. For each recorded event, the operator had sufficient time to diagnose and correct the cause of the inadvertent dilution before the shutdown safety margin was lost or seriously challenged.

17. KEY WORDS AND DOCUMENT ANALYSIS

- Boron Dilution
- Nuclear Power Plant Operating Experience

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