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1

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BORON INJECTION AT NATURAL CIRCULATION

CONDITIONS IN PWRs*

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ABSTRACT

Combustion Engineering has performed a boron injection test at San Onofre Unit 2 to demonstrate the ability to borate to the cold shutdown concentration at natural circulation conditions. The test was run in July 1983 and it has been analyzed with the BITRAN code developed at BNL. The test results will demonstrate injection and cooldown capability and provide data for validating boron transport and mixing models.

Extrapolation of the test to more severe emergency conditions indicates oscillations in boron concentration which are predicted to decay within one hour after injection.

INTRODUCTION

The purpose of the present paper is to analyze a test conducted at San Onofre to demonstrate boron injection and cooldown capability after loss of offsite power in a PWR. The analytical methods can then be used to extrapolate the test results to more severe emergency conditions.

The design of commercial light water reactors (LWRs) in the United States has included all systems and components which are necessary to reach and maintain hot standby conditions (design

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temperatures and pressures but with the reactor at least 1.0% subcritical).

Generally, it is considered prudent to remain at hot standby conditions and not to impose additional reactivity, temperature and pressure transients by proceeding to cold shutdown. However, the issuance of Regulatory Guide 1.139¹ which requires the consideration of methods to achieve cold shutdown and long-term cooling, has made it necessary for the nuclear industry to address the requirement to cool down and depressurize the reactor plant with safety-related systems and components. The current Regulatory position² indicates that in order to obtain compliance, startup test programs for (PWRs) "shall include tests with supporting analysis to (a) confirm that adequate mixing of borated water added prior to or during cooldown can be achieved under natural circulation conditions and permit estimation of the times required to achieve such mixing, and (b) confirm that the cooldown under natural circulation conditions can be achieved within the limits specified in the emergency operating procedures."

Southern California Edison (SCE) has submitted a test program (Reference 3) which is intended to meet the safety grade boron injection and cooldown requirements given in the NRC's Branch Technical Position (BTP) RSB 5-1. The test procedures are summarized in Table 1 to facilitate discussion.

Test B3 is intended to be a demonstration of boron injection and cooldown during natural circulation using safety grade equipment. However, it will not be conducted at "worst-case" conditions. Thus, it will be necessary to use analytical methods to extend the results to other conditions and other reactors. Combustion-Engineering has provided their analysis³ of the test but they have not included boron concentrations. The present results use BITRAN⁴ developed at BNL to calculate boron transport and mixing.

BITRAN DESCRIPTION

The special requirements of the boron concentration tests have necessitated the development of specialized calculational tools to efficiently analyze the long duration transients which are characteristic of natural circulation events. BITRAN⁴ has been developed with minimum complexity in order to achieve this efficiency goal. BITRAN has been written with the DARE-P⁵ simulator package in order to retain maximum flexibility in the modeling features as requirements change. The DARE-P package translates the differential equations into a finite difference formulation and solves them by optional methods. The method selected for the present results has been the variable-step Runge-Kutta with error control.

Table 1 Summary of Test B3 Procedures

I. Initial Conditions

1. Plant stable at 80% power
2. Pressurizer and steam generator controls on automatic

II. Natural Circulation Procedure

1. Trip reactor
2. Trip pump
3. Reduce main feedwater to 5% flow then secure 10 minutes later
4. Secure all but 1E pressurizer heaters
5. Steam generator control is shifted to manual with emergency feedwater per steam generator in on/off control
6. Stabilize plant
7. Measure power versus flow

III. Boron Injection Procedure

1. Determine required boron increase (minimum of 100 ppm)
2. Initiate boron sampling
3. Borate at 88 gpm
4. Stabilize within ± 10 ppm

When it is necessary to change the model, it is anticipated that this will be done by UPDATES to the program library. Since most of the routines used in BITRAN derive from DARE-P itself, the limited coding can be translated and compiled in about 20 seconds of CDC 6600 time. The transient can then be executed at a ratio of about 50 simulated seconds per computer second.

The applicable differential equations are given by example for typical components below. The full equation set is contained in the derivative block of the BITRAN listing in Appendix B of Reference 4.

Mass Conservation

Incompressible flow with injection and letdown:

$$DM_{out} = DM_{in} + DM_{inj} - DM_{ld}$$

where inj is injection and ld is letdown.

Species Concentration

Perfect mixing at: injection point, lower plenum, upper plenum, and Volume Control Tank (VCT):

$$\frac{d(CUP)}{dt} = -DMUP * (CUP - CUP_{in}) / MUP.$$

Pure transport delay in piping, core (COR), steam generator (SG) and pressurizer:

$$CCOR_{out}(t) = CCOR_{in}(t - DELAY)$$

where DELAY = VOL * RHO / DMCOR.

Momentum

One-dimensional neglecting injection momentum:

$$\frac{d(DM)}{dt} = - (DPF - DPB) * GC / ENRTIA$$

where DPF is the summation of frictional pressure drops and DPB is the integral of the gravitational force (buoyant force) around the loop.

Energy

Perfect mixing at injection point (inj), lower plenum (LP), upper plenum (UP), and pressurizer (PRZR):

$$\frac{d}{dt} (TLP) = - DMLP * CP * (TLP - TLP_{in}) / MCPLP$$

where MCPLP is the mass-specific heat product of the lower plenum including structure.

Pure Transport delay in piping:

$$THL_{out}(t) = THL_{in}(t - DELAY)$$

where $DELAY = VOL_{HL} * RHO / DM_{HL}$ for the hot-leg (HL).

For purposes of sensitivity studies each plenum may be divided into two volumes for which one portion of the plenum is assumed to be perfectly mixed while the remaining portion of the plenum sees pure transport delay.

Neglect transient conduction in core:

$$\frac{d}{dt} (TCOR) = [QCOR - DMCOR * CP * (TCOR - TCOR_{in})] / MCPCOR$$

where QCOR is the decay heat (from ANS Standard or tabular input) and MCPCOR is the mass-specific heat product of the core including fuel rods and structure.

Perfect control of the steam generator is assumed such that the primary side outlet temperature (TP) is a prescribed function of time. The temperature distribution is determined from a log-mean temperature difference approximation.

$$TP(X) = TSAT + (TP_{in} - TSAT) e^{-X/X^*}$$

where X is the distance along the heated tube and X* is the effective heating length given by $X^* = DM * CP / (H * PH)$.

Convective heat losses to the environment are a significant part of the cooldown transient and they are assigned to the upper plenum:

$$\frac{d}{dt} (TUP) = [(QLSRAT) \frac{(TUP - TENV)}{530} - DMUP * CP * (TUP - TUP_{in})] / MCPUP$$

where QLSRAT is the heat loss at rated conditions.

Pressurizer

A simplified pressurizer model is used to follow the pressure fluctuations during the boron injection and cooldown transients.

During injection, the pressurizer steam space is assumed to undergo isentropic compression such that:

$$PPRZR + \Delta PPRZR = PPRZR * [(VPRZR + \Delta VPRZR/VPRZR)]^{1.3}.$$

After reaching the pressurizer set point, perfect control is assumed such that the pressure remains constant until cooldown is initiated. During cooldown, isentropic expansion is assumed (with an exponent of 0.92 to account for condensation) until the saturation pressure is reached. A saturation process is assumed for the remainder of the cooldown.

TEST DESCRIPTION

The objectives of the Boron Injection Test (Test B3) are:

1. To measure the plant response to a total loss of forced reactor coolant flow from 80% power.
2. To verify natural circulation following the trip from 80% power.
3. To demonstrate that adequate boron mixing can be achieved under natural circulation conditions.
4. To demonstrate the ability to perform a natural circulation cooldown to shutdown cooling system initiation conditions.
5. To evaluate natural circulation flow conditions.

The test procedures are outlined in Reference 3. A summary of these procedures is given in Table 1 for the boron injection portion of the test.

The conditions for the boron injection test are described in Table 2. Note that the essential differences between the test and the hypothetical emergency conditions are that letdown will not be used (since it is not safety grade) and that the charging pumps will take suction directly from the boric acid transfer pumps without dilution. The decay heat and required boric acid addition could also change based on the plant's operating history. But for purposes of comparison, these parameters are left constant.

Table 2 SONGS Boron Injection Test Conditions

<u>Item</u>	<u>Value</u>
Prior operating time	34 hours
<u>Prior power level</u>	<u>80% (2712 MWt)</u>
CEA insertion time	0.2 s
Pump trip time	0.0 s
Natural circulation stabilized	2000 s
Automatic pressurizer level at	33%
Initial boron concentration	480 ppm
Cold-leg temperature	545°F
Boron injection initiation	5500 s
Boron injection rate	3.9 gpm for 12 min 20 gpm for 41.5 min
Boron injection temperature	165°F
Boric acid make-up (BAMU) concentration	8.25 wt% (14440 ppm)
Letdown flow rate	84 gpm
Charging flow	88 gpm

Assumed Differences Under Emergency Conditions

Letdown flow rate	0 gpm
Charging flow rate	0 gpm
Boron injection rate	88 gpm
Boron injection time	10 min

RESULTS

The boron injection test was performed on July 27, 1983. The analytical results for loop ΔT and hot-leg boron concentration are shown in Figures 1 and 2. This analysis is in substantial agreement with preliminary test results but the plant data has not been released yet. Note that for the low injection rate (≤ 20 gpm) of the test, the boron concentration rises smoothly to the equilibrium concentration with only small oscillations in concentration. The oscillations in the data are difficult to distinguish due to the sampling rate.

For purposes of comparison, BITRAN was used to generate predictions for a boron injection transient under emergency conditions. As indicated in Table 2, letdown is assumed not to be available since it is not safety grade. Boron injection would be accomplished through the charging pumps at both high flow rate and high concentration. The decay power level and the required amount of boron would also increase under "worst-case" conditions but these parameters are kept constant for ease of comparison. The resulting boron concentration transient is shown in Figure 3. For this case there are much more severe oscillations in concentration but they decay within about one hour.

Figure 1 Loop temperature difference (F) for the San Onofre boron injection test calculated with BITRAN.

Figure 2 Hot-leg boron concentration (ppm) for the San Onofre boron injection test calculated with BITRAN.

Figure 3 Hot-leg boron concentration (ppm) for the San Onofre plant under assumed emergency boron injection conditions predicted with BITRAN.

CONCLUSION

It is concluded that the test conducted at San Onofre provides a valuable demonstration of boron injection and cooldown under emergency conditions. However, preliminary results indicate that when the data is released it will provide limited validation of the mixing models needed to extrapolate the results to other conditions in other reactors.

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I=DELTA

FIGURE 1

I=CHLA

FIGURE 2

1=CHLA

FIGURE 3