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MARK II CONTAINMENT PROGRAM

CAORSO EXTENDED DISCHARGE TEST REPORT

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ABSTRACT

This report presents the results of the safety relief valve extended discharge test (Test 40) performed at the Caorso Nuclear Power Plant in Italy during February 1979. The objective of the test was to evaluate the thermal mixing characteristics of the Mark II suppression pool during an extended safety relief valve discharge through an X-Quencher.

1. INTRODUCTION

1.1 BACKGROUND

Phase II of the Caorso safety relief valve (SRV) discharge test program* was conducted during January and February 1979. The extended discharge test was included in the test program to demonstrate the thermal mixing characteristics of the Caorso suppression pool.

The X-Quenchers installed in Caorso have four arms which extend 5 feet from the quencher hub centerline (see Figure 1-1). Each arm is perforated with 374 holes for a total of 1496 holes per quencher (see Figure 1-2). The quencher was designed to mitigate the air clearing and steam condensation loads associated with SRV discharge.

Following the extended discharge, the residual heat removal (RHR) system was operated in the pool mixing mode to enhance thermal mixing. The RHR system consists of four twenty-inch suction lines (at the 140°, 164°, 222°, and 235° azimuths) and two sixteen-inch discharge lines (see Figure 1-3). The discharge portion of the RHR discharge line is horizontal near the pool bottom. Water is discharged into the suppression pool from two rows of holes 180° apart (see Figure 1-4). Each row contains 15 holes placed at 200-mm (7.9-inch) intervals.

1.2 TEST OBJECTIVES

The objective of the test was to obtain temperature data that could be used to evaluate the thermal mixing performance of an X-Quencher device discharging into an initially quiescent Mark II suppression pool.

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*C. Kawate et al., "Caorso Relief Valve Loads Tests - Test Plan," NEDE-20988 Revision 2, Addendum 1, October 1977, Addendum 2 April 1978.

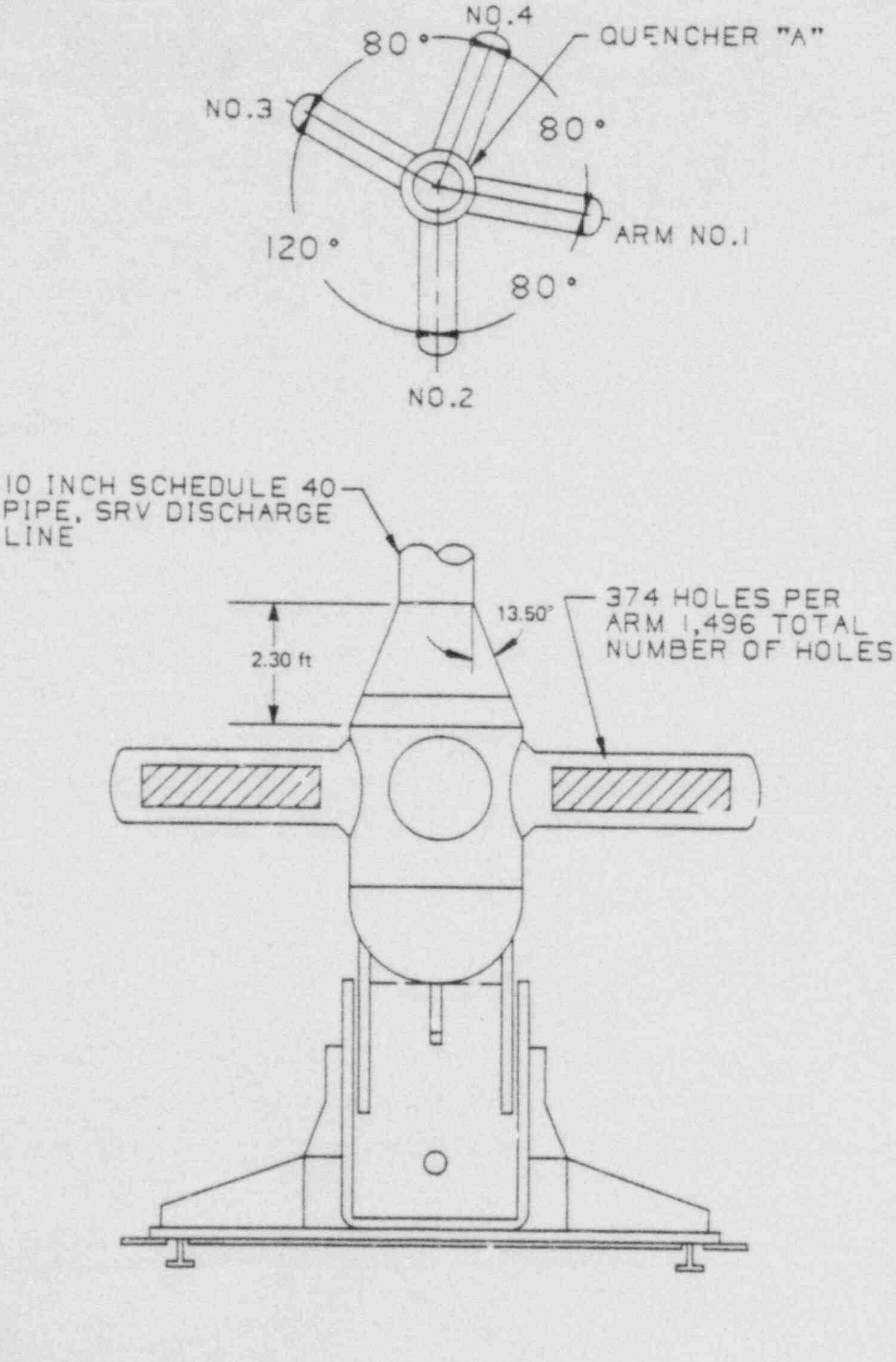
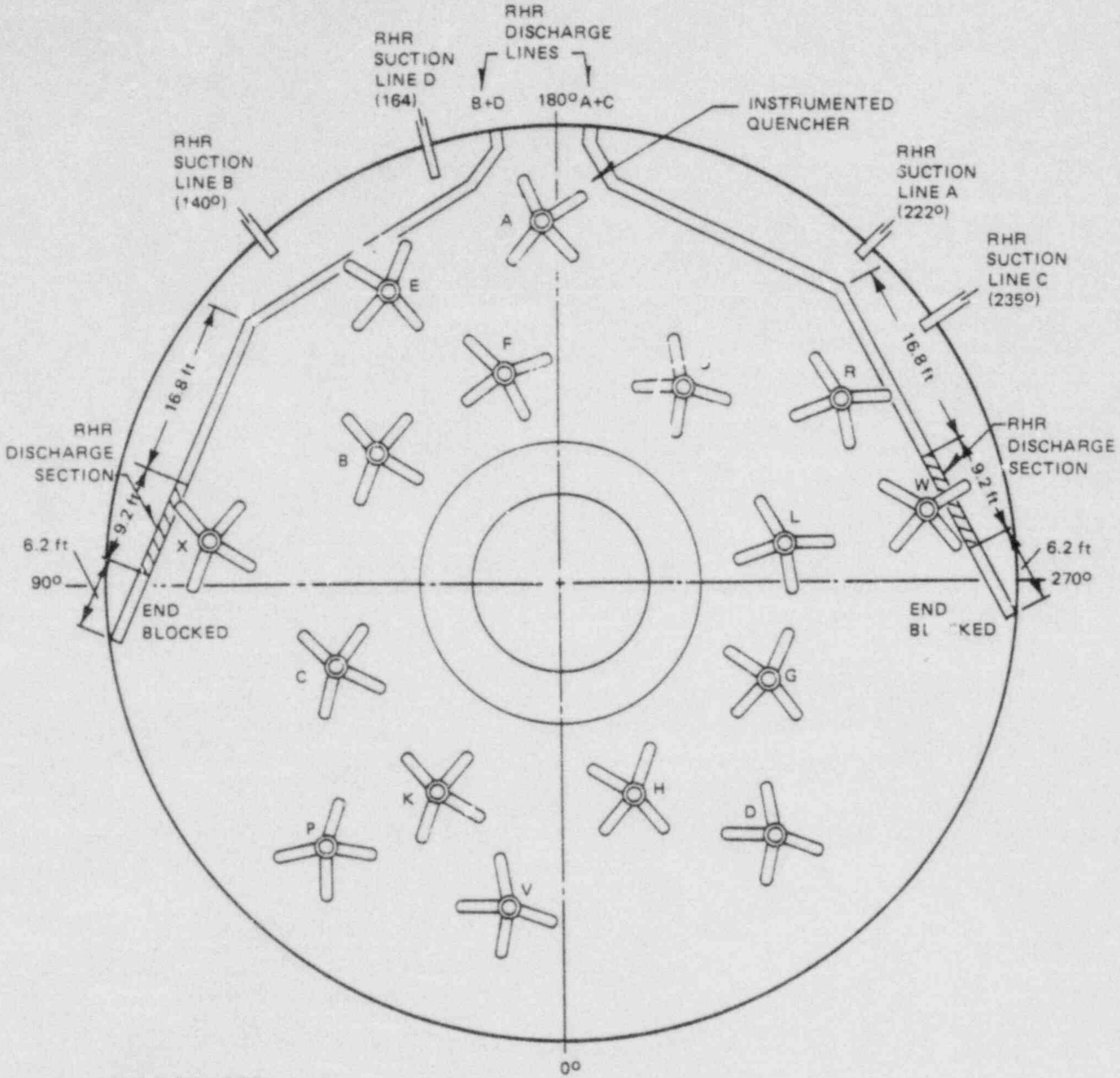


Figure 1-1. Caorso Quencher and Support

(General Electric Company Proprietary)

Figure 1-2. Quencher Arm



RHR DISCHARGE
℄ ELEVATION = 130.10 ft (39.65 m)
RHR SUCTION ELEVATION = 144.30 ft (44.00 m)
SUCTION LINE DIAMETER = 20 in.
DISCHARGE LINE DIAMETER = 16 in.

Figure 1-3. Orientation of Safety Relief Valve Discharge Quenchers Within Caorso Suppression Pool

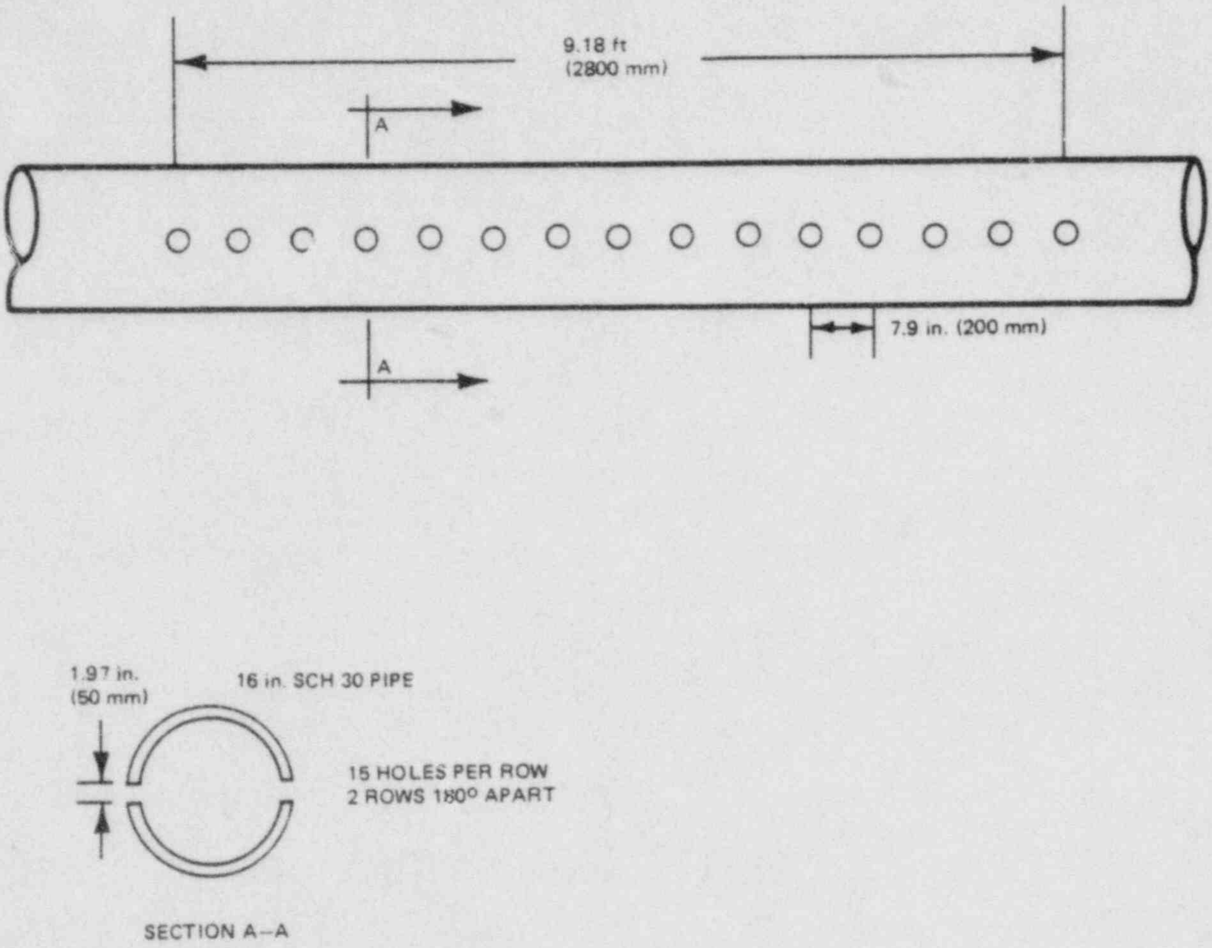


Figure 1-4. Discharge Portion of RHR Discharge Line

2. PRINCIPAL OBSERVATIONS

- At the time of the SRV closure, i.e., after 13 minutes, 7 seconds of steam discharge, the average temperature of the suppression pool water in the vicinity of the quencher rose to a maximum of 100°F. This corresponded to a calculated bulk pool temperature of 95°F.

- SRV discharge through the quencher causes convective currents in the pool. As a result, the energy introduced by the discharging steam is transferred away from the quencher allowing effective use of the suppression pool as a heat sink.

- After 4 minutes of RHR operation the vertical thermal stratification at the quencher location decreased from 12°F to approximately 5°F.

3. TEST PROCEDURE

SRV A was actuated for this extended discharge test. Prior to start of the test, the RHR system was operated in the pool cooling mode. This resulted in an initially uniform pool temperature of 60°F. Pool cooling was stopped 4-1/2 hours before the test in order to minimize pool motion. After verification that initial conditions were satisfactory (see Table 3-1) and proper communications established between the control room and the recording station in the reactor building, steady state data were collected. The actual test started with a 15-second countdown. All recording equipment was started before the count began and the valve actuated at time zero.

The valve was allowed to discharge until any one of the following limiting conditions was reached:

1. A calculated bulk pool temperature of 101.5°F* (see Appendix A).
2. Any in-plant temperature sensor reading of 101.5°F (38.6°C).
3. A suppression pool water level elevation of 46.28 m (151.8 ft).

The valve was closed 13 minutes and 7 seconds into the test when temperature sensor T302 registered a pool temperature of 102.2°F (39°C). RHR pumps A & C began operating in the pool mixing mode approximately 3 minutes 40 seconds after valve closure. Temperature data were recorded for 30 minutes after SRV A was closed.

The following information was recorded during the test in addition to the pool temperatures:

a. Feedwater flow rate

b. Reactor vessel water level

c. Reactor vessel pressure

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*101.5°F was the specified temperature limit for the test. In case an SRV stuck open, the reactor was to be scrammed at 110°F.

d. Generator output

e. Total steam flow

f. SRV actuation signal

g. Core flow

Table 3-1

INITIAL TEST CONDITIONS

Reactor Power Level	56%
Core Flow	91%
Reactor Water Level	3.15 ft
Reactor Pressure	975 psig
Suppression Pool Level	46.08 m (151.2 ft)
Water Temperature	60°F

4. INSTRUMENTATION

Ten resistance temperature detectors (T11 through T20) were placed in the suppression pool. These were GE assembled sensors using a Micro-measurement ETC-50A gage with a measurable temperature range of 0 to 500°F and a required accuracy of ±3°F (see Table 4-1). These sensors were complemented by the in-plant temperature monitoring system. Location of these sensors is shown in Figures 4-1 and 4-2.

Eight of the ten pool temperature sensors (T11 through T15, T18, T19 and T20) were positioned in the vicinity of the quencher. These sensors recorded the maximum pool temperatures expected to occur near the quencher.

Three sensors (T11, T12 and T13) were located in a vertical array centered between two of the quencher arms. Sensor T13 was located at the quencher arm elevation and measured the temperature of the pool water immediately adjacent to condensing steam. Temperature readings from sensors T11 and T12 were used to indicate the degree of vertical thermal mixing during the SRV discharge.

Temperature sensors T18, T19 and T20 were placed on a column 6 feet from the quencher (column 7) at the same elevations as T11, T12 and T13, respectively.

Temperature sensor T15 was placed on another column (column 8) 6 feet from the quencher in the opposite direction from column 7. These sensors recorded pool temperatures a short distance from the quencher.

Temperature sensor T14 was located on the outside of one of the quencher arms. Like sensor T13, T14 also measured the temperature of the water in direct path of the condensing steam.

Temperatures away from the discharging quencher were recorded by sensors T16 and T17. These sensors were placed vertically on a column on the 65° azimuth away from the quencher.

The in-plant temperature monitoring system consisted of five monitoring locations. Except for T302 each location included two temperature sensors placed close together at the same elevation, e.g., temperature sensor T308 contained temperature sensors T308A and T308B. In-plant sensors were placed circumferentially around the pool 2.3 ft from the pool surface. Due to their proximity to the upper pool surface, the in plant temperature sensors monitored the warmer temperatures expected to occur at higher elevations.

Data from temperature sensors T11 through T20 were recorded on real time charts and magnetic tape. In-plant temperature sensor measurements were read from the control room console at 37-second intervals and recorded manually.

During the test five brush recorders with 32 channels provided real-time monitoring. Of these, 10 channels were allocated for temperature sensors (T11 through T20). Digitized time histories of the temperature sensor data were obtained from the instrumentation system shown in Figure 4-3.

The predicted system "end-to-end" accuracy was calculated at ±1.7°F.* This included the specified sensor accuracy and the accuracy associated with the data recording system. All temperature sensors monitored during this test performed well.

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*Mark II Containment Supporting Program Caorso Safety Relief Valve Discharge Tests Phase I Test Report," NEDO-25100, August 1979.

Table 4-1

SENSOR SPECIFICATIONS

SENSOR REQUIREMENTS/CHARACTERISTICS

Type of sensor: Resistance temperature detector

Location: Wetwell - pool

Sensor designation(s): T11 through T20

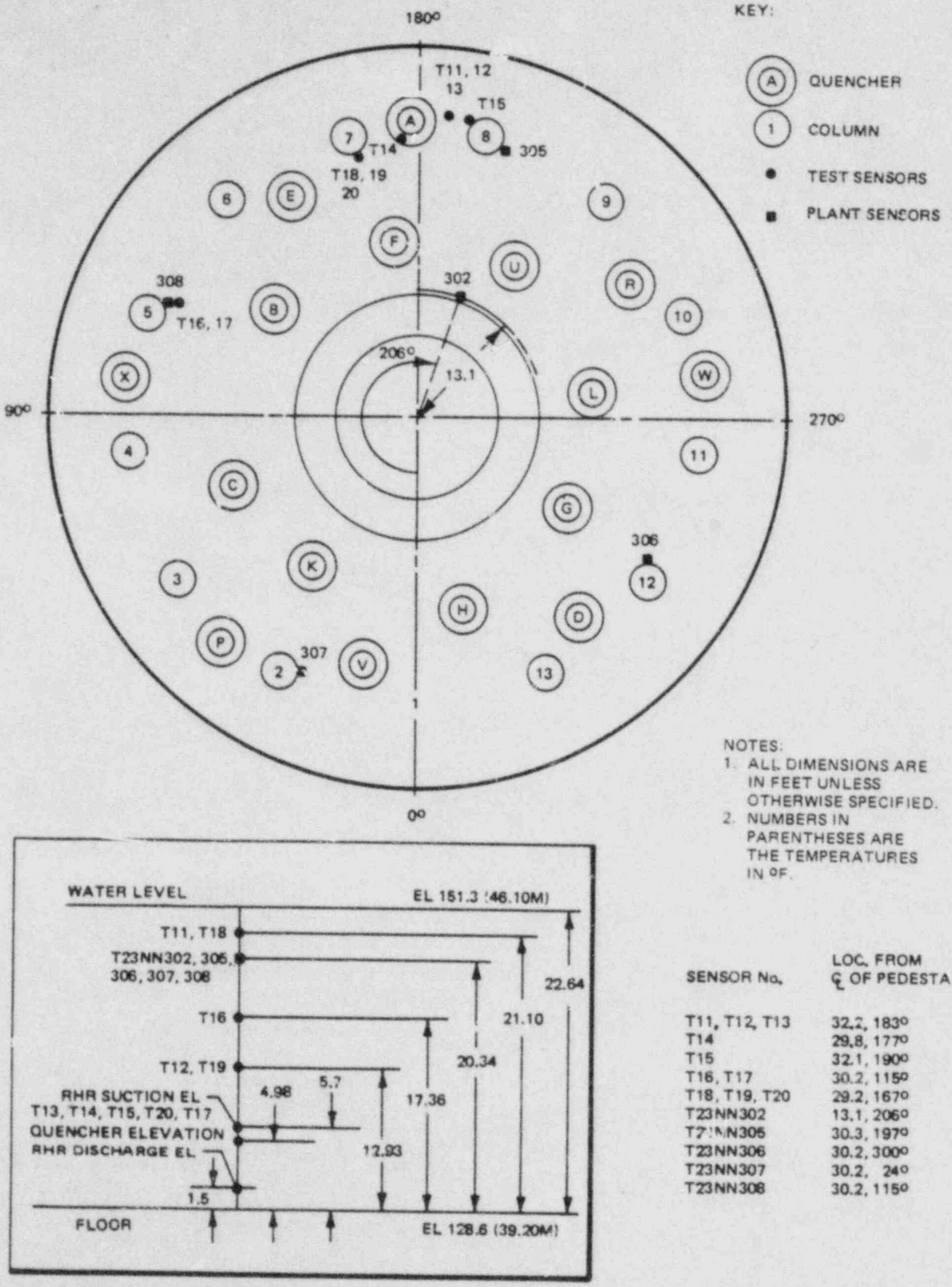
Variable to be measured: Temperature (of pool)

Highest frequency component (Hz): 2

Lowest frequency component (Hz): 0

Sensor manufacturer, model: GE-assembled using Micro Measurements - ETG-50A gage

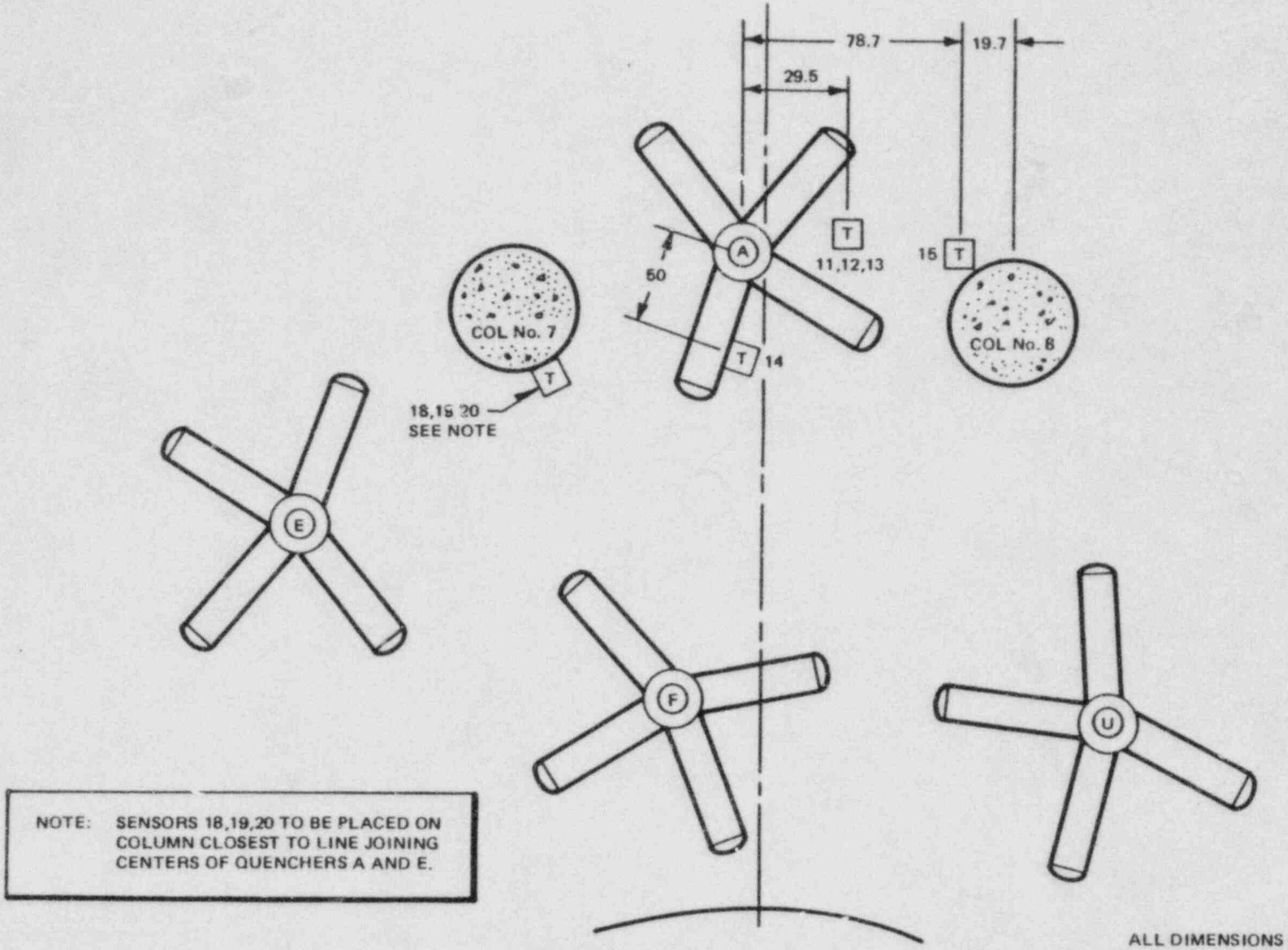
Range/Required Accuracy: 0°F to +500°F/±3°F steady state



NOTES:
1. ALL DIMENSIONS ARE IN FEET UNLESS OTHERWISE SPECIFIED.
2. NUMBERS IN PARENTHESES ARE THE TEMPERATURES IN °F.

SENSOR No.	LOC. FROM ℄ OF PEDESTAL
T11, T12, T13	32.2, 183°
T14	29.8, 177°
T15	32.1, 190°
T16, T17	30.2, 115°
T18, T19, T20	29.2, 167°
T23NN302	13.1, 206°
T23NN305	30.3, 197°
T23NN306	30.2, 300°
T23NN307	30.2, 24°
T23NN308	30.2, 115°

Figure 4-1. Pool Temperature Sensors Location



NOTE: SENSORS 18,19,20 TO BE PLACED ON COLUMN CLOSEST TO LINE JOINING CENTERS OF QUENCHERS A AND E.

ALL DIMENSIONS IN inches

Figure 4-2. Pool Temperature Sensors Location

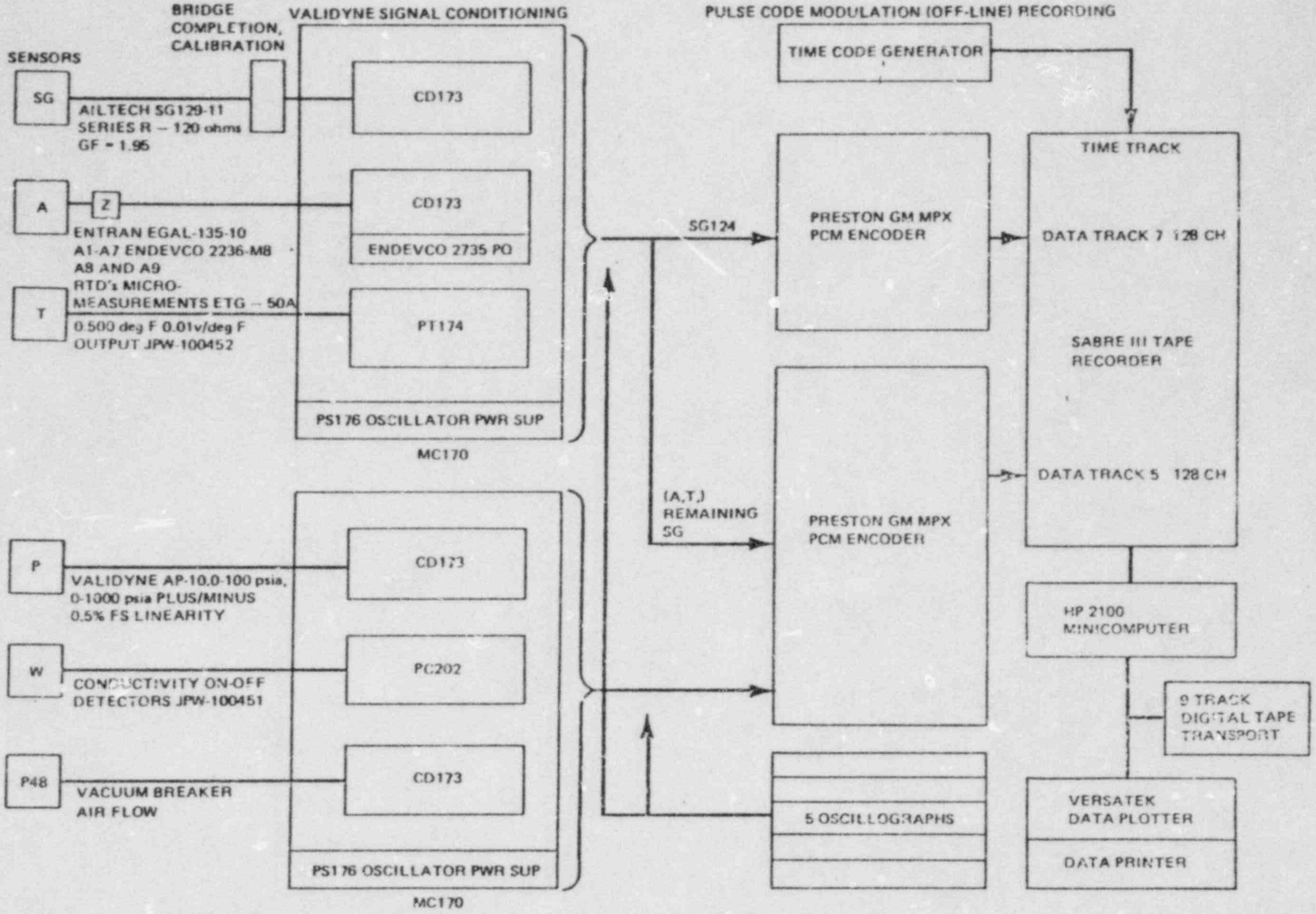


Figure 4-3. Block Diagram of Instrumentation System with Pulse Code Modulated System

5. DISCUSSION OF RESULTS

5.1 DESCRIPTION OF THE PHENOMENON

The steam flow rate through SRV A was calculated to be approximately 237 lbm/sec during the extended discharge (see Appendix A). During the discharge, momentum and thermal energy were imparted to the suppression pool in the vicinity of the quencher. As a result, pool motion was created near the quencher, where the water heated by condensing steam was carried away from the quencher and replaced by cooler water. The convection within this region intensified until the energy introduced locally by the quencher was equal to the energy carried away from the quencher.

5.2 RESULTS

5.2.1 Bulk Pool Temperature

The calculated bulk pool temperature rose to a maximum of 95°F at the end of the SRV discharge. The calculated bulk pool heat up is shown in Figures 5-1 through 5-5. The methods used to calculate bulk pool temperature are presented in Appendix B.

5.2.2 Local Pool Temperatures

Figures 5-1 and 5-2 show the temperature transient as recorded by temperature sensors in the vicinity of the quencher. As expected, the highest temperatures registered during the test were recorded by sensors T13 and T14. These were the temperatures of the water in direct path of the condensing steam and therefore not representative of the temperature of the pool water being supplied to the condensation process.

The average temperature in the quencher vicinity was obtained by averaging the recorded temperatures of sensors T11, T12, T15, T18, T19 and T20. Temperatures recorded by sensors T13 and T14 indicate that the temperature of the water immediately after condensation was 15 to 20°F warmer than the average temperature in the quencher area. The heated water was quickly carried away from the quencher by both natural and forced convection which also provided a continuous supply of pool water to condense the steam. As a result the heat introduced in the immediate vicinity of the quencher was quickly dissipated.

Figure 5-3 shows a comparison of the average temperature time history in the quencher vicinity with the calculated bulk pool temperature. This comparison resulted in a difference of only 5°F at the end of the SRV discharge. This was an indication that the energy being introduced into the pool water surrounding the quencher was being effectively transferred to the rest of the suppression pool during the SRV discharge. Also included is an average time history of sensors T15 and T20 only as an alternative method for determination of average local temperature in the quencher vicinity. This shows even a smaller local-to-bulk temperature difference at the end of the SRV discharge.

During the initial stages of the test, the temperatures recorded near the quencher were higher at the quencher elevation than near the pool surface as expected. For example, sensor T20, located at quencher elevation, measured higher temperatures than T18 and T19 for approximately the first 2 minutes of discharge (see Figure 5-2). However, this was not the case in the immediate vicinity of the quencher, as evidenced by the sensors T11, T12 and T15, located at the same elevations as T18, T19 and T20, respectively. Sensor T11, located near the pool surface, registered temperatures greater than or equal to the temperatures recorded by sensors T12 and T15 from the onset of the SRV discharge. This indicates that in the close proximity of the quencher, water circulation toward the pool surface began immediately after the steam discharge into the pool.

A rapid decrease in temperatures was recorded by temperature sensors T13 and T14 immediately after SRV A was closed. Sensors T11 and T12 continued to record rising temperatures for approximately 1 minute after SRV closure. This suggests continued circulation of heated water toward the pool surface after the valve closed. As a result, the temperatures measured by sensor T13 were approximately 12°F cooler than temperatures measured by sensor T11 1 minute after the discharge ended. Sensor T305 was mounted on a column near, but facing away from the discharging quencher. Temperature data from T305 is discussed in Paragraph 5.2.3.

5.2.3 Temperatures Around the Suppression Pool

Temperature data recorded away from the vicinity of the quencher was supplied by the in-plant temperature monitoring system and temperature sensors T16 and T17. Refer to Section 4 for sensor placement. Temperatures recorded by in-plant sensors are shown in Figure 5-4.

The highest in-plant sensor readings were recorded by temperature sensor T302 which was located on the pedestal wall facing the quencher. The lowest in-plant temperature sensor readings were recorded by sensor T308. These were lower than the temperatures registered by sensors T16 and T17 (see Figure 5-5) located at lower pool elevations. As mentioned earlier the sensor T305 measured the temperature of the pool water in the vicinity of the quencher, but due to its orientation (facing away from the discharging quencher) recorded lower temperatures than other sensors located in the same area and at the same elevation.

The temperatures measured farthest away from quencher A were recorded by sensors T306 and T307. Both sensors recorded similar temperatures during the SRV discharge indicating that heat was being transferred symmetrically through the suppression pool, relative to the quencher.

In-plant temperature measurements reached their peak values approximately 2 minutes after the SRV was closed. The temperature distributions within the suppression pool recorded before the test, during the test, and 1 minute after the valve was closed are shown in Figures 5-6 through 5-11.

5.2.4 RHR System Operation

Loop A-C of the RHR system was activated in pool mixing mode only, approximately 4 minutes 40 seconds after the SRV was closed. Refer to Subsection 1.1 for a description of the RHR system. As shown in Figures 5-1, 5-2 and 5-5, the degree of thermal stratification began to decrease shortly after RHR actuation. The suppression pool temperature distribution after approximately 4 minutes of RHR operation is shown in Figure 5-12. In locations where temperatures were measured in vertical arrays (see Figures 5-1, 5-2 and 5-5) thermal stratification ranged from 4 to 7°F. In-plant temperature measurements indicated that temperatures near the surface were approximately 90°F to 92°F after 20 minutes of RHR pool mixing.

The following Figures are GENERAL ELECTRIC COMPANY PROPRIETARY and have been removed from this document in their entirety.

Figure 5-1	Temperature Time Histories for Sensors T11 through T15
Figure 5-2	Temperature time Histories for Sensors T18, T19 and T20
Figure 5-3	Calculated Average Local Temperatures During the Transient
Figure 5-4	Temperature Time Histories from the In-Plant Monitoring System
Figure 5-5	Temperature Time Histories for Sensors T16, T17 and T308
Figure 5	Suppression Pool Temperatures Before SRV Actuation
Figure 5	Suppression Pool Temperatures 4 Minutes into the SRV Discharge
Figure 5-8	Suppression Pool Temperatures 7 Minutes into the SRV Discharge
Figure 5-9	Suppression Pool Temperatures 10 Minutes into the SRV Discharge
Figure 5-10	Suppression Pool Temperatures at the Time of Valve Closing (13 Minutes 7 Seconds into the Discharge)
Figure 5-11	Suppression Pool Temperatures 1 Minute after Valve Closure
Figure 5-12	Suppression Pool Temperatures 8 Minutes after SRV Closure (Approximately 4 Minutes after RHR Activation)

APPENDIX A

SRV STEAM FLOW RATE

Prior to the extended discharge test, an SRV flow rate of 250 lbm/sec was determined at a reactor pressure of 975 psig. This flow rate was used to determine the time required to raise the pool bulk temperature to 101.5°F (Reference Appendix B). After the test, the SRV flow rate was recalculated using information recorded during the test. A resultant flow rate of 237 lbm/sec was obtained. This is within the range of ASME-rated flow of 204 lbm/sec and maximum expected flow of 250 lbm/sec. The techniques used in obtaining these values are presented in the following discussion.

A.1 STEAM BYPASS METHOD

In this method the turbine bypass was used to determine the SRV flow rate. During plant operation the turbine bypass valve is used to maintain a constant power output, e.g., if the feedwater flow rate were increased, the bypass valve would allow the resultant increase in steam to bypass the turbine, and thereby maintain a constant electrical power output.

To determine the SRV flow rate a two-step procedure was conducted.

Step 1:

The position of the bypass valve was plotted versus increasing feedwater flow rate. As a result of this calibration procedure, the steam flow rate (equal to the increase in feedwater flow), through the turbine bypass valve could be obtained from the position of the valve.

Step 2:

The feedwater flow rate was held constant and the SRV opened. The decrease in flow through the bypass was equal to the SRV flow rate. A value for the SRV flow rate was calculated by measuring the decreased bypass flow as:

$$\dot{m}_{SRV} = \dot{m}_{1\ (bypass)} - \dot{m}_{2\ (bypass)}$$

where

$\dot{m}_{SRV}$ = steam mass flow rate through the SRV

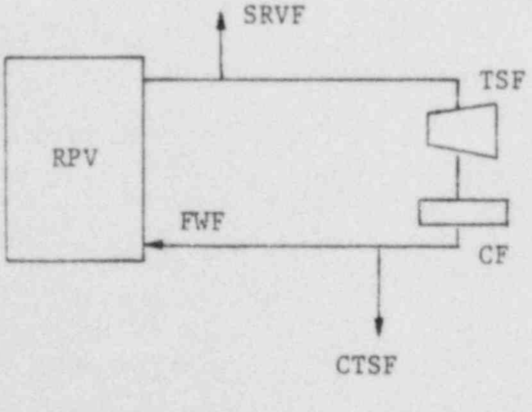
$\dot{m}_{1\ (bypass)}$ = bypass steam mass flowrate before the SRV was opened

$\dot{m}_{2\ (bypass)}$ = bypass steam mass flow rate after the SRV was opened

Using this equation a value of 289 lbm/sec was obtained at a reactor pressure of 1126 psig. The corresponding value for test conditions (at a reactor pressure of 975 psig) was calculated as 250 lbm/sec assuming that steam flow is proportional to reactor pressure.

A.2 MASS BALANCE

At the time of the extended discharge test, the plant process computer recorded turbine steam flow (TSF) and feedwater flow (FWF). A mass balance can be written on the reactor pressure vessel to determine the SRV flow (SRVF).



The measurement were taken during the steady state portion of the SRV discharge, i.e., after the initial transient immediately following the valve opening had been damped out. Under these conditions:

Output from RPV - Input to RPV = 0

or: (TSF + SRVF) - FWF = 0

where

TSF = Turbine Steam Flow

SRVF = Flow through SRV

FWF - Feedwater Flow

If we write the balance equations for both the condition before the test and during the test (after reaching steady state), we get after subtraction

$$\Delta TSF + \Delta SRVF - \Delta FWF = 0$$

where

ΔTSF = 237.0 lbm/sec, as recorded by the plant process computer

ΔSRVF = 0.0 - SRVF

ΔFWF = 0.0 (feedwater flow stabilized to pre-test value)

Substituting

$$SRVF = \Delta TSF - \Delta FWF$$

$$SRVF = 237.0 - 0.0 \text{ lbm/sec}$$

$$= 237.0 \text{ lbm/sec}$$

A.3 ASME SRV RATED FLOW

ASME rated capacity* (ARC) was calculated with the following empirical relation:

$$ARC \ \frac{lbm}{hr} = 51.5 \ A \ Pabs \ K^*$$

ASME Code, Section III, Division 1 - Subsection NB, Paragraph NB-7825.2.

where

A = $\pi/4$ (throat diameter in inches)^2

Pabs = Reactor pressure (psia)

K = 0.9 Kd for ASME rated flow

K = $(1.05)^2$ Kd for maximum expected SRV flow

Kd is the valve flow coefficient

The SRVs installed at Caorso have a throat diameter of 4.84 inches and a flow coefficient of 0.87. Reactor pressure during the test was 975 psig + 14.7 psia = 989.7 psia.

ASME rated capacity = 51.5 $\pi/4$ (4.84 inches)^2 989.7 psia (0.9) (0.87)

= 7.34×10^5 lbm/hr

= 204.0 lbm/sec

Maximum expected flow = 51.5 $\pi/4$ (4.84 inches)^2 989.7 psia $(1.05)^2$ (0.87)

= 8.99×10^5 lbm/hr

= 249.9 lbm/sec

APPENDIX B

BULK POOL HEAT UP

B.1 BULK POOL HEAT UP RATE

A limiting condition placed on the extended discharge test specified that the bulk pool temperature could not exceed 101.5°F. A calculation made before the test indicated that an SRV actuation time of 875 seconds (14.6 minutes) was required to raise the bulk pool temperature from 60°F to 101.5°F. The calculation is given in the following discussion.

In the procedure, the assumption was that all the available steam energy would be used to raise the pool temperature. The increase in the pool water mass during the test was neglected. The resultant simplified equation for the bulk pool heat up was

$$\dot{m}_{SRV}\, h_{steam}\, t = M_{pool} C_p\, \Delta T$$

$$t = M_{pool} C_p\, \Delta T / \dot{m}_{SRV}\, h_{steam}$$

where

$\dot{m}_{SRV}$ = expected SRV flow rate (Reference Appendix A, Subsection A.1).

h_{steam} = steam enthalpy (upstream of the SRV)

t = SRV discharge duration

M_{pool} = initial pool water mass

C_p = specific heat of water

ΔT = $T_{final} - T_{initial}$ (rise of pool temperature) substituting

$\dot{m}_{SRV}$ = [illegible] lbm/sec

h_{steam} = 1193 Btu/lbm

M_{pool} = 6.29×10^6 lbm

C_p = 1 Btu/lbm °F

ΔT = 101.5°F - 60°F = 41.5°F

the equation becomes

$$t = \frac{(6.29 \times 10^6 \text{ lbm})\ (1 \text{ Btu/lbm°F})(41.5\text{°F})}{(250 \text{ lbm/sec})(1193 \text{ Btu/lbm})}$$

$$t = 875 \text{ seconds (14 minutes, 35 seconds)}$$

B.2 BULK POOL TEMPERATURE

After completing the extended discharge test, the bulk pool temperature transient was examined in detail. The same energy balance considerations were employed as in B.1 to calculate the bulk pool temperature. This time, however, the effect of the increased pool mass was included and SRV flow rate of 237 lbm/second was used. This value was calculated from information recorded by the process computer during the test (see Appendix A, Subsection A.2).

The energy balance in differential form is

$$MC_p \frac{dT}{dt} = \dot{m}_{SRV}\ h_{steam}$$

where

T = bulk pool temperature

$\dot{m}_{SRV}$ = steam flow rate

t = duration of steam discharge

h_{steam} = steam enthalpy (upstream of the SRV)

M = pool water mass

C_p = specific heat of water (considered constant)

For this calculation the pool water mass M is a function of time:

$$M = M_{LWL} + \dot{m}_{SRV}\, t$$

where

M_{LWL} is the initial pool water mass.

The equation then becomes

$$(M_{LWL} + \dot{m}_{SRV}\, t)\, C_p \frac{dT}{dt} = \dot{m}_{SRV}\, h_{steam}$$

and integrating:

$$\int_{T_{initial}}^{T} dT = \frac{\dot{m}_{SRV}\, h_{steam}}{C_p} \int_{o}^{t} \frac{dt}{M_{LWL} + \dot{m}\, t}$$

or

$$\Delta T = \frac{h_{steam}}{C_p} \ln \left(1 + \frac{\dot{m}_{SRV}}{M_{LWL}} t\right)$$

If

$\dot{m}_{SRV}$ = 237 lbm/sec

h_{steam} = 1193 Btu/lbm

C_p = 1 Btu/lbm°F

M_{LWL} = 6.29×10^6 lbm

then

$$\Delta T = 1193 \ln (1 + 3.77 \times 10^{-5} t) \, ^\circ F$$

$$T = T_{initial} + \Delta T.$$

For

$$t = 787 \text{ seconds (actual duration of SRV discharge)}$$

and

$$T_{initial} = 60^\circ F$$

we get

$T = 94.9°F$ as the bulk pool temperature at the end of the SRV discharge.