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**SIMULATED DESIGN BASIS ACCIDENT TESTS OF
THE CAROLINAS VIRGINIA TUBE REACTOR CONTAINMENT --
PRELIMINARY RESULTS**

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ABSTRACT

Simulated design basis accident (DBA) tests were performed on the containment system of the recently decommissioned Carolinas Virginia Tube Reactor (CVTR). Preliminary data of the pressure-temperature response of the containment system to the simulated DBA conditions are presented and compared to analytical predictions of the containment response. Additionally, the pressure reduction sprays were demonstrated to be effective in reducing the containment pressure.

SUMMARY

Simulated design basis accident (DBA) tests were performed in the Carolinas Virginia Tube Reactor (CVTR) containment system^[1]. DBA conditions were achieved by rapidly injecting slightly superheated steam into the containment volume. For two of the four tests, a pressure reduction spray system was operated immediately following termination of steam injection.

Measurements were made of the pressure-temperature response of the containment system to the simulated DBA conditions. Preliminary experimental data evaluations and comparisons of the experimental with analytically predicted responses are presented in this report.

The results of these tests indicate higher rates for energy transfer from the steam-air containment atmosphere to heat absorbing structures than are usually assumed in current analytical prediction calculations. When a state-of-the-art computer code was used with currently accepted heat transfer coefficients, higher peak containment pressures were predicted than were measured experimentally. Additionally, substantial temperature stratification within the containment atmosphere was measured. Widely used single-node (one-volume) computer models do not account for such temperature (or potential pressure differentials) phenomena.

Pressure reduction sprays were found to be effective in reducing temperatures and pressures within the containment. Approximately 10 minutes after initiation of spray operation, the containment pressure was reduced by 30 and 50% for the 290 and 500 gpm spray flow rates, respectively, as compared to the natural (no spray) pressure decay.

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SIMULATED DESIGN BASIS ACCIDENT TESTS OF THE THE CAROLINAS VIRGINIA TUBE REACTOR CONTAINMENT -- PRELIMINARY RESULTS

I. INTRODUCTION

Presented in this report are preliminary results of the simulated design basis accident (DBA) tests [a] performed in the Carolinas Virginia Tube Reactor (CVTR) containment system [1]. The DBA tests were part of the In-Plant Testing Project [2] performed in the CVTR for the U. S. Atomic Energy Commission's Water Reactor Safety Program by Phillips Petroleum Company's Atomic Energy Division [b] and the Carolinas Virginia Nuclear Power Associates, Inc., owners of the CVTR facility.

Other major tests of the In-Plant Testing Project included leakage rate tests of the containment as a function of temperature and pressure [3] and tests of the vibrational characteristics of the containment system by two independent methods [4,5]. The project provided realistic information on containment system behavior that is being used to evaluate and improve analytical and experimental techniques to allow increased confidence in applying such techniques to safety analysis of nuclear power plants.

1. DBA TEST OBJECTIVES

Safety evaluations of power reactors require estimates of expected pressure-temperature histories of the containment atmosphere for postulated accidents in order to establish the potential for release of radioactive materials. At present, the containment response phase of reactor safety evaluation is based largely on analytical techniques. Limited data exist for evaluation of the accuracy and applicability of these techniques; therefore, realistic containment response data are needed for evaluating computational techniques and thereby allowing increased confidence in the safety analysis of power reactors.

Simulated DBA tests were performed in the CVTR containment to provide experimental information for use in developing and evaluating analytical

[a] DBA conditions, as used in this report, are containment environmental conditions resulting from a postulated loss-of-coolant accident, such as a primary system pipe break. The usual condition is an air-steam mixture with a pressure and temperature dependent on the particular reactor. No attempt was made to model any actual postulated CVTR accident.

[b] The In-Plant Testing Project previously under direction of the Atomic Energy Division of Phillips Petroleum Company is now under an Idaho Nuclear Corporation contract to the AEC.

methods for safety analyses of nuclear power plants. The specific objectives of the simulated DBA tests were:

- (1) To obtain experimental data on pressure and temperature for evaluating the capability of typical computer codes to predict the response of a containment atmosphere subjected to DBA conditions
- (2) To determine the effectiveness of a pressure-reduction containment spray system
- (3) To determine the gross effects of DBA conditions, exclusive of radiation, on the CVTR containment integrity.

The temperature-pressure history of the CVTR containment atmosphere was determined experimentally during simulated DBA conditions both with and without pressure reduction sprays. Also, during the tests, time-dependent heat transfer data (including convective behavior) were obtained at various locations throughout the containment structure. Strain data were obtained for the steel liner of the containment; however, these data have not been reduced as of this reporting.

The containment atmosphere response observed during these DBA tests has been compared with the response calculated by computer codes for the test conditions. Comparisons also have been made between the experimentally determined and predicted heat transfer characteristics, and recommendations have been made for improving computer code models.

Pretest and posttest visual observations and photographic recordings were made of both the inside and outside of the containment structure to help determine gross effects on the containment integrity caused by the DBA tests. Quantitative evaluation of the overall effects of the DBA testing on the containment leakage rate was determined by performing leakage rate measurements of the containment system both before and after the DBA tests.

2. DBA TEST SCHEDULE

CVTR facility modifications and preparations for DBA testing were initiated in August 1968, and the DBA tests were performed during April and May of 1969. The DBA tests immediately followed the hot-air leakage rate tests of the containment system^[3].

3. REPORT ORGANIZATION

The general organization of this report is as follows: Section II contains a discussion of the experimental method including descriptions of the CVTR containment structure, steam injection system, pressure reduction spray system, and instrumentation and data acquisition systems; Section III

presents preliminary test results of the experimental containment pressure and temperature response to simulated DBA conditions and miscellaneous information of DBA effects on equipment operation, containment painted surfaces, vessel expansion, and post-DBA containment leakage rate; Section IV presents comparisons of the experimental containment response to that calculated by computer techniques; and Section V states preliminary conclusions drawn from the test results and associated analyses.

II. EXPERIMENTAL METHOD

The In-Plant Testing Project was performed in the Carolinas Virginia Tube Reactor facility at Parr, South Carolina. A subcontract agreement between Phillips Petroleum Company, representing the USAEC, and the Carolinas Virginia Nuclear Power Associates, Inc., owners of the CVTR, provided the vehicle for implementation of the project.

1. FACILITY DESCRIPTION

The CVTR, a D_2O -moderated and -cooled pressure tube power-prototype reactor, was built and operated under the Commission's third-round power demonstration program. Power generation of the reactor was terminated in early 1967 after successful operation for about four years. The reactor was decommissioned in late 1967 and the In-Plant Testing Project was performed within CVTR's modified Part 30 By-Products Material License. The project interests involved only the CVTR containment system; therefore, the reactor is not described in this report.

1.1 CVTR Containment Structure

The CVTR containment, shown in Figure 1, is a reinforced concrete, right vertical cylindrical structure with a flat base and a hemispherical dome. Overall interior dimensions are a 57-foot 11-1/2-inch ID and a 114-foot 3-inch height from the basement floor to the inside top of the dome. Pressure retention is provided by the 2-foot-thick reinforced walls of the cylinder section and the 1/2-inch-thick steel dome which is covered with 20-1/2 inches of concrete for radiation shielding. A 5-foot 9-inch-thick reinforced concrete foundation mat supports the containment structure. The top of the foundation mat and the vertical cylinder wall are lined with 1/4-inch-thick steel plates. A 4-foot 6-inch concrete fill covers the liner plate above the foundation mat to form the basement floor. The liner plates are welded to vertical and horizontal support plates embedded in the concrete and to the steel dome support skirt to make the containment volume vapor tight. Entrance to the containment is provided by a 13-foot-diameter circular equipment hatch with a 7-foot-diameter personnel door and by a 2-foot 9-inch-diameter personnel escape hatch.

Structural surfaces, other than stainless steel and galvanized steel, exposed to the inside atmosphere of the containment are protected by a coating of machinery enamel, or in the case of porous surfaces, by an epoxy-base paint.

The containment structure housed the reactor and primary system, the steam generator, and various auxiliary systems and components. The structure is divided into two main volumes by the operating floor. For purposes of this report the lower volume is subdivided into two parts. The resulting three regions (operating, intermediate, and basement) are shown in Figure 1. The total free volume of the containment system is approximately 227,000 ft³. The structure is designed to withstand an internal pressure of 21 psig at a temperature of 215°F.

FIG. 1 CVTR CONTAINMENT STRUCTURE.

1.2 Steam Injection System

Steam for the DBA tests was obtained from the Parr Station Steam Plant, a South Carolina Electric and Gas Company coal-fired electric generating station, located about 500 feet from the CVTR. An existing 10-inch steam line, which originally supplied steam from the nuclear plant through an oil-fired superheater to the Parr Station header, was modified to permit reverse flow. The Parr header provides approximately 325,000 lb/hr of superheated steam at 725°F and 400 psig. The steam injection system, shown schematically in Figure 2, includes a desuperheater to adjust the injection steam to near saturated conditions.

To perform a DBA test, two of the Parr Station boilers were brought to full capacity by venting desuperheated steam to the atmosphere through the cylinder-operated vent valve located adjacent to the CVTR containment. When the boilers reached full capacity and steam flow to the atmosphere stabilized, the cylinder-operated charge valve was opened and the vent valve closed to direct total steam flow into the containment. Steam injection was terminated by reversing the valve operations. This procedure allowed close control of the steam conditions and pressure rise in the containment and permitted controlled startup and shutdown of the steam plant boilers.

1.3 Pressure Reduction Spray System

A containment pressure reduction water spray system, schematically shown in Figure 3, was installed in the CVTR for the DBA tests. The geometrical arrangement of the spray header and nozzles was patterned after the Connecticut Yankee system. Spray nozzles were selected to produce a droplet size range of 400 to 1400 microns based on calculated pressure differentials and recommendations of the manufacturer.

Spray flow rates of 290 and 500 gpm were used. These flow rates were achieved by changing the total number of nozzles in the spray header. Containment pressure reduction spray flow was initiated about 30 seconds following termination of steam injection and was stopped after about 12 minutes of operation. No provisions were made for spray water recirculation and all water added to the containment remained there until completion of a test.

FIG. 2 CVTR STEAM ADDITION SYSTEM.

FIG. 3 CVTR PRESSURE REDUCTION SPRAY SYSTEM.

2. INSTRUMENTATION AND DATA ACQUISITION

A primary objective of the simulated DBA tests was to measure the containment response to rapid steam injection and to relate this experimental response to that calculated by current analytical techniques. To accomplish this objective, the following measurements were made:

- (1) Containment pressures
- (2) Containment atmospheric temperatures
- (3) Containment liner surface temperatures
- (4) Containment liner stress
- (5) Condensate formation -- rate and gross
- (6) Heat flow at the containment liner surface
- (7) Temperature profile through the containment wall

- (8) Air movement within the containment
- (9) Injected steam quality and quantity
- (10) Spray system flow rate and water temperature.

2.1 Containment Pressure

The time-dependent pressure response of the containment atmosphere was measured with seven 0 to 25 psig fast response pressure transducers. Four of the transducers were located at various elevations within the containment, one transducer was positioned in a pipe which was open to the containment atmosphere and the remaining two transducers were located such that the pressure in the reactor header cavity and the refueling canal was measured. Figure 4 shows the locations of these transducers.

Output signals from the seven transducers were recorded on an oscillograph for all of the steam injection tests. To provide redundancy and time correlation, two of the pressure transducer signals were connected in parallel to the analog data multiplexing system during the last three DBA tests.

Pressure indication was also obtained from a 0 to 30 psig Heise gage which was located in the reactor control room. The Heise gage sampled the vapor containment atmosphere by means of 1/2-inch copper tubing. As the steam was injected (also during pressure decay), gage pressure was recorded as a function of time and compared with that obtained from the pressure transducers.

The Heise gage readings were used to control steam injection for all the DBA tests except the first (preliminary) test. The Heise gage was monitored, and when the pressure reached a predetermined value steam injection was terminated.

2.2 Containment Atmospheric Temperature

The temperature of the containment atmosphere was measured by the same fast response thermocouples (in slightly different locations) that were used for air temperature measurements during the integrated leakage rate tests [3]. Containment atmosphere temperature data were also obtained from resistance bulb thermometers; however, since the time response of these devices is much slower than that of the thermocouples, they were used mainly for spot checking the air temperature.

Thirty-four Chromel-Alumel thermocouples and 15 platinum resistance thermometers were located throughout the vapor containment atmosphere to provide temperature information from each of the three major containment regions. Ten of the thermocouples were positioned to obtain temperature profile data adjacent to the containment liner surface.

The output signals of all containment atmosphere thermocouples were recorded on the oscillograph or the analog data multiplexing systems to provide temperature-time information. Temperature data from the resistance thermometers were recorded periodically during the pressure decay period and

FIG. 4 TRANSIENT PRESSURE MEASURING SYSTEM.

were used for comparison with the corresponding temperature data obtained from the thermocouples.

2.3 Surface Temperature

Twenty-three Chromel-Alumel thermocouples were positioned at selected locations on the containment liner surface and on the surfaces of interior concrete structural sections. Output signals of these thermocouples were recorded on one or more of the oscillograph, the analog data multiplexing system, or the digital data acquisition systems.

2.4 Condensation Heat Transfer Measuring System

Data were taken to determine the condensation rate at several locations on the containment steel liner. During the DBA tests, time-dependent measurements were made of (a) the temperature profile through the containment wall, (b) the condensate collected from various containment wall areas, and (c) heat flow at the containment liner surface. Information from these measurements, in conjunction with other DBA test data, will be analyzed by computer techniques to determine the condensation heat transfer rate at the surface of the containment steel liner. Figures 5 and 6 are schematic diagrams of the temperature profile measuring scheme and the condensate rate gage system, respectively.

2.41 Total Condensate Formation and Rate of Formation. Selected areas on the vapor containment liner were defined by outlining them with a bead of Dow Corning Compound 111, and the condensate from each area was collected in a catch bottle. Figure 7 shows a section of the area defined by the compound.

Determination of total condensate formation was obtained by measuring the amount of water that had been collected in the bottles after each test. Rate of condensate formation was obtained by suspending five of the catch bottles from specially designed strain gage load cells from which the weight of the water collected was recorded as a function of time. Figure 8 shows one of the condensate rate gages.

2.42 Heat Flow at the Containment Liner Surface. To aid in the determination of heat transfer processes, four special heat flow devices were installed on the containment liner surface in the operating region. The detectors used were bidirectional calorimeter-type devices and provided an output signal of 1 mV per Btu/ft²-hr, which was recorded on the analog data multiplexing system.

2.43 Temperature Profile Through the Containment Wall. Two heat transfer assemblies were installed in the containment wall. These assemblies consisted of a 10-inch-diameter, 1/4-inch thick carbon steel plate with special thermocouples embedded across the thickness of the plate. A 10-inch-diameter section of the liner was removed and a one-inch-diameter hole was drilled through the concrete containment wall. The 10-inch plate containing the thermocouples was welded in the liner, and a concrete plug with thermocouples embedded along its length was installed in the hole through the containment wall (Figure 5).

Output signals from the thermocouples of the heat transfer assembly were recorded on the analog data multiplexing system and the digital data system. Temperature profile data across both the steel liner and the two-foot-thick concrete wall were obtained. Figure 9 shows a heat transfer assembly installed in the containment liner. Also shown are two of the heat flow gages and one set of thermocouples for determining the temperature profile near the liner surface.

2.5 Containment Liner Stress

Strain measurements on the steel liner were made at 83 locations with rosette strain gages having three components. Figure 10 shows a section of

FIG. 5 TEMPERATURE PROFILE MEASURING SCHEME.

the containment liner with strain gages installed. A bonding and water proofing technique developed at the NRTS was used to attach the gages to the liner to facilitate their operation in the steam environment. Figure 11 shows a typical strain gage installation. All of the strain gages were installed before the leak rate and hot air tests were conducted, and the liner strain levels were measured under the three different test conditions. The output signals from the strain gages were recorded on the analog data multiplexing system or the digital data system, or both.

2.6 Air Movement Within the Containment

Three ultrasonic anemometers developed by Phillips Petroleum Company^[6] for the LOFT experiment were installed inside the containment. Two of the anemometers were located in the vicinity of one of the heat transfer assemblies approximately 2-3/8 inches and 7/8 inch from the liner. The third anemometer was located in the annulus between the operating floor and the containment

Typical Catch Can Assembly

Typical Catch Can Arrangement
On Containment
Steel Liner Surface

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FIG. 6 CONDENSATION RATE GAGE SYSTEM.

FIG. 7 DOW CORNING COMPOUND 111 ON CONTAINMENT LINER.

liner. These instruments measured air velocities during the steam tests. No containment circulation equipment was operated during the steam tests.

2.7 Process Instrumentation

Standard process type sensors and recorders were used for measurements of (a) steam flow, pressure, and temperature; (b) desuperheater water flow and temperature; and (c) spray water flow, pressure, and temperature. During testing, most of the output signals were connected in parallel to the oscillograph. Figures 2 and 3 of Sections II-1.2 and -1.3 show schematic diagrams of the steam and spray systems with associated instrumentation.

FIG. 8 CONDENSATION RATE MEASURING SYSTEM.

FIG. 9 HEAT TRANSFER ASSEMBLY.

FIG. 10 STRAIN GAGE INSTALLATION ON CONTAINMENT LINER.

FIG. 11 TYPICAL STRAIN GAGE INSTALLATION.

2.8 General Installation of Sensors

Sensors, cables, and connectors were selected or designed to withstand operation in the steam-air environment. As far as possible, all sensors, cables, and connectors were tested under simulated environmental test conditions before installation in the vapor containment.

After installation and before the initial DBA test, in-place calibrations were made on all systems. Data acquisition system calibration checks were made using an mV calibration source prior to each DBA test.

2.9 Data Acquisition Systems

The principal data acquisition equipment consisted of a digital data acquisition system (slow scan), an analog data multiplexing system (fast scan), an oscillograph system, and a digital voltmeter with a digital printer. Figure 12 shows the data acquisition systems.

2.91 Digital Data Acquisition System (Slow Scan). The digital data acquisition system provided the capabilities for scanning and recording data from 198 channels of low-level dc signals. These signals were those of strain gage bridges and other transducers. Figure 13 shows a functional block diagram of the digital data acquisition system. The output signals from the transducers or the strain gage bridges are sequentially scanned, and the analog output is converted to digital form by a digital voltmeter. A visual digital display of the input signal is provided by the voltmeter that also provides an output to the digital recorder (paper-tape printer) or to a paper-tape perforator. A time code generator was connected to the system so that time was recorded digitally once during each scan cycle. Data were recorded on this system at the rate of one point about every two seconds.

2.92 Analog Data Multiplexing System (Fast Scan). The analog data multiplexing system provided the capabilities for scanning, conditioning, and recording up to 100 analog input signals. Each signal was conditioned and recorded about three times per second. Figure 14 shows a simplified block diagram of the analog data multiplexer. Low-level analog signals could be patched into the system as desired. The input signals are multiplexed in groups of 10 channels with respect to the output of the multiplexer; that is, each of the 10 multiplexed channels contained 10 input signals. Each of the 10 multiplexer output channels was conditioned by a separate low-level amplifier. The 10 amplified outputs are recorded on 10 channels of a 14-channel magnetic tape recorder. Channel 14 of the tape recorder was used for channel identification and time synchronization with the multiplexer inputs. One of the remaining three channels was used for recording time trace information.

2.93 Oscillograph System. The oscillograph system provided capabilities for signal conditioning and continuous recording of up to 36 channels of low-level signals. Figure 15 shows a block diagram of the oscillograph system. Low-level signals from suitable transducers were connected to the input terminals. These signals were amplified by the low-level dc amplifiers (which also provide galvanometer protection) and fed into the oscillograph. The oscillograph provided a permanent analog record of the input signal. A low-level calibration source was used to calibrate the system prior to each test.

2.94 Digital Voltmeter System. The digital voltmeter with the digital printer provided capability for recording in digital form one channel of data at the rate of five times per second. The system accepted low-level millivolt signals directly and was equipped with an ohms-to-volts converter so that it could be used as a readout for resistive devices such as the resistance thermometers. A manual-switch timer unit permitted up to 15 channels of resistance thermometers to be manually scanned and the data recorded digitally. Figure 16 is a block diagram of this system.

FIG. 12 DATA ACQUISITION SYSTEMS.

FIG. 13 DIGITAL DATA ACQUISITION SYSTEM.

FIG. 14 ANALOG DATA MULTIPLEXER SYSTEM.

FIG. 15 OSCILLOGRAPH SYSTEM.

FIG. 16 DIGITAL VOLTMETER AND DIGITAL PRINTER SYSTEM.

III. TEST RESULTS

Four simulated DBA tests were performed in the CVTR containment system. These tests included: (a) a system checkout test in which the containment was pressurized to about 7 psig and the spray system was operated for about three minutes; (b) an initial DBA test in which the containment was pressurized to about 18 psig and the resulting pressure allowed to decay by natural processes; (c) a second DBA test, similar to the initial DBA test, in which a 290 gpm pressure reduction spray was initiated shortly after the pressure peak and was operated about 12 minutes; and (d) a third DBA test identical to the second test except the pressure reduction spray flow rate was increased to 500 gpm.

In the checkout test, steam was injected for a short duration to evaluate the steam control-injection system and to compare the measured containment response with pretest predictions. The test results were used to determine whether a safety margin existed in pretest analysis and also to determine the injection time for the full-scale 18-psig DBA tests.

Preliminary results of the 18 psig tests are given in the following sections. Discussions of analytical models and comparisons of the experimental containment response with the predicted response are presented in Section IV.

1. PRESSURE HISTORY

Pressure histories for the three 18 psig tests are given in Figure 17. The data presented were obtained from a Heise gage which measured pressure at a point in the containment near the operating floor. The effectiveness of the spray system as a pressure reduction mechanism is illustrated by pressure comparisons for the decay region of the tests.

A quantitative evaluation of the spray effectiveness is obtained by comparing the potential reductions in containment leakage resulting from the spray operation. Since pressure is the driving force for leakage from the containment, a reduction in pressure correspondingly results in a reduction in leakage. The leakage rate tests of the CVTR showed that for certain leak paths the leakage rate pressure dependence was represented by the molecular flow equation[7]

$$L_r = K_m (1 - 1/\bar{P}_a)$$

where

L_r = leakage rate per time increment (time⁻¹)

K_m = proportionality constant for molecular leakage

$\bar{P}_a$ = containment pressure (atmospheres absolute).

FIG. 17 PRESSURE RESPONSE OF FULL-SCALE CVTR STEAM TESTS.

The fact that the leakage rate pressure dependence follows the molecular flow equation does not necessarily mean that the paths were molecular type paths; they may have been a combination of laminar and turbulent flow paths. If this equation is valid for a DBA-pressure reduction spray environment, the percent reduction in leakage for the CVTR containment resulting from spray operation can be estimated. The percent reduction in leakage expressed in terms of change in mass of the contained volume for a specified period is

$$\Delta L = (100) \frac{M_1 - M_2}{M_1}$$

where

ΔL = leakage reduction (percent)

M_1 = mass loss at greater leak rate, L_1

M_2 = mass loss at smaller leak rate, L_2 .

By applying the molecular flow leak rate equation the following mass losses are obtained:

$$M_1 = \int_{t_1}^{t_2} L_1 dt = K_m \int_{t_1}^{t_2} \left(1 - \frac{1}{P_1}\right) dt$$

$$M_2 = \int_{t_1}^{t_2} L_2 dt = K_m \int_{t_1}^{t_2} \left(1 - \frac{1}{P_2}\right) dt.$$

Thus, for a time period $t_2 - t_1 = t$, the percent reduction in leakage can be expressed as

$$\Delta L = (100) \left[\frac{\left(\int_0^t \frac{1}{P_2} dt - \int_0^t \frac{1}{P_1} dt \right)}{t - \int_0^t \frac{1}{P_1} dt} \right] [a]$$

In the derivation of this expression the assumption was made that the coefficient K_m does not vary with pressure.

Table I compares the areas under the curves of Figure 17 corresponding to the time period between 5 and 15 minutes, and the associated percent reduction in leakage calculated from the preceding expression for this 10-minute period of spray operation. Had the sprays been operated for an extended time period, as is usual for power reactor spray systems, the containment pressure would have rapidly approached ambient conditions thereby essentially eliminating the driving force for leakage. The percent reduction of leakage with spray operation versus that without sprays (natural decay) would then have been considerably larger for a longer pressure decay than is indicated by the relatively very short 10-minute time period represented in Table I.

TABLE I
EFFECT OF PRESSURE REDUCTION SPRAY

Test	Area Under Curve (psig-min)	Normalized to Natural Decay Test	Area Reduction (%)	Molecular Flow Leakage Reduction, ΔL (%)
Natural Decay (no spray)	134	1.0	0	0
290 gpm spray	111	0.82	18	13
500 gpm spray	92	0.68	32	25

[a] $\frac{1}{P_1}$ and $\frac{1}{P_2}$ are dimensionless because in the derivation of the molecular flow equation, the numeral 1 in the numerator represents one atmosphere pressure.

2. TEMPERATURE HISTORY

The CVTR containment is divided by an operating floor into two distinct volumes with interconnecting flow paths. The upper and lower regions have about 142,000 and 85,000 ft³ free volume, respectively, and the total flow path area is about 330 ft². The upper volume is relatively clear of obstructions whereas the lower volume which can be subdivided into a region (intermediate region shown in Figure 1 of Section II-1.1) below the operating floor and a basement region contains tanks, pipe runs, support structures, and equipment.

Temperature data for the 18-psig natural decay test is given in Figure 18. Three of the temperature curves represent atmospheric temperature histories in the three separate regions of the containment, that is, the upper region (dome) above the operating floor, the intermediate region below the operating floor, and the basement region. The large temperature differences are indicative of the effect on the temperature distribution of containment subdivision into compartments. Additional considerations related to this aspect of the CVTR temperature behavior will be provided in Section IV, Analytical Predictions and Comparisons with Experimental Results.

FIG. 18 TEMPERATURE HISTORY FOR 18 PSIG NATURAL DECAY TEST.

Steel liner temperature data, also shown in Figure 18, represent one sample point located near the containment bend line in the upper region. The magnitude of the liner temperature is nearly that of the bulk containment atmosphere temperature in this region and is one indication of the high rate of heat transfer from the steam-air mixture to containment structures occurring in the upper region during the steam injection period.

Temperature data for the two tests with pressure reduction sprays are shown in Figures 19 and 20. As for the natural decay test, a large spread in temperatures is noted prior to spray initiation. However, the spray operation effectively increases the rate of temperature decay and also, apparently, contributes to atmosphere mixing throughout the containment volume since the temperature of the basement region is convergent to a higher value earlier. The mixing mechanism is influenced by the transfer of energy to the lower regions by the migration of the spray water and condensate. The larger spray rate produces more rapid mixing.

FIG. 19 TEMPERATURE HISTORY FOR 18 PSIG 290 GPM SPRAY TEST.

FIG. 20 TEMPERATURE HISTORY FOR 18 PSIG 500 GPM SPRAY TEST.

3. MISCELLANEOUS INFORMATION

Experimental information regarding equipment operation, containment coatings, containment stress, and containment leakage were obtained from the DBA testing. This section briefly discusses this information.

3.1 Equipment Operation

The CVTR emergency coolant injection pump motor and a motor-driven valve were operated during the pressure decay phase of the DBA tests to determine operability under DBA conditions. Each unit operated as intended. Posttest visual inspection of the equipment revealed that some lubricant had leaked out of each unit; however, the equipment apparently was not effected during the short time of operation.

The original CVTR recirculating air fan motors were replaced for the test program to enable fan operation over the full range of test conditions. The replacement motors, purchased from Reliance Electric Company, were 60 hp each and utilized a standard protected and weatherproofed frame and motor circuit. Special construction and treatments were given to the internal wiring and motor windings to permit operation in the elevated temperature and steam environments. Silicone grease was used in the bearings.

Power cables to the motors were of a special grade and utilized high temperature insulation and a fire retardent jacket. The cable was obtained from Kerite Company and is the same type as is being used in some of the newer commercial power reactor plants.

Both motors and power cables performed satisfactorily throughout the complete test program.

3.2 Containment Paint

Visual and photographic observations of painted surfaces in the containment were made following the DBA tests. Figure 21 shows typical blistering of the paint on the steel liner surface following DBA testing. The blistering is believed to be temperature dependent because the blisters were found only on the liner in the region above the operating floor. The blisters apparently were formed by steam and water penetrating the paint at a weak spot or pin-hole-type inclusion and running down under the temperature softened enamel coating. Blistering was also noted in the paint covering the concrete floor surfaces. These blisters first appeared after the hot air tests^[3] performed prior to the DBA testing and are believed to be the result of temperature related off-gasing of the concrete. The DBA tests caused additional blistering of these surfaces, particularly on the operating floor.

During the DBA tests, special paint samples provided by Oak Ridge National Laboratories were installed in the containment at a location above the operating floor and adjacent to the containment liner surface as shown in Figure 22. The DBA exposed samples were inspected in place by ORNL personnel and subsequently shipped to ORNL for further evaluation following completion of the DBA test series. Results of this experiment are to be reported by ORNL.

3.3 Liner Strain Measurements

Containment liner strain measurements were made at various conditions during the entire CVTR Testing Project. A primary purpose of these measurements was for backup data in the event of liner or containment vessel failure because of the testing. No such failure occurred; however, the data are currently being reduced and analyzed to determine strain magnitudes and gross stress patterns.

3.4 Containment Vessel Expansion

Visual and photographic observations of the containment concrete surface were made during the DBA testing. Since expansion due to temperature was the principal cause of the cracking of the concrete surface, the cracks (first observed during hot air testing on the dome and in the upper cylindrical regions of the containment) were noticeably larger during the DBA tests. This cracking would be expected because the inside temperature of the upper region of the containment was higher during the DBA tests than during the hot air tests. Figure 23 is a photograph of a typical concrete surface crack in the upper cylindrical region of the containment structure.

3.5 Post-DBA Containment Leak Rate Tests

An ambient temperature, 21 psig leak rate test of the containment was performed following the DBA testing. The purpose of this test was to determine

FIG. 21 BLISTERS IN PAINT OF LINER OF CONTAINMENT.

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FIG. 22 ORNL PAINT SAMPLES INSTALLED IN CVTR CONTAINMENT.

FIG. 23 TYPICAL CRACKING IN THE SURFACE OF THE CONCRETE IN THE UPPER CYLINDRICAL REGION OF THE CONTAINMENT STRUCTURE.

whether DBA test conditions had affected the leak tightness of the containment. A leak rate of about 0.23%/day was measured following the DBA tests compared to about 0.31%/day measured for similar conditions prior to the DBA tests.

IV. ANALYTICAL PREDICTIONS AND COMPARISONS WITH EXPERIMENTAL RESULTS

An important objective of the CVTR DBA tests was to obtain data for comparison of experimental results with analytical predictions. CONTEMPT[8], a containment response computer code that is representative of the state-of-the-art, was utilized for much of the CVTR analysis. In addition, CONDRU II[a], a developmental containment response code which is an extension of CONDRU I, was used to predict and evaluate temperature differences between CVTR compartments. CONTEMPT is a single-volume, uniform temperature model whereas the CONDRU II model has the capability of calculating pressures and temperatures in a containment made up of two volumes (compartments) separated by a flow path. Additional details of the calculational codes and some of the input data necessary for calculating the CVTR containment response are included in Appendices A and B, respectively.

Pretest CONTEMPT calculations based on the computer input data presented in Tables B-I and -II of Appendix B were used to design the experiments. The pretest calculations were successful in that the overall features of the CVTR containment response were reasonably predicted such that adequate design parameters were selected.

An important parameter to be determined from the CVTR DBA tests is the time-dependent coefficients for heat transfer by steam condensation. The CVTR test instrumentation provided data for use in determining the values of these coefficients (Section II-2.4) but to date the data have not been reduced and analyzed. A rough estimate of condensation heat transfer, however, was determined from measured temperature differences between the steel liner and containment atmosphere through use of the relationship

$$h A (T_c - T_1) = C \frac{dT_1}{dt} A X$$

where

h = heat transfer coefficient (Btu/ft²-hr-°F)

A = unit area (ft²)

T_c = temperature of vapor and air in dome (°F)

T_1 = liner temperature (°F)

C = volumetric heat capacity (55 Btu/ft³-°F)

[a] CONDRU I and II were written by H. G. Seipel, a West German National recently on assignment to Phillips Petroleum Company through an AEC training agreement, and is an extension of earlier work performed in Germany by Mr. Seipel and others.

X = liner thickness (0.02 ft)

$\frac{dT_1}{dt}$ = rate of liner temperature rise (°F/sec).

Figure 24 is a plot of three time-dependent heat transfer coefficients. The posttest curve represents the coefficient as tentatively determined by the given relationship from very limited liner surface and bulk steam-air temperatures measured in the containment upper region. The coefficient is applicable only for the specified region. Also given in Figure 24 is the best estimate heat transfer coefficient curve representing a combination of sources of heat transfer data. The curve is similar to that obtained from the often used Uchida correlations for steel^[9] which are usually combined with a constant coefficient for concrete of about 40 Btu/hr-ft²-°F. For comparison, a time-dependent curve representative of the Uchida data for steel is also shown in Figure 24.

To compare CONTEMPT containment response predictions to the measured response, calculations were made using the data in Tables B-I and -II of Appendix B except that the estimated steam flow rate and enthalpy given in Table B-II were replaced by the experimental values shown tabulated in Tables B-III, B-IV, and B-V. Figure 25 shows a typical strain injection curve.

Best estimate and posttest experimental heat transfer coefficients shown in Figure 24 were applied. The calculated response curves are presented

FIG. 24 HEAT TRANSFER COEFFICIENT COMPARISONS FOR CVTR CALCULATIONS.

FIG. 25 FLOW AND ENTHALPY RESULTS FOR NATURAL DECAY TEST.

in Figure 26 along with the experimental response for the 18-psig natural decay DBA test. Calculations based on commonly used best estimate heat transfer data significantly overestimated the experimental CVTR pressures. For this test, better agreement is achieved with the posttest experimentally estimated heat transfer coefficient. This better agreement may be fortuitous because the heat transfer was assigned uniformly to all heat slabs, and some slabs, particularly those in the basement (low temperature regions), may not participate in heat transfer to the same extent as those in upper regions. The implication is that the actual heat transfer coefficient for the upper region may be even higher than was estimated from the experimental temperature data. Analysis of all the test data is necessary to determine the overall heat transfer behavior in the containment.

Pressure-time results for the 290 and 500 gpm spray tests are shown in Figures 27 and 28, respectively. In each case CONTEMPT calculation results using the posttest experimentally estimated heat transfer coefficient and the experimental steam injection rates and enthalpies (Tables B-IV and -V of Appendix B) are compared to the measured results. The same general comments that apply to Figure 26 also apply to Figures 27 and 28. The lower pressures predicted by CONTEMPT for the 500 gpm spray test are believed to be a result of underestimating the steam injection flow rate.

Figure 29 shows a comparison between temperature data from the natural decay (no spray) test and temperature results from a CONTEMPT calculation in which the posttest heat transfer coefficient was used. The CONTEMPT

FIG. 26 PRESSURE RESULTS OF NATURAL DECAY TEST.

temperature results are the volume-weighted average temperatures. No indication of temperature differences due to geometry or temperature differences from stratification can be expected from the CONTEMPT or similar one-volume analytical models. Data from the same test are compared in Figure 30 to calculated temperatures obtained from the two-volume model of CONDRU II, previously described. Excellent agreement for the calculated and experimental temperatures in the upper region is exhibited. A volume-weighted average temperature is determined by CONDRU II for the lower regions. CONDRU II pressure predictions (not shown) are about 10% higher than measured values. The CONDRU calculations utilize the posttest experimental heat transfer coefficient data; however, the same general comments concerning the use of the heat transfer coefficient apply to this calculation as applied to the previously discussed CONTEMPT calculations.

FIG. 27 PRESSURE RESULTS OF 290 GPM SPRAY TEST.

FIG. 28 PRESSURE RESULTS OF 500 GPM SPRAY TEST.

FIG. 29 CONTEMPT TEMPERATURE RESULTS FOR NATURAL DECAY TEST.

FIG. 30 CONDUR II TEMPERATURE RESULTS FOR NATURAL DECAY TEST.

V. CONCLUSIONS

Several general conclusions can be made based on preliminary evaluations of the test results. Most significant of these conclusions is the apparent high rate of energy transfer from the steam-air mixture in the containment volume to the heat absorbing structures of the containment. This high energy transfer rate resulted in lower peak pressures than were predicted by CONTEMPT calculations using currently accepted heat transfer correlations and also may account for the higher than predicted pressure during the decay period following the steam injection.

The large temperature stratification in the containment volume resulting from the steam injection is another significant finding of these tests. Similar phenomena may be expected to a greater or lesser degree if a DBA should occur in other nuclear plant containment structures, depending on the particular geometry or type of compartmentation and the location of primary system rupture. Since most current analytical models used to calculate containment response to accident conditions are single-node (one-volume) representations, temperature differentials are not obtained from such calculations. Because of the interrelation of temperature and heat transfer, a multinode-type model appears to be needed for more accurate representation and prediction of containment response.

As shown by the experimental results, the pressure reduction spray system effectively reduced the containment pressure following termination of the steam injection. Since containment leakage rate is a function of pressure, use of pressure reduction sprays can substantially reduce the potential for fission product release from containments during accidents involving a nuclear reactor.

Finally, the gross integrity of the containment was not compromised by performance of the DBA tests. Containment leakage rate measurements performed after DBA testing was completed showed that the DBA tests appear to have produced a reduced containment leakage.

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APPENDIX A
DISCUSSION OF CALCULATIONAL MODELS

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APPENDIX A

DISCUSSION OF CALCULATIONAL MODELS

Three containment response computer codes were employed for the CVTR calculations -- CONTEMPT, CONDRU I, and CONDRU II; however, only results of CONTEMPT and CONDRU II are discussed in this report. The principal differences in mathematical model assumptions among the codes are discussed in the following sections to aid in evaluating the comparison of results, but no attempt is made to provide complete code descriptions.

1. CONTEMPT

The CONTEMPT computer program predicts the pressure-temperature response of a containment building to a loss-of-coolant accident. The analytical model assumes that the loss-of-coolant accident can be separated into phases such that the results of the analysis of one phase serves as the initial conditions of the time-dependent input to the next phase. The model is concerned only with the pressure and temperature in the containment volume and the temperature throughout the containment structure. The computer program input provides for the description of the discharge of coolant, the boiling of residual water by decay heat, the superheating of steam passing through the core, and metal-water reactions. The program also calculates the effect of building leakage and the effects of engineered safety systems.

CONTEMPT differs from most other containment response codes in that it does not assume thermodynamic equilibrium between water and vapor in the containment. For CONTEMPT, the containment volume is separated into a liquid region and a vapor region. Each region is assumed to have a uniform temperature, but the temperatures of the two regions may be different. For each time step, primary coolant and other sources of energy addition are usually added to the vapor region. Pressure and temperature in each region are calculated by standard methods of energy and mass balances which include energy absorption by walls and internal structures. From a mass balance and calculated quality value, the amount of water in the vapor region is determined. This water is transferred to the water region, and the temperature of the water region is calculated by an energy balance. If the temperature determined for the water region is higher than the saturation temperature corresponding to the total pressure of the vapor region, boiling is permitted such that enough water boils off to bring the water to the saturation temperature. The amount of water boiled off and the associated energy are transferred to the vapor region. Additionally, heat exchange between the water and vapor region can be included by an input heat transfer coefficient. With these assumptions, the vapor temperature may be either higher or lower than the liquid temperature depending on the conditions, and the mass and energy distribution between the vapor and water region is a function of the blowdown and heat exchange history.

2. CONDRU I

In comparison to CONTEMPT, CONDRU I is a fairly simple model which uses the more conventional assumption of a homogeneous mixture and equal temperature of water, vapor, and air throughout the containment volume. As in CONTEMPT, heat exchange between walls and internal structures is considered, and pressures and temperatures are calculated after each time step from a mass and energy balance for the total system.

3. CONDRU II

CONDRU II is a modification of CONDRU I which has the capability of calculating the pressures and temperatures in a containment made up of two volumes (compartments) connected by a flow path. Pressures and temperatures in both compartments are evaluated in the same way as in CONDRU I. In one compartment, coolant blowdown energy addition from chemical reaction or spray water addition can be considered by input tables. In either compartment heat exchange among an arbitrary number of structures is allowed. To account for separate vapor-to-air ratios, each compartment can have a different table of heat transfer coefficients as functions of time. The flow area between the compartments can be changed either as a function of time or pressure. Either an isentropic or isenthalpic quasisteady state flow calculation is made for the vapor, water, and air vent flow between the two compartments. Thus, CONDRU II can evaluate pressure differentials in a two-compartment system and simultaneously consider energy addition, water spray addition, and heat exchange among internal structures.

APPENDIX B
CVTR CODE INPUT DATA

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APPENDIX B

CVTR CODE INPUT DATA

For the CVTR containment response predictions much of the CONTEMPT code capabilities are not utilized; for example, heat exchangers, fan cooler, metal-water reaction, liquid region heat, or water addition are not required, and entries controlling these calculations are zero. The principal code inputs for CVTR are specification of the initial containment environmental conditions, the composition of the heat conducting structures, including material types, dimensions and heat transfer coefficients, and the enthalpy and rate of the steam addition. Additional input is required if a pressure reduction spray or some special effect such as containment pressurization by electrical heating is to be evaluated.

Each code is capable of utilizing 20 heat sink structures. Table B-I presents code input parameters for 20 CVTR containment structural features. These input parameters are common to all codes and calculations used for the CVTR containment response prediction.

A complicated containment system such as CVTR contains a large number of minor heat sinks, and the storage capability of the computer and the ingenuity of a programmer are insufficient to permit the heat transfer characteristics of each sink to be assessed accurately. Thus, for calculations, these additional structures are often lumped and assigned as a variable parameter to one of the major heat slabs. The pretest best estimate and upper and lower limit estimate of code input parameters are given in Table B-11.

Posttest values for blowdown rates and steam enthalpies are given in Tables B-III, -IV, and -V. Table B-VI is a tabulation of the preliminary heat transfer coefficients as estimated from measured differences between a temperature on the steel liner at the containment bend line and a containment atmosphere temperature in the upper region.

Although the accuracy of the measurements and calculations used to determine the values presented in the tables do not in most cases justify the number of significant figures shown, these figures are the ones used for the computer code input and are therefore included without rounding.

TABLE B-I

GENERAL INPUT PARAMETERS

Containment Volume -- 226,920 ft³
 Initial Bulk Temperature -- 80°F
 Outside Air Temperature -- 64°F
 Slab Geometry for Heat Conducting Structures
 Thermal Conductivity for Steel -- 25 Btu/hr-ft-°F
 Thermal Conductivity for Concrete -- 0.8 Btu/hr-ft-°F
 Volumetric Heat Capacity for Steel -- 55 Btu/ft³-°F
 Volumetric Heat Capacity for Concrete -- 30.2 Btu/ft³-°F
 Spray Flow Rates -- 290 or 500 gpm
 Spray Water Temperature -- 60°F

CVTR CONTAINMENT HEAT SINKS

<u>Number</u>	<u>Sink</u>	<u>Material</u>	<u>Area (ft²)</u>	<u>Thickness (in. or ft)</u>	<u>Volume (ft³)</u>
1	Cylindrical shell	Steel Concrete	15,470	0.25 in. 2.0 ft	332 30,440
2	Dome of shell	Steel Concrete	5,370	0.50 in. 1.75 in.	224 9,400
3	Foundation mat	Concrete	2,640	4.5	11,880
4	Operating floor	Concrete	2,478	2.50 ft	6,195
5	Header cavity	Concrete	1,305	4.0 ft	5,220
6	Reactor compartment	Concrete	1,660	4.75 ft	7,880
7	Fuel canal	Concrete	1,600	2.0 ft	3,200
8	Fuel canal support	Concrete	280	1.0 ft	280
9	Floor of reactor compartment	Concrete	143	3.0 ft	429
10	Concrete supports	Concrete	960	2.5 ft	2,400
11	Steam generator shield	Concrete	400	2.0 ft	800

TABLE B-I (Contd.)
GENERAL INPUT PARAMETERS

<u>CVTR CONTAINMENT HEAT SINKS</u>					
<u>Number</u>	<u>Sink</u>	<u>Material</u>	<u>Area (ft²)</u>	<u>Thickness (in. or ft)</u>	<u>Volume (ft³)</u>
12	Moderator overflow tank	Steel	552	0.75 in.	34.5
13	Pressurizer	Steel	176	4.5 in.	66
14	Pressurizer discharge tank	Steel	227	0.5 in.	9.5
15	Steam generator	Steel	513	3.0 in.	128.2
16	Moderator coolers	Steel	280	0.25 in.	5.8
17	Shutdown coolers	Steel	66	0.12 in.	0.7
18	Pumps, primary and injection	Steel	250	1.0 in.	20.8
19	Fuel handling apparatus	Steel	500	0.94 in.	39.0
20	I beams	Steel	2,250	1.62 in.	303.8

TABLE B-II

PARAMETER VALUES

Parameter	Best Estimate	Upper and Lower Estimates	
Volume	226,920 ft ³	238,226 ft ³	+ 5%
		215,574 ft ³	- 5%
Surface Area			
Steel	25,654 ft ²	38,481 ft ²	+50%
Concrete	13,943 ft ²	15,337 ft ²	+10%
Steam Injection [a] Rate	400,000 lb/hr	424,000 lb/hr	+ 6%
		376,000 lb/hr	- 6%
Steam Enthalpy [a]	1,188 Btu/lb	1,200 Btu/lb	+ 1%
		1,176 Btu/lb	- 1%
Heat Transfer [a] Coefficient	Time dependent from 6.13 to 40.96 Btu/ft ² - hr-°F; Average = 23.55 Btu/ft ² -hr-°F	81.92 Btu/ft ² -hr-°F 16.38 Btu/ft ² -hr-°F	

[a] Pretest estimates.

TABLE B-III

STEAM INJECTION RATES AND STEAM ENTHALPIES FOR NATURAL DECAY

STEAM TEST

<u>Time (sec)</u>	<u>Steam Injection Rate (103 lb/hr)</u>	<u>Enthalpy (103 Btu/lb)</u>
0	0	1.219
1	0	1.219
1.7	100	1.219
4.5	200	1.214
8.5	240	1.208
11.0	380	1.205
22.5	371	1.1965
40	366	1.200
60	364	1.203
68	364	1.2025
69.5	378	1.202
108.5	380	1.1995
110	390	1.1995
150	387	1.198
160	387	1.210
161	200	1.210
168	0	1.205
1800	0	1.200

TABLE B-IV

STEAM INJECTION RATES AND STEAM ENTHALPIES FOR 290 GPM

SPRAY STEAM TEST

<u>Time (sec)</u>	<u>Steam Injection Rate (10³ lb/hr)</u>	<u>Enthalpy (10³ Btu/lb)</u>
0	0	1.2
1	0	1.2
3	180	1.201
8	240	1.197
11	360	1.194
17	352	1.193
30	378	1.192
85	368	1.193
120	372	1.196
150	370	1.196
168	370	1.193
170	140	1.2
175	0	1.2
1800	0	1.2

TABLE B-V

STEAM INJECTION RATES AND STEAM ENTHALPIES FOR 500 GPM
SPRAY STEAM TEST

<u>Time</u> <u>(sec)</u>	<u>Steam Injection Rate</u> <u>(10³ lb/hr)</u>	<u>Enthalpy</u> <u>(10³ Btu/lb)</u>
0	0	1.198
1.5	0	1.198
7	100	1.198
10.2	200	1.193
13.5	356	1.195
30	340	1.195
90	334	1.199
150	336	1.2
160	348	1.199
166.5	346	1.206
175	40	1.207
176	0	1.207
1800	0	1.207

TABLE VI
HEAT TRANSFER COEFFICIENTS FROM
NATURAL DECAY STEAM TEST
TEMPERATURE DATA

<u>Time</u> <u>(sec)</u>	<u>Coefficient</u> <u>(Btu/hr-ft²-°F)</u>
0	5
5	80
10	93
20	100
35	110
75	80
105	220
135	230
165	230
175	50
180	20