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THE CONTAINMENT SYSTEMS EXPERIMENT

by

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THE CONTAINMENT SYSTEMS EXPERIMENT

The Containment Systems Experiment (CSE) at Pacific Northwest Laboratory (PNL) is a large-scale program to evaluate the effectiveness of containment vessels and related engineered safeguard systems in reducing the release of radioactive fission products in the event of a serious accident in a nuclear electric generating plant. The program is an integral part of a comprehensive series of AEC programs related to nuclear reactor safety. The main objective of the CSE program is to obtain experimental information against which calculational models can be tested and from which improved models can be developed; thereby permitting improved methods of predicting events following a reactor accident. The results will furnish better technical basis for reactor site evaluation and for those parts of reactor plant design which involve public safety.

Scope of the CSE Program

The scope of the CSE program includes evaluating the effectiveness of selected engineered safeguard systems in limiting fission product release to the environs under conditions representative of maximum credible accidents for pressurized and boiling water reactors. These evaluations are being directed toward the following major objectives.

- ① Determination of the effects of the natural processes of agglomeration, deposition, and condensation of steam in attenuating airborne fission product concentration in the containment vessel.

- ⑥ Evaluation of the effectiveness of active and passive safeguards including spray systems, air filter systems, and water pool scrubbing for fission product removal from the containment atmosphere as well as for reduction of postaccident containment pressure.
- ⑥ Investigation of the dynamic effects of large ruptures in high temperature water piping systems as they relate to containment system design and performance and to evaluation of the differential pressures and mechanical loads exerted on reactor vessel internal structures during coolant blowdown.
- ⑥ Determination of the relations between air leakage rate tests on containment vessels and the escape of fission products under postaccident conditions for several types of representative leakage paths.

The experimental program is divided into the four major tasks stated below and described in greater detail later in the paper.

Task A. Containment Leakage Studies

Performance of leakage rate experiments with the CSE containment vessel using air, steam-air mixtures, and steam-air fission product mixtures at various pressures and temperatures.

Task B. Fission Product Transport Studies

Performance of fission product transport studies by releasing test aerosols directly into containment vessels to permit

studies of the effectiveness of steam condensation, spray systems, air filter systems, and pool scrubbing systems under a range of possible accident conditions.

Task C. Coolant Blowdown Studies

Performance of coolant blowdown experiments using a large reactor simulator vessel to study the effects of coolant conditions, break size, and location on the blowdown rates and to determine hydraulic effects and forces within representative core components.

Task D. Combined Systems Experiments

System performance tests of containment will be conducted combining blowdown, fission product transport, and leakage. These tests will start with the sudden release of high-pressure, high-temperature water followed by continued heating to simulate decay heat and chemical reactions in the reactor core. Aerosols representing the fission products evolved from a core during an accident will be injected into the system and their behavior and ultimate locations will be determined by analyses of appropriate samples. Stresses, pressures, and temperatures which occur throughout the containment vessel complex will be measured by appropriate fast response instruments. Comparison will be made of the experimental results with mathematical models, to allow refinement of analytical descriptions of the consequences of reactor accidents.

Experimental Facilities

The main components of the experimental facilities are shown in Figure 1. These consist of the following:

Containment Vessel. The containment vessel is 25 ft in diameter, 66 ft 8 in. high, has a gross volume of 30,700 ft³, and is designed for 75 psig internal pressure. The vessel is provided with a beam near the top for 25 ton hoists to lift the reactor simulator vessel or other heavy objects, an 8 ft diameter equipment access opening, a 3 ft diameter personnel access hatch and numerous penetrations for ventilation, drains, power and instrument cables, spray water, and similar functions for the internal equipment. Doubler plates are provided to permit attachment of a portion of a multiple barrier containment system at a later date, and the equipment access door can be converted to the relief diaphragm and valve to model pressure relief containment.

Drywell and Wetwells. The drywell and wetwells are structurally part of the containment vessel, but are functionally separate. They provide the scale model pressure suppression containment facility. The drywell top is removable to provide access to the model reactor vessel. The drywell vessel has several penetrations for blowdown venting; four are the downcomer pipes into the wetwells, four are flanged openings to the wetwells near the level of the bottom reactor vessel blowdown nozzles, and three are flanged openings into the main containment volume placed directly in line with the two top and the middle reactor vessel blowdown nozzles. There are also service penetrations for ventilation and for the simulator.

The wetwells are four adjacent chambers occupying two-thirds of the annular space between the drywell and containment vessel shell. The partitions between wetwell segments support the drywell. The top plate of the wetwells provides a working level platform in the containment vessel. The total wetwell volume is 4220 ft³; normally the water pool will occupy about 2000 ft³. Fill and drain connections are provided in each wetwell segment, and the partitions between segments have flanged openings to provide circulation of water and air between chambers if desired. The end chambers have rupture discs venting the air space into the containment vessel for protection against overpressure beyond their 25 psig rating.

Reactor Simulator Vessel. The reactor simulator vessel is 42 in. ID, 17 ft high, has a volume of 150 ft³, and is designed for 2750 psig at 600 F. The vessel is carbon steel with a stainless steel lining and was designed and fabricated in accordance with the ASME Boiler and Pressure Vessel Code Section III for Nuclear Vessels. Five 8 in. blowdown nozzles are provided; top and bottom nozzles are diametrically opposite so that the blowdown orientation with respect to the wetwell vent downcomers can be changed without rotating the simulator vessel, and a middle nozzle is provided on one side. Numerous smaller nozzles are provided on each side at top, middle, and bottom for instrument sensors or other experimental requirements. The vessel head is removable to allow installation of dummy cores or other internal apparatus. A collar ring is provided at the head flange to allow installation of instrument lead wires. At the

present time the reactor simulator vessel is mounted in a test stand outside the containment vessel to allow preliminary blowdown tests during the time that leakage tests and fission product transport tests are performed in the containment vessel. Later, the reactor vessel will be supported on a beam structure in the drywell. Strut links pivoted on trunnions will be used to resist the lateral forces due to blowdown. These forces will be transferred to the drywell walls and thence to the main containment vessel.

Simulator Water Heating Loop. The water for charging the reactor simulator vessel is heated by a 300 kW Dowtherm-to-water heat exchanger system. Demineralized, deoxygenated water is supplied to the loop and circulated at a maximum flow rate of 75 gal/min during the heating period.

Ventilation System. The ventilation system provides a flexible arrangement of equipment for control, circulation, and cleanup of the atmosphere in the various containment volumes. Air circulation for adequate ventilation when personnel are working in the containment vessel can be once through. Ventilation to control air temperature, especially in the drywell when the simulator vessel water is at high temperature, can either be once through or cooled and recirculated with or without filtration to control particle concentration in the containment atmosphere before a test. Provision is made for an air cleaning system for reducing the fission product content of the containment vessel in certain tests and also to evaluate effectiveness of commercial air cleaning equipment.

Sampling Systems. Gas and liquid samples are taken as a function of time and space during each experiment. Samples of steam condensed on walls are taken from troughs located at various elevations. Liquids accumulated in vessel sumps are sampled from a recirculation line. For tests using a containment spray system, spray drops are collected by funnels located at several radii and elevations in the free gas space.

Gas samples are taken at as many as 25 locations within the main gas space. Each of the smaller adjoining compartments are also sampled. At each sample location is a manifolded cluster of twelve individual samplers, each with an electrical valve operated when desired from a nearby laboratory. Thus, samples can be taken at a maximum of twelve times during an experiment. The sample clusters are retrieved after the test and analyzed by gamma spectrometry.

Laboratory. The laboratory is a reasonably conventional radio-chemical room with fume hoods for work with low level activity materials and a shielded cave for higher activities. Materials are prepared here for generation of the fission product simulant aerosol for injection into the containment vessel. The generator is installed in a shielded cave where a straight pipe gives direct access to the containment vessel.

Control Room. The control room provides a central location for the direction and coordination of operational and experimental activities. Instrumentation and controls for the operational equipment and systems are grouped in the control room, as is permanently installed data acquisition and readout equipment for pressure, temperature, stress and other experimental data.

Simulated Fission Product Aerosol

Ideally, a study of the behavior of fission products in a containment vessel would involve the use of real fission products. The use of real fission products in the CSE containment vessel would require excessive shielding and extensive decontamination between tests. Therefore, to permit the most efficient performance of the program, a simulated fission product aerosol is used rather than highly radioactive real fission products. The simulant materials are traced with sufficient radioisotopes for analytical purposes.

The fission product simulant used to date has consisted of five mass transport species: elemental iodine, methyl iodide, particulate-associated iodine, cesium (oxide and hydroxide) particles, and submicron particles formed by volatilization of unirradiated Zircaloy-clad UO_2 . The suitability of this simulant aerosol for mass transport experiments in containment atmospheres has been verified by an extensive investigation in small-scale equipment.

EXPERIMENTAL PROGRAM AND RESULTS

Containment Leakage Studies

The Technical Specifications for a nuclear generating station specify a maximum permissible leakage rate for the containment vessel. This leakage rate is derived from a calculation of the integrated radiation dose to persons near the plant after a hypothetical maximum credible accident releases fission products to the containment vessel and is based on a number of assumptions, one of which is that the fractional rate of fission product leakage from containment is the same as the fractional rate of air leakage during a test. This approach is used because of the absence of experience or experimental data on the effect of postaccident atmospheres on containment leakage rates and on the leakage of fission products.

The basic objective of the leakage testing studies is to relate the leakage of fission product activity after an accident to the results of leakage rate tests performed with ambient temperature air. The following specific objectives are to be achieved during the containment leakage program:

- ① Measure air leakage rates on the CSE containment vessel to identify and characterize individual leak points and to determine the leakage rate as a function of pressure.
- ② Assess the practical importance of factors affecting the sensitivity and accuracy of leakage rate measurements; for example, the errors resulting from inadequate sampling of containment temperature and humidity and the variation of

leakage rate as a function of time on the limiting practical sensitivity of measurement.

- Determine the relations between leakage rates of steam-air-fission product mixtures and that of air through representative containment vessel leakage paths.

Results to Date

Leakage rate tests on the CSE containment vessel were conducted earlier with room temperature air at 3 levels of nominal leakage rate (1.0, 0.5, and 0.1%/day) and at multiple pressures at each leakage rate level. The leakage rates of heated air atmospheres and of steam-air containment atmospheres are now being measured at three pressure levels with a containment vessel configuration for which the cold air leakage rates were determined at the same pressures immediately before the tests with higher temperature atmospheres began. As in previous tests, both reference vessel techniques and absolute pressure and temperature techniques will be employed for integrated leakage rate measurements, and leakage at individual penetrations will be monitored since the sensitivity of the integrated leakage rate methods may be poor because of more rapid temperature changes.

The leakage of fission product aerosols at individual leak points will be measured during selected fission product transport runs, and will be compared with predictions based on previously measured air or steam-air leak rates for the leak path.

In the leakage rate test series performed, the general procedure was to adjust the naturally occurring leaks until the correct nominal leakage rate was established at 60 psig. The individual leaks were not adjusted further during tests at the several pressure levels at that nominal leakage rate.

The data collected on variation of leakage rate with pressure indicate that laminar flow extrapolation is not too conservative an estimate for upward extrapolation of leakage rates. Most of the leakage test data collected at leakage rates above about 10 ml/min tend toward the laminar flow regime. Individual leakage measurements were largely in the laminar flow regime. Leakage at individual leakage points was successfully collected. Double valve arrangements and collection with plastic bags allowed measurement with sensitive flowmeters. Leakage points which were too small to measure (less than about 5 ml/min) were located using a halogen gas detector. The total of the flowrates of the individual leaks was in reasonably good agreement with results of the integrated vessel leakage rates determined by both absolute pressure and temperature techniques and by the reference vessel technique. This agreement provided an independent verification of the correctness and sensitivity of the integrated test techniques.

Data collected in the CSE tests indicates that there is considerable uncertainty in both absolute and reference method leakage determinations at pressures below about 15 psig and about 0.1% per day weight leakage. Error analysis of instrumentation predicts some of this uncertainty, and temperature fluctuations caused by diurnal cycles, weather conditions and building temperature control increase the uncertainty to as much as $\pm 500\%$ in some cases.

Fission Product Transport Studies

The objectives of the fission product transport studies are to perform experiments leading to the development and verification of analytical models which provide a means for predicting fission product transport behavior within containment vessels during postulated accidents to large pressurized and boiling water reactors. This knowledge, when combined with knowledge of the rate of release from primary reactor vessels and leakage from containment vessels, will provide improved methods of accident analysis. This, in turn, will provide more realistic technical bases for power reactor site selection, operational guides in event of an accident, and for improved design of reactor plant features which affect public safety.

Four areas of fission product transport technology are to be investigated:

Fission Product Transport by Natural Processes in the Absence of Engineered Safeguards - The effects of diffusion in the bulk gas, diffusion across boundary layers, agglomeration and gravitational settling, steam condensation, and intercompartment transfer are to be evaluated. The results will be compared with theoretical models. A thorough understanding of transport by natural processes is necessary not only for its own merit but to provide the means of evaluating the effects of engineered safeguards.

Containment Spray Systems - The effects of spray flow rate, drop size, containment atmosphere and spray solution on the removal of fission products from the gas space are to be demonstrated for selected cases. Experimental results, corrected for natural transport effects, will be compared with theoretical predictions.

Air Cleaning Systems - The effectiveness of conventional filter-adsorber systems in the recirculating mode for decontaminating the atmosphere within containment vessels during accident conditions is to be demonstrated. Results will be compared with small-scale studies performed elsewhere and with predictions of analytical techniques.

Pool Scrubbing Experiments - The performance of aqueous pools in removing fission products during pressure suppression is to be investigated. The effects of bubble size, flow rate, atmosphere and pool solution additives will be shown for selected cases. Results will be compared with theoretical predictions.

Results to Date

Two aerosol transport experiments investigating fission product behavior in a saturated steam plus air containment atmosphere under the influence of natural processes were carried out in the uninsulated containment vessel at relatively low temperature but at relatively high steam condensation rates. The objectives of these tests were: (1) demonstrate on a significant size scale the removal of fission product materials from the containment vessel vapor space that would occur in the absence of active engineered safeguards; and (2) obtain information needed to verify

mass transport models which can be used in evaluations of the consequences of meltdown accidents in large power reactors.

Figure 2 shows a schematic view of the arrangement used in the large-scale tests, Runs A-1 and A-2. The atmosphere within the containment vessels was a mixture of steam and air at about 180°F, 23 psia. These conditions were established prior to release of aerosol material by addition of building supply steam, and they were kept constant throughout the tests by continued steam addition to replace loss by condensation. The condensate was allowed to accumulate in the vessel sumps.

Although this is an idealized case, the conditions are within the range of those possible in the event of a loss-of-coolant accident to a reactor which continues to release steam by fission product decay heat, residual pool boil-off and emergency core coolant evaporation, with concurrent heat loss to the containment structure and its environs. By purposely selecting equilibrium atmospheric conditions, the verification of mathematical models is greatly simplified. Subsequent tests at other steady state conditions will be required; but the models will be suitable for predicting transport behavior in unsteady conditions.

Table I lists the important conditions used in Runs A-1 and A-2. These tests were essentially duplicates except that about 100 times more iodine and 10 times more cesium were injected into the containment vessel in the second test. Also, the painted interior had not been exposed to steam prior to the first test, but could be considered well aged prior to the second.

Samples of the containment atmosphere were taken at various times by Maypack clusters installed within the vessels at different locations. Fifteen clusters were used in Run A-1; eleven in Run A-2.

Figure 3 shows the iodine concentration in the main vapor space as a function of time for Run A-2. Individual lines are plotted for each of the Maypack components. The solid line is the sum of the four components plus the material deposited on the inlet check valve and nose cone. The latter two items were <5% of the total.

As expected, the elemental iodine (silver surfaces) and particulate iodine (filters) rapidly left the gas space with a concentration "half-life" of 10-11 minutes, while the organic iodide (charcoal sections) concentration decreased only slightly. Since organic iodides were not purposely added, their concentration was only 0.1% of the total iodine injected. Previous experience has shown, this figure varies between 0.01% and 1.0%, depending on the total iodine mass released and the system used. Backup traps showed that penetration of the Maypacks was <0.1%.

The containment configuration used on these tests was such that the aerosol was released into a main vapor space which was connected to a lower, smaller room by two 4-foot diameter openings in the deck. This space is termed the "middle room"; and it in turn is connected to the bottom head space by one 4-foot diameter opening. The iodine concentration in each of these rooms is shown in Figure 4. The concentration in the lower rooms increased with time due to diffusion from the high-concentration in the main room. Removal processes in the lower rooms were slower than in the main room because steam condensation rate and convection currents were lower.

Cesium Concentration in Gas Phase

Figure 5 shows the gas phase concentration of cesium in the main room (including drywell), middle room and lower room as a function of time. The concentration in the main room fell exponentially with a "half-life" of 20-22 minutes to less than 10^{-5} of its initial value. At later times, the concentration in the middle and lower room exceeded that in the main room.

Analyses for uranium are not finished, but preliminary results plotted in Figure 6 indicate that uranium concentration in the vapor space decreased with about a 30 minute "half-life" for both tests. We have no explanation at this time for the apparent discontinuity at 1.5 hours in Run A-1.

Figures 7 and 8 show the distribution of iodine and cesium within the containment system as a function of time. The figures are based on the calculated amount of material injected, which should be accurate to $\pm 5\%$. The two curves showing gas phase and condensate in sumps were obtained by data collected with multiplication by appropriate volumes and division by the calculated total mass injected. The third curve, showing the fraction on surfaces is merely the difference between the total and the sum of the first two curves. This curve represents the material which is in the flowing condensate film plus that reacted or adsorbed on solid surfaces. Twenty-four hours after aerosol release, about 47% of the iodine and 10% of the cesium was on the surfaces. Continued decontamination

by steaming for 70 additional hours, alternated with water spraying, resulted in a final estimate of wall holdup of 36.5% of the iodine and 4.4% of the cesium.

It may be concluded that natural processes of removal were rather effective in the large vessel because of the rapid mixing and turbulent boundary layer conditions that resulted from the high gas phase velocity produced by modest temperature differentials. It was also concluded from these two tests that aerosol transport behavior was independent of initial iodine and cesium concentration; and that the condition of the paint on the vessel interior had no significant effect on iodine transport behavior or chemical form late in the test.

An analytical model was developed to predict aerosol removal by natural processes for an assumed containment system geometry and post accident conditions based on the analogy between heat and mass transfer. The model satisfactorily accounts for the observed removal of elemental iodine in experiments ranging from a 1 m^3 vessel to the 800 m^3 CSE containment vessel. The method permits the estimation of mass transfer from containment atmospheres to vessel surfaces with the conservative assumption of steady state temperature and pressure conditions. Other important assumptions are:

- o the bulk gas is well mixed at all times.
- o flow patterns within the vessel are caused only by natural convection.

- the fission product mass is transferred across the gaseous boundary layer at all containment interior surfaces by diffusion due to concentration gradients and by flow of condensing steam to heat transfer surfaces.
- the mass transfer rate is gas phase limited; i.e., all surfaces act as perfect sinks.

The starting information required is the bulk gas temperature, T_b ; total pressure, P ; partial pressure of water vapor in the bulk gas, P_b ; temperature of the gas surrounding the containment vessel, T_a ; the thicknesses and thermal conductivities of the wall structure; and the vessel volume, surface area and characteristic height. The calculational steps are as follows.

1. Estimate the gas-liquid interface temperature, T_i .
2. Calculate the condensing steam flux.
3. Estimate the mass transfer coefficient due to flow of condensing steam to walls.
4. Estimate the mass transfer coefficient due to ordinary diffusion across the gas boundary layer. Treat each mass transport species separately.
5. Calculate the total fission product mass transfer rate. Express in terms of concentration half life.

The one case where a comparison can be made between experiment and the model (CSE Run A-2) shows remarkably good agreement. A future CSE test is planned for the case where the containment vessel will be insulated.

Other conclusions and comments are that interior surface areas must be known in order to predict transport rates; that iodine gas phase concentration half-life is independent of vessel size (L) per se but depends on the surface area to volume ratio which may be surprisingly constant due to the extensive compartmentation in larger vessels. Also, larger containment vessels tend to have more thermal insulation in the form of thicker concrete walls, and this results in longer half lives. The equations on which the heat-mass transfer analogy are based were derived empirically from heat transfer experiments with short vertical plates of length < 1 foot. They are claimed to be valid for values of the Gr·Pr modulus in the range 10^9 to 10^{12} . Large containment systems can have values of this modulus exceeding 10^{13} and their validity of the values at these higher ranges should be verified.

The model is admittedly a considerable simplification of a complex process; but it provides a means of making useful estimates of fission product transport for any containment system with information available from the reactor facility design.

Two large-scale containment spray runs have been made in the CSE vessel to measure the removal of simulated fission product aerosols from air at 75°F by boric acid-sodium hydroxide spray solutions. The two experiments were duplicates except that the spray flux was four times higher in Run A-4 (0.10 gpm/ft^2) and the final spray in Run A-3 was with demineralized water rather than recirculated spray solution from the sump (see Table II). The spray drop size was fixed at 1210 $\mu \text{ MMD}$, $\sigma_g = 1.53$; fall heights in the 25 foot diameter containment vessel were

from 34 to 50 feet. The initial aerosol concentration for both runs was approximately 100 mg/m³ of elemental iodine, 1.7 mg/m³ of methyl iodide, 10 mg/m³ of cesium oxide fumes and 10 mg/m³ of uranium-Zircaloy cladding fumes.

The experiments were designed to (a) verify mass transport mechanisms; and (b) detect departures from the assumptions on which the mathematical models for spray systems are based. For molecular iodine the gas film mass transfer coefficient to the falling drops can be estimated from the Ranz and Marshall correlation.⁽¹⁾

$$\frac{k_m d}{D} = 2.0 + 0.60 Sc^{1/3} Re^{1/2} \quad (1)$$

For a well mixed vessel the gas phase concentration will be

$$c/c_o = \exp \left[- k_m \frac{A}{V} t \right] \quad (2)$$

For particles the gas phase concentration can be similarly expressed as

$$c/c_o = \exp \left[- \frac{3 F h E}{2 V d} t \right] \quad (3)$$

where:

k_m = mean gas phase mass transfer coefficient, cm/sec

A = surface area of drops in vessel at any time, cm²

V = free volume of gas in vessel, cm³

c = concentration of material being removed from gas phase, g/cm³

c_o = concentration of material being removed at time zero, g/cm³

F = flow rate of spray solution, cm³/sec

h = spray fall height, cm

(1) Ranz, W. E. and W. R. Marshall, Jr., "Evaporation From Drops," Chemical Engineering Progress, 48, 173, (1952).

E = single drop collection efficiency

d = spray drop diameter, cm

t = time after aerosol release, sec.

D = diffusivity, cm^2/sec

Sc = Schmidt number

Re = Reynolds number

The experiments were divided into several spray periods so that natural transport effects between spray periods could be measured and allowed for. Table III shows the measured concentration half-times and those calculated on the basis of equations 1, 2, and 3. Particle diameters were measured before and after the first spray.

The chief conclusion derived from these large scale experiments is that all of the transport materials behaved as predicted by the models for short spray periods but that large deviations were noted during longer spray periods. Molecular iodine transport to the fresh caustic-boric acid spray drops was gas film diffusion limited. Methyl iodide was removed to only a slight extent, as expected. The removal rates for particulate material fit impaction equations when reasonable values of particle diameters and drop collection efficiencies are used.

Coolant Blowdown Studies

The maximum credible accident usually postulated for either a pressurized or boiling water reactor is the full double ended pipe-break in the primary reactor coolant loop. This break will result in rapid depressurization (blowdown) of the coolant inside the reactor vessel and

primary cooling system and rapid pressurization of the containment system. The depressurization could result in large forces being applied to the reactor internals which could damage the core, the support structure, the control rods or mechanisms, the emergency core cooling system, or cause blockage of core coolant channels. The thrust forces, impingement forces, and the pressurization could cause damage to systems (including emergency features) within the containment vessel as well as penetration of the containment barrier itself.

The design of adequate and safe structures to withstand such an accident and the design of various proposed safeguard systems requires some means to predict the results of such an accident both accurately and in some detail for the particular design considered. Because of the wide variety of designs for reactor systems, the development of generalized mathematical models are necessary to describe the processes occurring.

The objectives of the coolant blowdown studies in the CSE program are to concurrently obtain engineering data from large-scale experiments and develop mathematical models with the objective of predicting the consequences of primary coolant system accidents postulated for pressurized water and boiling water reactors.

Results to date

About 20 experimental blowdowns have been made from a bottom nozzle on the reactor simulator vessel without internal structures. Most runs have been from initially saturated water conditions although some initially subcooled runs have been made using nitrogen gas for pressurizing. Experience has been gained in the measurement techniques and in digital computer data logging.

The general arrangement of the vessel and blowdown facility is shown in Figure 9. Blowdown weight flow rates have been measured by weighing the vessel during blowdown. Figure 10 shows our data with other results illustrating that the mass velocity decreases with increased nozzle size during saturated blowdown. Measured mass velocities compare favorably in this decreasing trend with gross mass velocities reported by other investigators. The mass velocity effect can be allowed for by using a flow coefficient depending on the break size and the predictive method used. The decrease in mass velocity with nozzle size is probably on entrance quality effect. Figures 11 and 12 are typical results showing the pressure in the vessel and the mass of fluid remaining in the vessel as functions of time for saturated blowdowns. The experimental results show that the pressure transient is reasonably well predicted by a model such as that of F. J. Moody, while the mass data is not well predicted.

The void fraction of the fluid in the pipe upstream of the discharge orifice has been measured in a few runs with a neutron densitometer. This device utilizes the scattering and moderating effects of the fluid on fast neutrons to give an indication of fluid density or void fraction, from which fluid quality is calculated. Densitometer readings show a higher quality with larger nozzle size or blowdown temperature. Figure 13 shows representative results.

The saturated mass velocities are about the same at the same fluid temperature whether the blowdown was started from an initially

subcooled or saturated condition. Temperature and pressure measurements made at several stations in the vessel show that both the liquid and the vapor zones follow the saturation curve during blowdown.

Blowdown thrust forces during the two-phase portion of the blowdown can be expressed as $F = C 2PA_B$

where: P = vessel pressure

A_B = break area

C = coefficient with value from .6 to .7

The subcooled mass velocity measurements are subject to error because of the short duration of the subcooled portion of the blowdown. Although some runs gave substantial agreement, others showed significantly higher mass velocities than predicted by Zaloudek's correlation particularly at high pressure drops. Figures 14 and 15 illustrate some typical results. More tests will be needed to resolve this discrepancy.

Subcooled decompression pressure histories have been similar to those shown by the blowdown studies for the LOFT program. The frequency of oscillations is a strong function of pipe length and fluid temperature.

We had trouble with the structure supporting the vessel in thrust. The lower member was inadequately designed and failed in buckling. The result has been six months program delay. During nondestructive testing of the reactor simulator vessel for possible damage, it was found that the vessel heads have some laminar type defect indications which have grown significantly during vessel service.

The next phase of blowdown testing will include runs with a simple dummy core plate inside the vessel. During these runs, the possible further growth of the defect indications will be closely monitored.

TABLE I

TEST CONDITIONS - RUNS A-1 & A-2

Vessel Used	Run A-1 Main CSE vessel plus Drywell, wetwalls sealed off.	Run A-2 Same as A-1
Volume above deck (including Drywell) m ³	596	596
Surface above deck (including Drywell) m ²	570	570
Surface area/volume, m ⁻¹	0.958	0.958
Volume middle room, m ³	59	59
Surface middle room, m ²	127	127
Surface area/volume, m ⁻¹	2.16	2.16
Volume lower room, m ³	96	96
Surface lower room, m ²	191	191
Surface area/volume, m ⁻¹	2.00	2.00
Previous steam exposure, hr	0	114
Avg. temp., main vapor space, °F	181 +2	185 +2
Avg. temp., middle room, °F	151 +2	163 +2
Avg. temp., lower room, °F	127 +2	128 +2
Avg. total pressure, psia	22.5	23.2
Avg. steam makeup, lb/hr	510	660
Condensing steam flux on main CV walls, lb/hr-ft ²	0.096	0.110
Aerosol release duration, min	7	10
C ₀ , calc'd initial conc. in main vapor space, mg/m ³		
Total iodine	1.16	94.5
Total cesium	0.62	6.1
Uranium-Zircaloy	~ 2	~ 3

TABLE II
SPRAY TEST CONDITIONS

Test No.	A-3			A-4		
	1	2	3	1	2	3
Spray Period						
Time from 0, min	40	140	1470	40.5	140	1205
Duration, min	10	30	60	10	30	45
Spray Flux, gpm/ft^2	0.026	0.026	0.025	0.10	0.10	0.085
Drop size MMD, μ	1210	1210	1210	1210	1210	1360
Solution, pH	9.5 ^a	9.5 ^a	6.8 ^b	9.5 ^a	9.5 ^a	9.6 ^c

^a3000 ppm H_3BO_3 , 1.5 g/l NaOH

^bdemineralized water, not recirculated

^crecirculated from sump

TABLE III
CSE SPRAY REMOVAL HALF-TIMES, minutes

<u>Material</u>	<u>Form</u>	<u>Spray</u>	<u>A-3</u>		<u>A-4</u>	
			<u>Calculated</u>	<u>Measured</u>	<u>Calculated</u>	<u>Measured</u>
I ₂	elemental	1	5.1	5.4	1.50	1.64
	"	2	5.1	6.2	1.48	10.4
	"	3	---	~20	---	(a)
U	0.6 μ dia	1	32	39	9.7	7.8
	0.3 μ dia	2	---	31	52	14
		3	---	35	---	65
Cs	0.5 μ dia	1	170	16	50	3.5
	1.4 μ dia	2	25	16.7	7.7	10.3
		3	---	~25	---	~50

(a) Airborne concentration increased about twofold

FIGURE 2

Schematic of Containment Vessel
Arrangement Used in CSE Runs A-1 and A-2

FIGURE 3

Iodine Gas Phase Concentration
Versus Time in the Main
Vapor Space - Run A-2

FIGURE 4
Iodine Gas Phase Concentration
Versus Time in Interconnected
Vessel Compartments - Run A-2

FIGURE 5

Cesium Gas Phase Concentration
Versus Time in Interconnected
Vessel Compartments - Run A-2

FIGURE 6

Uranium Gas Phase Concentration
Versus Time in the Main Vapor Space -
Runs A-1 and A-2

FIGURE 7

Iodine Distribution Within
Containment as a Function of Time -
Run A-2

FIGURE 8

Cesium Distribution Within
Containment as a Function of Time -
Run A-2

TABLE 2.IX. Summary of High Temperature Blowdown Runs

FIGURE 11

Pressure Decay CSE
Simulator Vessel-Saturated Blowdown

FIGURE 2.20. Weight of Water in CSE Simulator Vessel

FIGURE 12

Weight of Water in CSE Simulator Vessel

*FIGURE 2.29. Quality Versus Time
(Outlet Pipe)*

FIGURE 13
Quality Versus Time
(Outlet Pipe)