A PARAMETRIC STUDY OF TEMPERATURE,
PRESSURE, AND BURNING RATE RESULTING
FROM LARGE SODIUM POOL FIRES
IN THE CSE CONTAINMENT VESSEL

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DECEMBER 1974

MASTER

Prepared for the U.S. Atomic Energy
Commission under Contract AT(45-1):1830

BNWL-B-391

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U.S. ATOMIC ENERGY COMMISSION
Under Contract AT(45-1)-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$4.00; Microfiche \$1.45

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A PARAMETRIC STUDY OF TEMPERATURE, PRESSURE, AND
BURNING RATE RESULTING FROM LARGE SODIUM POOL
FIRES IN THE CSE CONTAINMENT VESSEL

For

Division of Reactor Safety Research
Experimental Fast Reactor Safety Branch
U. S. Atomic Energy Commission

By

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ABSTRACT

A parametric study was conducted to determine the effect of sodium burning conditions on the temperature, pressure, and sodium burning rate in the CSE containment vessel. The study was needed to determine the maximum range of the physical parameters in the scheduled large scale sodium aerosol tests. The study was conducted as part of the RSR sponsored program: "Experimental Studies of Aerosol Behavior Associated With Low Probability Accidents in an LMFBR". For the expected values of experimental parameters, average gas temperature as high as 360°F, and pressures as high as 4.5 psig were predicted. During the burn period, considerably higher temperatures were reached in the fire plume. The dominant heat input comes from the heated burn pan rather than the fire itself. The predicted temperatures and pressures were found to be well within the design ratings of the vessel, and the predicted streamlines resulting from the fire are expected to be helpful in selecting locations for particle samplers in the containment vessel.

ACKNOWLEDGMENTS

This work was carried out under the contractual supervision of L. N. Rib, Chief, Experimental Fast Reactor Safety Branch, Division of Reactor Safety Research. The authors wish to acknowledge Mr. Rib's interest and guidance in this study. We would also like to thank Mr. D. L. Reid for his technical guidance in this study.

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INTRODUCTION

The PNL research program entitled "Experimental Studies of Aerosol Behavior Associated With Low Probability Accidents in an LMFBR" is designed to provide large-scale proof tests of aerosol models used to analyze hypothetical core disassembly accidents in LMFBR's. An aerosol model, whose validity had been verified at large scale would serve as an important tool in analyzing postulated accidents in an LMFBR.

Initial aerosol tests planned for this PNL research program are sodium fire tests to be carried out in the CSE (Containment Systems Experiment) containment vessel. This vessel is 67 ft in height, 25 ft in diameter, and is designed for 75 psig pressure at 300°F. Numerous sampling devices and other instruments are to be installed throughout the containment volume to characterize the behavior of sodium oxide aerosol formed by the sodium fire. In order to assure that the design limits of the vessel would not be exceeded by conditions resulting from experiments, and to determine sampler requirements, it was necessary to make pretest predictions of temperatures, pressures, and convection currents resulting from sodium fires in the CSE vessel.

The present report deals only with pool fire tests. Spray fire tests are planned for a later program phase, and a similar pretest parametric study will be required. Although pressures resulting from pool fires are modest, considerably higher pressures may be developed by spray fires of short duration because heat transfer to the vessel wall would tend to be less complete in spray fires as compared to pool fires.

Two existing computer codes were used to make the predictions for pool fire tests. SOFIRE II, developed at Atomics International, was used to compute sodium burning rates, and average temperatures and pressures in the containment gas phase. The COVEC code, developed at PNL, was used to predict spatial temperature and air velocity distributions within the containment gas space.

Parametric calculations were made using SOFIRE II. Temperatures and pressures resulting from pool fires were computed for several values of six important parameters. Two runs were made with the COVEC code using parameters selected as typical for planned tests.

SUMMARY AND CONCLUSIONS

Thermal and flow conditions accompanying sodium pool fire tests in the CSE containment vessel were analyzed as part of the experimental design effort. Average temperatures, pressures, and sodium burning rates were predicted for a range of conditions using the SOFIRE II Code. Flow patterns and temperature distributions in the vessel atmosphere were computed using the COVEC Code.

The results of these calculations provided important information to the design of the fire source and airborne sampling system. In general, the results indicated that the desired fire tests could be safely carried out in the CSE vessel. Important conclusions resulting from this brief study include the following:

1. Two hundred pounds of sodium can be burned in an 80 ft² burn pan maintained at 1100°F in about 30 minutes in an air atmosphere. Based on previous calculations, this burning rate was required to reach an airborne oxide concentration of 50 g/m³ in 30 minutes.
2. Temperature and pressure buildup in the vessel atmosphere depend primarily on hot plate conditions and are only weakly related to the fire itself. This is so because the hot plate is the main energy source in the pool fire tests.
3. Peak pressures produced in pool fire tests considered here are less than 10 psig, and therefore are small compared to the vessel pressure rating of 75 psig.
4. During a typical fire, wall steel temperature is lower by 80°F than the gas temperature. If wall temperatures are to be limited to 300°F, continuous operation of the hot plate at 1100°F will be limited to time durations less than 5 hr.

5. When the hot plate is operating, a large convection cell is predicted to exist in the vessel. The hot plume will rise with velocities of 10 ft/sec along the vessel centerline, and then fall near the wall at lower velocities. No stable, stratified, layers are expected, and a well-mixed atmosphere is expected at least for long times. However, the plume flow pattern may be expected to influence time-concentration histories for particles during the first few seconds of their lifetimes.
6. Temperatures in the plume fall rapidly with distance above the burn pan due to entrainment of surrounding air. However, temperature damage considerations limit the placement of samplers directly over the burn pan. At a centerline height of 20 ft, above the burn pan, the gas temperature is predicted to be 150°F higher than the average gas temperature.

COMPUTER CODE DESCRIPTIONSSOFIRE II CODE

SOFIRE II⁽¹⁾ is a digital computer code which solves a set of transport equations describing the simultaneous transfer of heat and mass by a finite difference method. The test cell (containment vessel) and liquid sodium is simulated by a nodal network in which the nodes are connected along a heat transfer path by admittances, equal to the reciprocal of the thermal resistance. The thermal capacity of the node is equal to that of the material. The temperature assigned to or calculated at each node is that at the centroid of the node.

The sodium burning rate is computed from the oxygen mass transfer rate to the surface of the sodium pool. An instantaneous reaction between oxygen and sodium at the pool surface is assumed. Burning is assumed to continue as long as both oxygen and sodium are present.

The test vessel used in sodium fire tests at Atomics International contained four elements: a steel liner, an air gap, a steel jacket, and an insulating jacket. The code therefore includes four nodes, so that each vessel element may be accounted for. The CSE vessel, on the other hand, may be classed as a two nodal system because the vessel wall is composed of a steel membrane covered by fiber glass insulation. The SOFIRE II Code was modified by deleting the extra two nodal calculations.

In the tests planned for the CSE vessel, a large part of the thermal energy input is generated by the hot plate. This was accounted for in the model by setting the temperature of the deepest node in the sodium pool equal to the pan temperature. This approach tends to lead to overpredictions in gas temperatures and pressures because the thermal resistance of solid sodium oxide in the burn pan, and the burn pan itself, is neglected.

Input/output parameters and plotting routine of SOFIRE II were modified to run on the CYBER computer system at Richland. The SOFIRE II Code modified to be applicable to CSE test conditions is identified as the RLC version of SOFIRE II.

COVEC CODE

The COVEC Computer Program is a fluid mechanics code developed at Battelle-Northwest for predicting temperature, concentration and velocity distribution of multi-component, density driven flows in closed systems. The computational techniques are based on a finite difference solution to the continuity, momentum, energy and constituent transport equations for steady, incompressible flow in systems having axial symmetry^(2,3).

To carry out the numerical calculations, values of eddy viscosity had to be assumed since data were unavailable. A constant value of eddy viscosity for the entire calculational field was chosen based on data obtained from axisymmetric plume experiments published in the literature.

The interior of the CSE vessel was approximated as a right circular cylinder with a raised central portion representing the burn pan. Nodal spacing was varied to give the finest mesh where velocity gradients were expected to be greatest; i.e., near the wall of the vessel and near the flame front.

Computed output from the COVEC Code includes for each nodal point a listing of vertical and radial velocity, stream function value, and temperature. For the sake of brevity, only temperatures and streamlines are presented here.

PARAMETER RANGES

In order to evaluate the importance of parameters, calculations were performed using parameters valued at the expected test condition and at spaced intervals. For the SOFIRE II calculations, the numerical values of parameters used are shown in Table 1.

TABLE 1. Parameter Values Used in SOFIRE II Calculation

<u>Parameter</u>	<u>Expected Experimental Value</u>	<u>Parametric Calculation Value</u>
1. Time the hot plate is on	4 hrs	1,2,3,4 hrs
2. Mass of sodium burned	200 lbs	200,400,600,800 lbs
3. Ratio of sodium oxide and sodium peroxide generated	100% Na ₂ O	100% Na ₂ O 50% Na ₂ O
4. Burn pan area	80 sq ft	80,40 sq ft
5. Oxygen concentration	21% (Vol)	21%, 2% (Vol)
6. Hot plate temperature	1100°F	700,900,1100,1300°F

Each of the six parameters was varied while the remaining five were held constant at the expected experimental value.

For the COVEC Code calculations, two runs were made for conditions expected to accompany a fire in air with an 80 sq ft burn pan. In one run, the wall heat transfer coefficient was assumed to be very large (no wall film resistance), and in the other the surface heat transfer coefficient was set equal to 5 BTU/hr ft²°F. This range was expected to cover the actual values of wall heat transfer coefficient likely to be encountered under test conditions.

The containment vessel arrangement used in the SOFIRE II calculations is shown in Figure 1.

FIGURE 1. Schematic Representation of Facility for Pool Fire Tests in CSE Vessel.

RESULTS

EFFECT OF DURATION OF HOT PLATE OPERATION ON TEMPERATURE AND PRESSURE

The temperature rise in the gas phase resulting from hot plate operation is shown in Figure 2. The hot plate is assumed to begin operation at time zero and continue after sodium burning has ceased at about 30 minutes. The peak temperature reached in the gas phase increases from 260°F to 355°F as the time the hot plate operates from 1 to 4 hours. The temperature falls rapidly from the peak as soon as power to the hot plate is turned off. This occurs because the steel walls of the vessel are appreciably cooler than the bulk gas temperature.

Pressure in the gas phase is shown in Figure 3 as a function of the time the hot plate operates. Peak pressure is 4.5 psig when the hot plate operates for 4 hours as compared to 2.3 psig when it operates for only 1 hour. Between about 0.1 and 0.5 hour, the gas pressure decreases as a result of oxygen depletion. After the fire is extinguished the pressure increases with temperature. The peak pressures are small compared to the design rating of the CSE vessel (75 psig). Pressures decrease as soon as the hot plate is turned off. For long times the pressure would become less than atmospheric, and this would have to be recognized in carrying out fire tests. It seems likely that in designing experiments, one would start with an air pressure great enough to prevent final pressures from falling below atmospheric pressure.

In Figure 4, the sodium burning rate is shown as a function of time. The average burning rate is approximately 5 lb/hr ft², leading to burnout at about 30 minutes. Since the burning period is completed within the first hour, longer operation of the hot plate has no influence on the burning rate.

FIGURE 2. Effect of Hot Plate Operation on Gas Temperature in Vessel.

FIGURE 3. Effect of Hot Plate Operation on Pressure Caused By a Sodium Pool Fire in CSE Vessel.

FIGURE 4. Burning Rate of Sodium For Base Case.

EFFECT OF MASS OF SODIUM BURNED ON TEMPERATURE AND PRESSURE

The vessel gas temperatures resulting from burning 200, 400, 600, and 800 lb of sodium are shown in Figure 5. It is obvious from these results that the heat of sodium combustion is small compared to that produced by the hot plate. The peak temperature reached for 800 lb of sodium is only a few degrees higher than when 200 lb of sodium is burned. From an energy release standpoint, a sodium fire falls very low compared to a fire involving a typical hydrocarbon.

Pressures resulting from sodium fires in which the sodium consumed varies from 200 to 800 lb are shown in Figure 6. The peak pressure is reached for the case of 200 lb of sodium burned. While this is at first surprising, it is explainable in terms of oxygen consumption by the fire, and the fact that the primary energy source is the hot plate rather than the fire. For fires involving larger quantities of sodium the final vessel pressure would be appreciably below atmospheric (up to -3 psig) and could cause buckling of vessels not designed for such vacuums.

The sodium burning rate is shown in Figure 7. The burning rate peaks early at about 5.2 lb/hr ft^2 and then decreases with time. In about 0.5 hr 200 lb of sodium is burned, and the average burning rate is about 4.8 lb/hr ft^2 . Approximately 1.2 hr is required to burn 400 lb of sodium, and the average burning rate is about 4.2 lb/hr ft^2 . Some 2 hr is required to burn 600 lb of sodium. For 800 lb of sodium, the fire would last about 3 hr. For the largest burn, the average rate is approximately 3 lb/hr ft^2 . The decrease in burn rate with time results primarily from the reduced oxygen concentration in the gas phase.

FIGURE 5. Effect of Mass of Sodium Burned on Gas Temperature in Vessel.

FIGURE 6. Effect of Quantity of Sodium Burned on Pressure in Vessel.

FIGURE 7. Sodium Burning Rate As a Function of Time.

EFFECT OF OXYGEN CONCENTRATION ON TEMPERATURE, PRESSURE, AND BURNING RATE

Temperatures attained in the vessel atmosphere for air and for an inerted atmosphere containing 2% oxygen are shown in Figure 8. As shown, the temperature hardly depends on the oxygen concentration level. This is so because the hot plate supplies much more energy than the fire.

The pressures developed for fires in air and in an inerted atmosphere are compared in Figure 9. The pressure in the inerted atmosphere is higher by about 0.4 psi than that developed in air because less oxygen is consumed by the fire in the former case. At long times, the pressure becomes lower for the air atmosphere case because more oxygen is consumed by the fire, leaving fewer moles of gas remaining in the containment vessel. It should be remembered that these results would not be fully representative of accident conditions because in accidents the hot plate would not exist.

Sodium burning rate is reduced by one to two orders of magnitude when the oxygen concentration is reduced to 2%. This may be seen by comparing burning rates shown in Figures 10 and 11. Also, the fire duration is appreciably different for the two cases. For an air atmosphere, all sodium is burned in about 30 minutes. However, for the inerted atmosphere burning rate decreases from an initial maximum rate of 0.5 lb/hr ft^2 to 0.14 lb/hr ft^2 at 4 hr when the hot plate is turned off. Theoretically the burning continues at a very low rate until either sodium or oxygen is exhausted. In reality, the fire would be expected to be self-extinguishing when the hot plate power is turned off. One of the simplifications of the SOFIRE II Code is that the fire is assumed to burn until sodium or oxygen is exhausted, and the code does not account for the fact that the fire would be extinguished when the temperature falls below a critical value.

FIGURE 8. Effect of Oxygen Concentration on Gas Temperature in Vessel.

FIGURE 9. Effect of Oxygen Concentration on Pressure Developed by Fire in CSE Vessel.

FIGURE 10. Sodium Burning Rate in Air.

FIGURE 11. Sodium Burning Rate in an Inerted Atmosphere.

EFFECT OF BURN PAN AREA ON GAS TEMPERATURE, PRESSURE AND BURNING RATE

According to SOFIRE II, the burning rate per unit area is only weakly dependent on the total area of the burn pan. Therefore, one would expect the aerosol generation rate to be approximately proportional to the area of the burn pan. Also, for the present application, the hot plate area was equated to the area of the burn pan. Therefore, the heat energy addition rate would also be proportional to the burn pan area.

Gas temperatures attained in the CSE vessel for fires in pans of 40 sq ft and 80 sq ft are shown in Figure 12. The maximum temperature occurs at 4 hr, the time at which hot plate electrical power is terminated. For the 40 sq ft burn pan, the maximum temperature is 255°F, which is about 100°F lower than for the 80 sq ft hot plate. It should be noted that the hot plate area is the controlling factor here, and if an 80 sq ft hot plate were used with a 40 sq ft burn pan, the temperature rise would follow that for the 80 sq ft burn pan shown in Figure 12.

The effect of burn pan area on vessel pressure is shown in Figure 13. As expected, the pressure rise for the smaller burn pan is appreciably less due to the lower heat addition rate. During the burn period the pressure decreases as the oxygen is depleted. The burn period is extended about 0.5 hr for the smaller burn pan and as a result the early dip in pressure persists longer for the small burn pan.

Burning rate for the 80 sq ft pan falls off more rapidly than the burn rate in the 40 sq ft pan. This is caused primarily by the more rapid decrease in airborne oxygen concentration for the larger pan.

This is shown in Figure 14. According to SOFIRE II the burning rate per unit area decreases slightly as pan area increases, other factors remaining the same. However, it should be recognized that fire data used in building SOFIRE II was obtained from fires smaller than those planned in the present tests. Therefore some discrepancy between predicted burning rates and those ultimately attained in tests would be expected.

FIGURE 12. Effect of Burn Pan Area On Gas Temperature Rise.

FIGURE 13. Effect of Burn Pan Area on Pressure Rise in Containment Vessel.

FIGURE 14. Effect of Burn Pan Area On Sodium Burning Rate

EFFECT OF OXIDE FORM ON TEMPERATURE, PRESSURE, AND BURNING RATE

The products of combustion in sodium fires are sodium monoxide (Na_2O) and sodium peroxide (Na_2O_2). The relative abundance of each of these products depends on the thermodynamic conditions at the point of formation, and this may change during the course of a fire. In SOFIRE II, the ratio of abundance of these two products is treated as an input parameter. Formation of other sodium compounds, such as sodium hydroxide and sodium carbonate, was not considered in the present study.

Temperatures in the gas phase are virtually independent of the chemical state of the combustion products, as is demonstrated in Figure 15. The entire temperature history is nearly identical for the case in which the combustion product is 100% Na_2O and the case in which the products of combustion are 50% Na_2O and 50% Na_2O_2 . This result is expected because the dominant heat source is the hot plate.

Calculated pressure increases for these two oxide cases are compared in Figure 16. It is apparent from the results displayed in Figure 16 that a slightly lower pressure develops when the peroxide is formed. This lower pressure occurs because more oxygen is consumed when the reaction product is Na_2O_2 , decreasing the total moles of gas in the vessel.

Burning rate, which is controlled by oxygen transport to the surface of the molten sodium, is lower where sodium peroxide is formed. As shown in Figure 17, the burning rate is some 25% lower where the products of combustion are 50% Na_2O and 50% Na_2O_2 as compared to 100% Na_2O . Likewise, one would expect the burning rate to be reduced by a factor of two if 100% Na_2O_2 were formed compared to the case when 100% Na_2O were formed. This follows because twice as much oxygen is required for each pound of sodium combusted when the product is Na_2O_2 .

FIGURE 15. Effect of Sodium Oxide Species Formed on Gas Temperature in Vessel.

FIGURE 16. Effect of Sodium Oxide Species Formed on Pressure Rise in Containment Vessel.

FIGURE 17. Effect of Sodium Oxide Species Formed On Burning Rate.

EFFECT OF HOT PLATE TEMPERATURE ON GAS TEMPERATURE, PRESSURE AND BURNING RATE

The dominant factor in determining gas temperature attained in a pool fire test is the power input to the hot plate. This is clearly shown in the results presented in Figure 18. Peak gas temperatures of 220°F, 275°F, 355°F, and 455°F are reached when the hot plate temperatures are 700°F, 900°F, 1100°F, and 1300°F respectively. All peak temperatures are attained when power to the hot plate is terminated. Temperatures fall off rapidly when hot plate power is terminated.

The relatively high temperature ramp accompanying operation of high temperature hot plates represents an operating limitation on pool fire tests in the CSE vessel. Hot plate surface area, operating temperature, and time of operation must be chosen to prevent the vessel design temperature from being exceeded.

These results show that the temperatures and pressures reached in pool fire tests depend almost exclusively on how much thermal energy is added by the hot plate. The energy added by the sodium fire has very little influence on temperature and pressure peaks. If tests were performed without an electrically heated burn pan, temperatures would be much lower than shown in Figure 18.

Pressure developed in pool fire tests which use hot plate temperatures of 700°F, 900°F, 1100°F, and 1300°F are shown in Figure 19. Except for the burn period when pressure falls due to oxygen depletion, the pressure follows the temperature history as predicted by ideal gas law behavior. Even for the hottest burn pan temperature used (1300°F) the maximum pressure reached (7 psig) is modest compared to the vessel design pressure (75 psig).

Sodium burning rate is appreciably influenced by hot plate temperature as shown in Figure 20. Peak burning rates attained in air are 3.7, 4.6, 5.4, and 6.1 lb/hr ft² for pan temperatures of 700°F, 900°F, 1100°F, and 1300°F respectively. Thus pan temperature causes a change in burning rate of approximately 8% per 100°F. The change in burning rate with temperature is predicted in SOFIRE II primarily because gas diffusivity increases with temperature.

The variation in burning rate with temperature allows some control of aerosol generation rate via pan temperature. This can be significant if particular concentration levels in specified time periods are required.

FIGURE 18. Effect of Burn Pan Temperature On Vessel Gas Temperature.

FIGURE 19. Effect of Hot Plate Temperature On Vessel Gas Pressure.

FIGURE 20. Effect of Hot Plate Temperature On Sodium Burning Rate and Duration.

COMPARISON OF AVERAGE GAS TEMPERATURE WITH STEEL WALL TEMPERATURE

The design pressure rating of the CSE vessel applies for the case where wall temperature is equal to 300°F. For steam-air atmospheres, the wall temperature is very close to the gas temperature due to the large heat transfer coefficient. For sodium fire tests, the wall temperature may be appreciably lower than gas temperatures because heat transfer to the walls is limited by convection.

Wall temperature is compared to gas temperature in Figure 21. During most of the fire period, the wall temperature is lower than the gas temperature by about 80°F. As soon as hot plate power is turned off, wall temperature and gas temperature approach each other rapidly.

If the vessel design temperature of 300°F were the maximum allowable temperature, then hot plate operation at 1100°F would be limited to about 5 hours. For longer times, wall temperatures would exceed 300°F. Inasmuch as gas pressures are far below the 75 psig design value, the temperature limit could likely be relaxed. However, it is unlikely that the 300°F limit will pose a problem because no need is foreseen to operate the hot plate at 1100°F for more than 5 hours.

FIGURE 21. Comparison of Vessel Wall Temperature With Gas Temperature in Typical Pool Fire Test.

PREDICTED TEMPERATURE AND VELOCITY DISTRIBUTIONS DURING A POOL FIRE

Fluid flow streamlines predicted by the COVEC computer code for a fire situation are shown in Figures 22 and 23. In Figure 22, the wall heat transfer coefficient was assumed to be $5 \text{ BTU/hr ft}^2 \text{ }^\circ\text{F}$ and in Figure 23, heat transfer resistance at the boundary node was neglected. Wall temperatures were set equal to 150°F for both cases; hence, the calculations apply to conditions expected during the first 30 minutes, the interval when the fire would be burning.

The streamlines shown in Figure 22 correspond to those in a vessel half-section. By symmetry, a mirror image set of streamlines would exist on the left side of segment shown.

A large scale convection cell is predicted, with a warm plume rising in the center of the vessel, and a downward flow near the walls. A small circulating eddy is predicted near the top of the vessel. Theoretically, the center part of this eddy would receive material only by turbulent diffusion. Aerosol concentration at this point might be expected to lag that at other areas during the fire.

This convection pattern was predicted under the assumption that the hot plate was maintained at 1100°F . For fire situations in which less heat was transferred to the gas, the convection velocities would be smaller. For the present case, maximum buoyant velocities of about 10 ft/sec are predicted along the vessel centerline.

The convection currents generated by the sodium fire, even with a heated burn pan, are weak compared to those of typical fires. Convection currents are weak for sodium fires because the energy release rate (BTU/hr ft^2) is small compared to other combustion sources.

It is important to note that no stable stratification in the vessel is predicted for these pool fires. Therefore, the calculation lends support to aerosol models in which a well-mixed atmosphere is assumed for relatively long time periods.

FIGURE 22. Streamlines and Isotherms Predicted by COVEC For Fire Conditions in CSE Vessel.

FIGURE 23. Streamlines and Isotherms Predicted by COVEC For Fire Conditions in CSE Vessel.

The plume character of the circulation currents also indicates that during a fire, the center part of the vessel atmosphere will contain higher than average aerosol concentrations, and also will contain particles with shorter than average life times. These factors must be considered in applying models which assume perfect mixing at all times.

Temperature profiles shown in Figure 22 show that relatively large temperature gradients exist during fires. As expected, the highest temperatures exist in the center of the vessel just above the burn pan. Temperatures decay rapidly in the plume as cooler air is entrained. Twenty feet above the burn pan, the centerline temperature is about 400°F when the average gas temperature is about 250°F. The location of specific isotherms is important in locating particle samplers in positions in which they will not be damaged by heat.

A second calculational case, in which the wall heat transfer coefficient was assumed to be infinitely large, is shown in Figure 23. The results are similar for this case, but the flow streamlines are closer to the wall, and gas temperatures are slightly lower. Based on the similarity in the figures, it is concluded that the precise value of wall heat transfer coefficient is not critically important.

LITERATURE CITED

1. Beiriger, P., et al, "SOFIRE II User Report", AI-AEC-13055
Atomics International, Canoga Park, California, 1973.
2. D. S. Trent and J. R. Welty, "Numerical Computation of Convection Currents Induced by Fires and Other Sources of Buoyancy",
Western States/Combustion Institute, Seattle, No. WSCI 72-18,
1972.
3. D. S. Trent, "A Numerical Model For Predicting Energy Dispersion
In Thermal Plumes Issuing From Large, Vertical Outfalls In Shallow
Coastal Water", Ph.D. Thesis, Oregon State University, Corvallis,
Oregon, 1973. Also available as AEC document BNWL-SA-4479.

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