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Performance Of ALMR Passive Decay Heat Removal System

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ABSTRACT

The Advanced Liquid Metal Reactor (ALMR) concept[1] has a totally passive safety-grade decay heat removal system referred to as the Reactor Vessel Auxiliary Cooling System (RVACS) that rejects heat from the small (471 MWt) modular reactor to the environmental air by natural convection heat transfer. The system has no active components, requires no operator action to initiate, and is inherently reliable. The RVACS can perform its function under off-normal or degraded operating conditions without significant loss in performance. Several such events are described and the RVACS thermal performance for each is given and compared to the normal operation performance.

The basic RVACS performance as well as the performance during several off-normal events have been updated to reflect design changes for recycled fuel with minor actinides for end of equilibrium cycle conditions. The performance results for several other off-normal events involving various degrees of RVACS air flow passage blockages are presented. The results demonstrated that the RVACS is unusually tolerant to a wide range of postulated faults.

INTRODUCTION

The ALMR plant has three redundant methods for shutdown heat removal: 1) the normal heat transport system including the primary and secondary sodium systems, steam generator system and condenser, 2) an auxiliary cooling system (ACS) which removes heat from the steam generator outside surface by natural convection of air and transport of heat from the core by natural convection in the primary and intermediate systems, and 3) a safety-grade RVACS which removes heat passively from the reactor containment vessel. The combination of one active and two passive systems provides highly reliable and economical shutdown heat removal. The RVACS operates continuously but functions at its intended high heat removal rate only when the normal and ACS decay heat removal systems are inoperative and the reactor system temperature increases. The basic RVACS heat removal capability is self-regulating with the reactor temperature. Thus, the heat removal rate is only 0.9 MWt during normal operation temperature conditions (0.19% of power produced) and increases to about 2.8 MWt at the higher reactor temperature experienced during an "RVACS only" transient in which both the condenser and ACS are not available.

RVACS DESCRIPTION

The RVACS can dissipate all of the reactor decay heat through the reactor and containment vessel walls to the ambient air heat sink by the inherent processes of natural convection in fluids, heat conduction in solids, thermal radiation heat transfer, and convective heat transfer. Operation of RVACS is explained using the diagram of Fig. 1. Heat is removed from the core and transported to the reactor vessel wall by natural convection of primary sodium. Two alternate sodium flow paths exist in the vessel during most of the decay heat removal period. Initially, the sodium flow path is the same as that during normal reactor power operation, i.e. from the core upwards to the hot pool, then down through the Intermediate Heat Exchangers (IHXs) to the bottom of the vessel and then upward into the pump duct. The sodium then enters eight inlet pipes which lead to the high pressure core inlet plenum.

Second, a parallel sodium flow path becomes available after sodium temperatures have increased and the corresponding sodium volume expansion has resulted in overflow through slots provided in the reactor vessel liner. This parallel path is a somewhat more efficient overflow path downward through the annular gap between the reactor vessel and its liner. This path allows the sodium to give up some of its heat directly to the reactor vessel wall prior to exiting at an elevation near the IHX outlets. The remainder of the flow path is the same as during normal operation.

Heat transport through the reactor and containment vessels is by conduction, while from the reactor vessel to the containment vessel heat transport is mainly by thermal radiation (only 3 % is by natural convection in the argon-filled space between the two vessels). Thermal radiation heat transfer is promoted by providing high thermal emissivity coatings on the heat transfer surfaces. The surface coating consists of an oxide layer generated in conjunction with the normal heat treatment of the vessels.

In the last stage of the heat removal process, naturally convecting air removes heat from the containment vessel and collector cylinder and dissipates the heat to the sink (atmospheric air) as indicated schematically in Fig.1. Atmospheric air enters the RVACS through four inlet openings in the tornado hardened concrete stack structures protruding about 5 meters (15 feet) above grade level. It is directed downward into the lower of two horizontal plena and from there into the annular region between the concrete reactor silo and the collector cylinder (cold air downcomer). This incoming air turns around at the bottom of the silo and enters the 0.178 m (7-inch) annular gap between the containment vessel and the collector cylinder (hot air riser), where it is heated by the hotter, surrounding steel structures. The air heating provides the natural draft needed to maintain air flow in this loop. The heated air flows into the outlet plenum and from there it is discharged to the atmosphere through four outlet stacks as indicated in Fig. 1.

The inlet and outlet air openings are protected by heavy steel screens or gratings with openings small enough to prevent large objects from entering. The openings are also protected to limit harmful amounts of rain and snow from entering the RVACS. As an additional precaution, a sump pump is available at the bottom of the reactor silo (not shown in Fig. 1) to remove any water that might enter by seepage, floods, etc., in such quantities that it is not evaporated by the air stream and the hot steel structures located in the cavity. Every reasonable effort has been made in the design to reduce form and frictional hydraulic losses in the air flow path to enhance the air flow rate.

The RVACS thermal performance is monitored continuously at normal and other operating conditions. The Proposed monitoring instrumentation consists of thermocouples measuring inlet and outlet air temperatures as well as Pitot velocity probes calibrated to measure the air flow rate in each of the four RVACS stacks. The monitoring instrumentation is intended to be accurate enough to measure significant changes in parameters affecting RVACS operation such as, the air flow rate, system temperature rise, heat transfer coefficient, and thermal emissivity and air flow path resistance. Thus, from the performance monitoring of normal operating conditions the readiness of the system to perform its function if called upon to remove decay heat during emergency conditions can be ascertained.

BASIC RVACS PERFORMANCE

The performance analysis of the basic RVACS event conservatively assumes that the normal and auxiliary heat removal systems, as well as the Intermediate Heat Transport System (IHTS) sodium, are lost immediately following reactor and primary pump trips. The passive RVACS only is available to remove reactor decay and sensible heat. The present analysis was performed with the decay heat calculated for the reference ALMR metal core containing liquid metal reactor recycled fuel with minor actinides for end of life equilibrium cycle conditions. The decay heat for this core is about 6% higher than that used in previous analyses. Other parameters and the transient analysis model used in this analysis were similar to those used previously[2,3], except for slight changes in the air-flow path flow resistance reflecting recent design changes.

Transient analysis results for the basic RVACS event for nominal expected analysis assumptions and with clean heat transfer surfaces are given in Fig. 2. The curve gives the average core sodium outlet temperature. The maximum average reactor core sodium outlet temperature reached is 607°C (1125°F). It should be noted that sodium and structural temperatures in most other regions of the reactor are considerably lower than the average core outlet temperature. The slight discontinuity in the curve at about 4 hours occur when overflow starts at a hot pool temperature of 538°C (1000°F). The discontinuity is slight because the performance of RVACS is excellent both with and without overflow.

An assessment of the uncertainty in the maximum core outlet temperature value was made by perturbing each of the parameters listed in Table 1 individually in the transient model. The parameter change or the actual values used represent the 2-sigma uncertainty level. For example, it was estimated that the 2-sigma uncertainty in the decay heat is +15%. The individual parameter changes resulted in the maximum average core outlet temperature increases indicated in Table 1. The individual temperature changes were added up by taking the square root of the sum of the squares of the individual contributions to get the upper 2-sigma temperature as indicated in Table 1. This approach was judged to be the most correct one for the present system.

Table 1 RVACS Performance Uncertainty Evaluation for Basic Performance Case

Parameter	Nominal Case	Upper 2-Sigma Case	Increase in Max. Average Core Outlet Temp (°C/°F)
o Decay Power	Nominal(1)	Nominal + 15%	39/71
o Thermal Emissivities			12/21
- Stainless Steel	0.77(2)	0.70	
- 2 1/4 Cr-1 Mo Steel	0.85	0.80	
o Air-Side Heat Transfer Coefficient	Nominal Data (ANL)[4]	Nominal - 18%	13/24
o Others			6 /10

Upper 2-sigma limit = $1125 + (71^2 + 21^2 + 24^2 + 10^2)^{1/2} = 1125 + 78 = 1203$°F/651°C

(1) As calculated by the Origin II Code
(2) Values at 538°C/1000°F

DEGRADED RVACS PERFORMANCE

Several postulated events and scenarios considered beyond the design basis have been analyzed to illustrate the acceptable performance of the RVACS under unusual and severe conditions. The events include various degrees of RVACS air inlet and outlet flow area blockages and different reactor silo water flooding scenarios.

Blockages of Air Inlets and Outlets

Various postulated RVACS air blockages at the air inlets and outlets (see Fig. 1) have been considered as indicated in Table 2. The arbitrary 75% blockage considered might, for example, correspond to someone attempting to sabotage the RVACS operation by putting tarps on the openings but not quite successful in so doing. It is seen from the table that partial area blockages of the air inlets and outlets have small effects on the maximum average core sodium temperature reached during an RVACS transient. Thus, blocking each of the four air inlet openings 75% and each of the four air outlets also by 75% causes an increase in the maximum core outlet temperature of only 32°F (18°C). This illustrates the tolerance of RVACS to this type of postulated event. The main reason for the slight influence of area blockages at the air inlets and outlets is that their flow resistance are only 2.6% and 4.5%, respectively of the total RVACS air flow path resistance.

Table 2 Temperature Increases Due to Air Inlet and Outlet Blockages

Case	Maximum Avg. Core Outlet Temperature and	Tempature Increase Above Nominal Peak (°C/°F)
75% Area Blockage of Each Air Inelt Opening	614/1137	7/12*
75% Area Blockage of Each Air Outlet Opening	619/1146	12/21
75% Area Blockage of Each Air Inlet and Outlet	625/1157	18/32
One Stack Inoperative	611/1132	4/7
Two Stacks Inoperative	623/1153	16/28
Three Stacks Inoperative	663/1226	56/101

*Increase relative to 607°C/1125°F for normal RVACS operation

The effect of removing one or several RVACS air stacks from the system as a result of a postulated major external event is more pronounced than area blockage only. This is because the stack portions of the inlet and outlet ducts (See Fig. 1) forming the air flow path constitute about 22% and 7% of the total air flow resistance, respectively. Removal of one or several of the stacks from service means that the total RVACS air flow is diverted to the remaining stacks or stack. The results for three postulated cases are given in Table 2. It is noted that removing one stack has only a slight effect and results in an increase of 7°F (4°C) in the core outlet temperature. However, the removal of three of the four stacks from service entirely increases the maximum core outlet temperature by 101°F (56°C). Although this increase is significant, the peak RVACS temperature is still will below the ASME Level D service level temperature limit of 1350°F (732°C).

Complete Blockage of Air Inlets

Another, more severe postulated event evaluated is complete blockage of all air inlets while the four air outlets remain fully open. This case might correspond to the case where a potential saboteur was successful in blocking the inlets because of the suction at the inlets but was not successful at the outlets where the hot air stream exits with some force. There are four air outlet stacks connected via the inlet plenum to the hot air riser annulus as indicated in Fig. 1. Several assumptions subject to experimental verification were made in the analysis of this case. For example, it was postulated that preferential downflow and upflow zones are created as illustrated in the sketch of Fig. 3. In this so-called U-air flow model it is assumed that one-half of the hot air riser annulus cross-sectional area is for downflow while the other half is for upflow and that cold air downflow is established in two of the four air outlet stacks while the hot air upflow is in the remaining two air outlet stacks.

The results of the transient analysis for this postulated case is summarized in Fig. 4 which gives the average core outlet temperature. The maximum core sodium outlet temperature increases to 1168°F (631°C) which is well below the design basis temperature limit of 1250°F (677°C) for ASME service Level C conditions, i.e. only 43°F (24°C) higher than that expected for the normal RVACS event.

An uncertainty evaluation was performed for the blocked inlet case similar to the one performed for the basic performance case. The results are given in Table 3. It is noted that the 2-sigma uncertainties were taken to be the same for the three first parameters. However, for the fourth item ("others" in Table 2) a significant uncertainty of 100% was conservatively included to reflect the lack of experimental information about the air-side flow distribution and the adequacy of the U-flow model to represent this situation.

Table 3 RVACS Performance Uncertainty Evaluation for Blocked Inlet Case

Parameter	Case	Increase in Nominal Case	Upper 2-Sigma Peak Core Outlet Temp Increase (°C/°F)
o Decay Power	Nominal(1)	Nominal + 15%	44/9
o Thermal Emissivities			10/18
- Stainless Steel	0.77(2)	0.70	
- 2 1/4 Cr-1 Mo Steel	0.85	0.80	
o Air-Side Heat Transfer Coefficient	Nominal Data (ANL)[4]	Nominal - 18%	13/24
o Air-Side Flow Resistance	Nominal	Nominal +100	30/54

Upper 2-sigma limit = $1168 + (79^2 + 18^2 + 24^2 + 54^2)^{1/2} = 1168 + 100 = 1268$°F/687°C

(1) As calculated by the Origin II Code
(2) Values at 1000°F/538°C

Complete Blockage of Air Outlets

The case of complete blockage of the air outlets while the air inlets remain open was also considered. Blocking of the outlet is, of course, much more difficult to accomplish for a saboteur than blocking of the inlets since the force of the air exiting at about 5 ft/sec (1.5 m/s) at a temperature of 190°F (87.8°C) during normal operating conditions makes it difficult. In addition, the geometry posed by the weathercap provided to limit inflow of water during heavy rains (See Fig. 1) is much more difficult to close off than the air inlet configuration.

The U-flow model used for analysis purposes for the blocked outlets case is given in Fig. 5. The analysis assumptions were similar to those used for the blocked inlets case. In this case, however, the recirculation pattern occurs in the cold air downcomer annulus and heat has to be transferred across the hot air riser gap primarily by thermal radiation (assumed in the present analyses). In addition, heat has to be conducted across the insulated collector cylinder. The thermal insulation provided on the collector cylinder was added to provide thermal protection for the concrete in the concrete silo wall. It is currently assumed that this insulation consists of a 2-inch (0.051 m) layer of glass wool insulation having an average thermal conductivity of 0.043 Btu/hr ft°F (0.074 W/m°C).

Results of the transient analysis for the blocked outlets case show that the maximum core outlet temperature reached exceeds the service level D limit and is unacceptable from a structural point of view. Since the main reason for the high temperature is the collector cylinder thermal insulation, another case was run with no thermal insulation. The results of the transient analysis show that the core outlet reaches 1393°F (756°C) which is on the limit of being acceptable. However, thermal insulation is required to protect the concrete silo during normal operation events. Unless the thermal insulation is designed to fail when high temperatures are reached, complete blocking of the air outlets would be unacceptable. However, just a small amount of air flow leaking through the outlets would result in increased cooling and an acceptable situation. It should also be pointed out that there is more than 13 hours available to accomplish some degree of outlet unblocking before temperatures exceed acceptable structural limits.

Complete Blockage at Silo Bottom

Complete blockage of the RVACS air flow path at the bottom of the reactor silo just below the lower edge of the collector cylinder (see Fig. 1) is extremely unlikely. Postulated events that could produce such a blockage are a partial collapse of the concrete silo wall or a severe sand storm in which large quantities of sand enters the air inlets and is transported to the bottom of the silo. Even such events, however, are unlikely to block flow completely since the blockage materials, i.e. rubble or sand, possess some permeability to air flow.

If such a blockage should occur, the U-flow models (Figs. 3 and 5) of cooling would be active in both the annuli of the hot air riser and the cold air downcomer. Thus, the analysis performed for the blocked inlets case using the model of Fig. 3 is applicable. However, there will also be some cooling in the cold air downcomer resulting in slightly better performance for this case relative to the blocked inlets case. Because, of the expected slight performance improvement, the blocked silo bottom case was not run.

Tolerance to Reactor Silo Water Seepage

The RVACS stacks provided with weathercaps to prevent significant amounts of precipitation from entering the system. However, in the event that water finds its way into the RVACS by other means, for example, seepage of groundwater through the silo walls, precipitation through the inlet gratings, etc. it will collect at the bottom of the silo as indicated in Fig. 6. This trapped water will eventually be evaporated due to the heat generated inside the silo and carried out by the RVACS air.

The rate of evaporation is dependent on the water and air temperatures, air velocity near the surface of the water, and the air humidity. Assuming that the air flow rate through the RVACS remains constant, the air velocity decreases as the water level decreases since the flow area increases. The entering air, assumed to be at 70°F (21°C) and having a 20% relative humidity, is humidified by picking up water vapor in the silo before the air is discharged through the air outlets. The pool of water was assumed to be at uniform temperature. Two cases were considered. In the first case an initial mass of water was assumed to be deposited on the reactor floor and the subsequent seepage rate was zero. In the second case various seepage rates were assumed with a small mass of water initially on the floor.

Results of the analysis for the first case show that the RVACS performance is not significantly affected when the silo is partially flooded with water. In fact, if the air passages are not blocked, the high temperatures inside the silo coupled with the high air flow rate contribute to the removal of more than 3,600 gal (13.6m^3) corresponding to an initial water level of 1 ft (0.304m) in less than 24 hours. The analysis results for the second case show that a water seepage rate through the concrete silo wall into the cavity of approximately 1.6 gpm (0.0001m^3/s) can be accommodated on a steady-state basis without the water level ever reaching the containment vessel. When the flood water reaches a higher level and comes in contact with the containment vessel, sufficient heat is transferred from the collector cylinder and containment vessel to boil the water pool. The rate of water removal in this mode increases significantly and much higher seepage rates can be accommodated.

Additional analysis was performed for the extremely unlikely event of an instantaneous, catastrophic complete flooding of the reactor cavity in which the complete air-flow path is filled with water. The results show that the containment and collector cylinders will experience thermal shocks as they are quenched by 70°F (21°F) water. The calculated vessel temperature transients are given in Fig. 7. The maximum rate of change of temperature for the containment vessel was about 1.2°F/sec (0.7°C/sec) which is acceptable from a structural point of view. The reactor vessel is insulated by the gas gap between the containment and reactor vessels and experiences no noticeable effects from the postulated flooding. Reactor sodium temperatures decrease quickly following reactor scram. Evaporation of water in contact with the steel structures would provide effective decay heat removal. For example, evaporation of about 14 gpm (0.0009m^3/s) of water would remove 2 MWt under steady-state conditions.

SUMMARY

The totally passive, safety-grade RVACS decay heat removal system in the ALMR is inherently reliable and is not subject to the failure modes commonly associated with active cooling systems. Significant temperature margins exist in the RVACS for design basis events, and its performance is not highly sensitive to normal variations and changes in thermal parameters. The RVACS performance is also very tolerant to many hypothetical accident conditions, including air flow blockages and flooding. The natural convection thermal performance characteristics have been confirmed experimentally.

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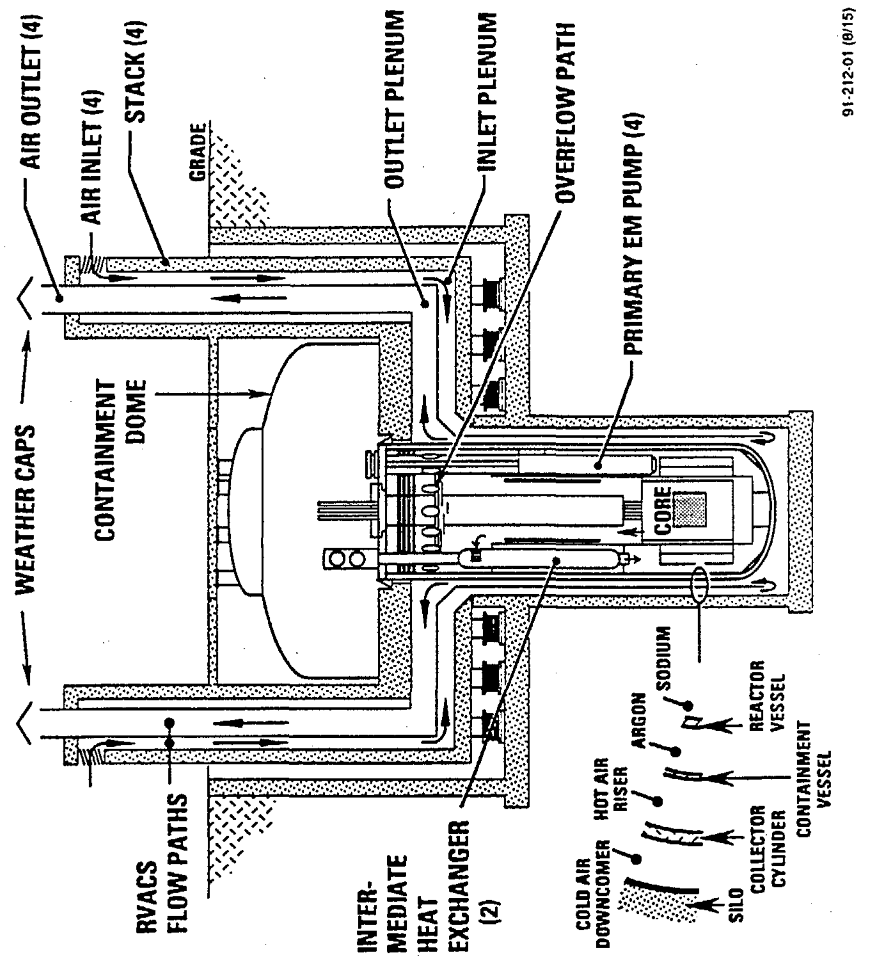

Figure 1 REACTOR VESSEL AUXILIARY COOLING SYSTEM

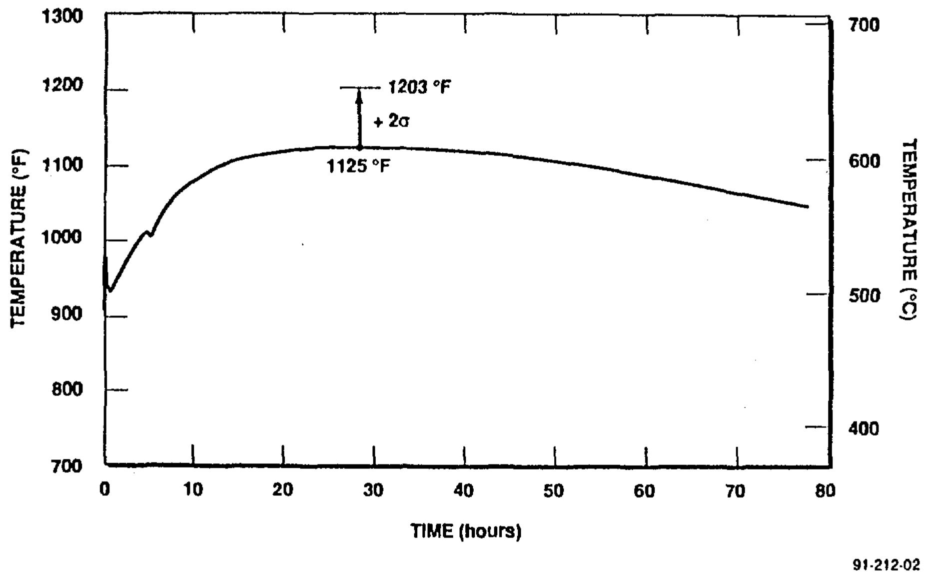

Figure 2 AVERAGE CORE SODIUM OUTLET TEMPERATURE FOR NATURAL OPERATING CONDITION

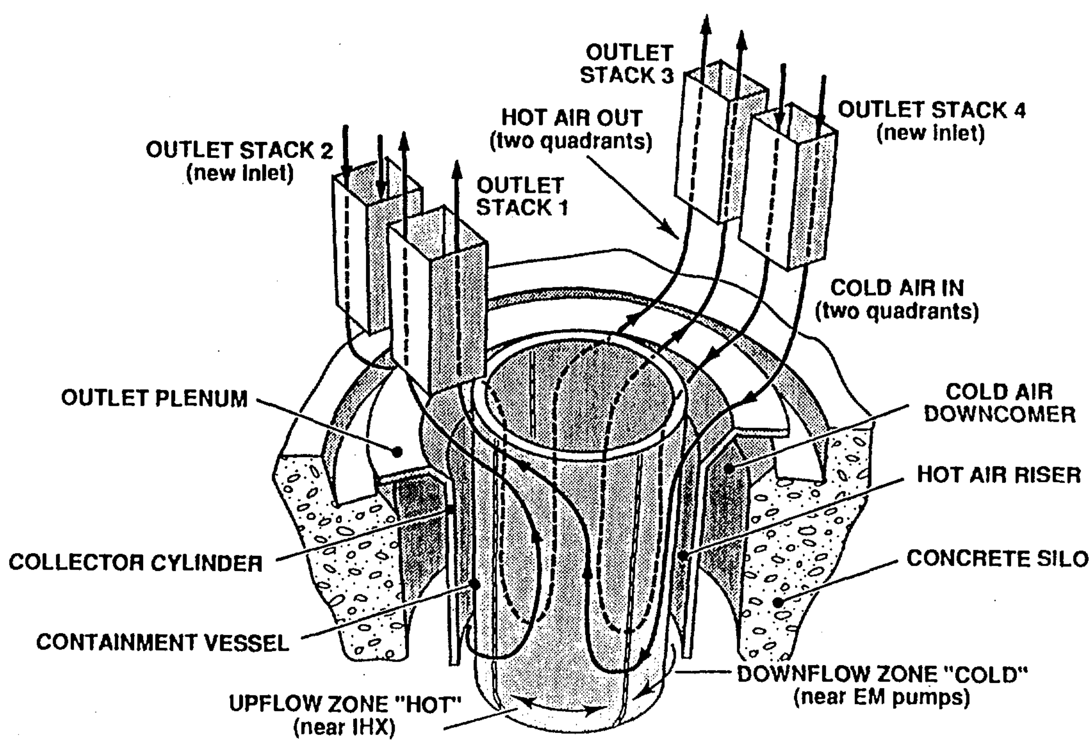

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Figure 3 U-AIR FLOW MODEL FOR NATURAL CONVECTION FLOW PATTERN IN RVACS HOT AIR RISER WITH TOTAL BLOCKAGE OF AIR INLETS

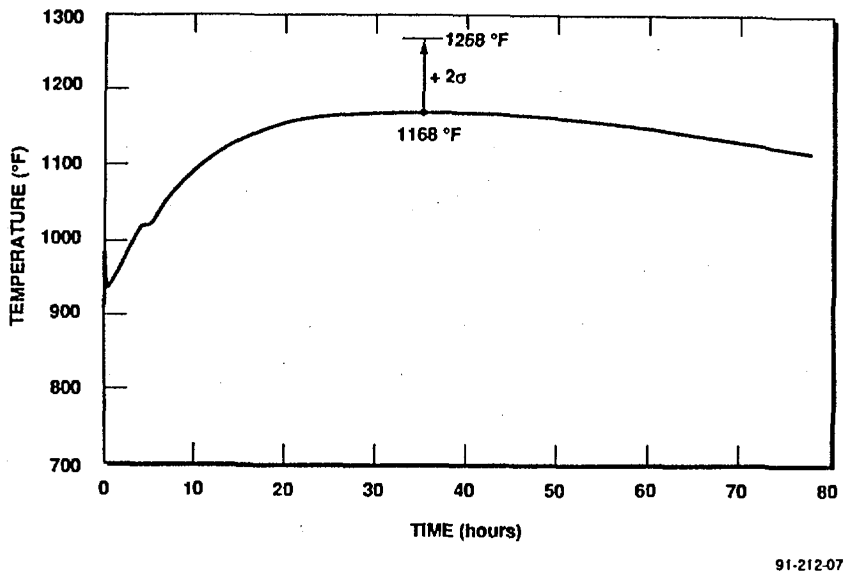

Figure 4 AVERAGE CORE SODIUM OUTLET TEMPERATURE FOR BLOCKED INLETS CASE

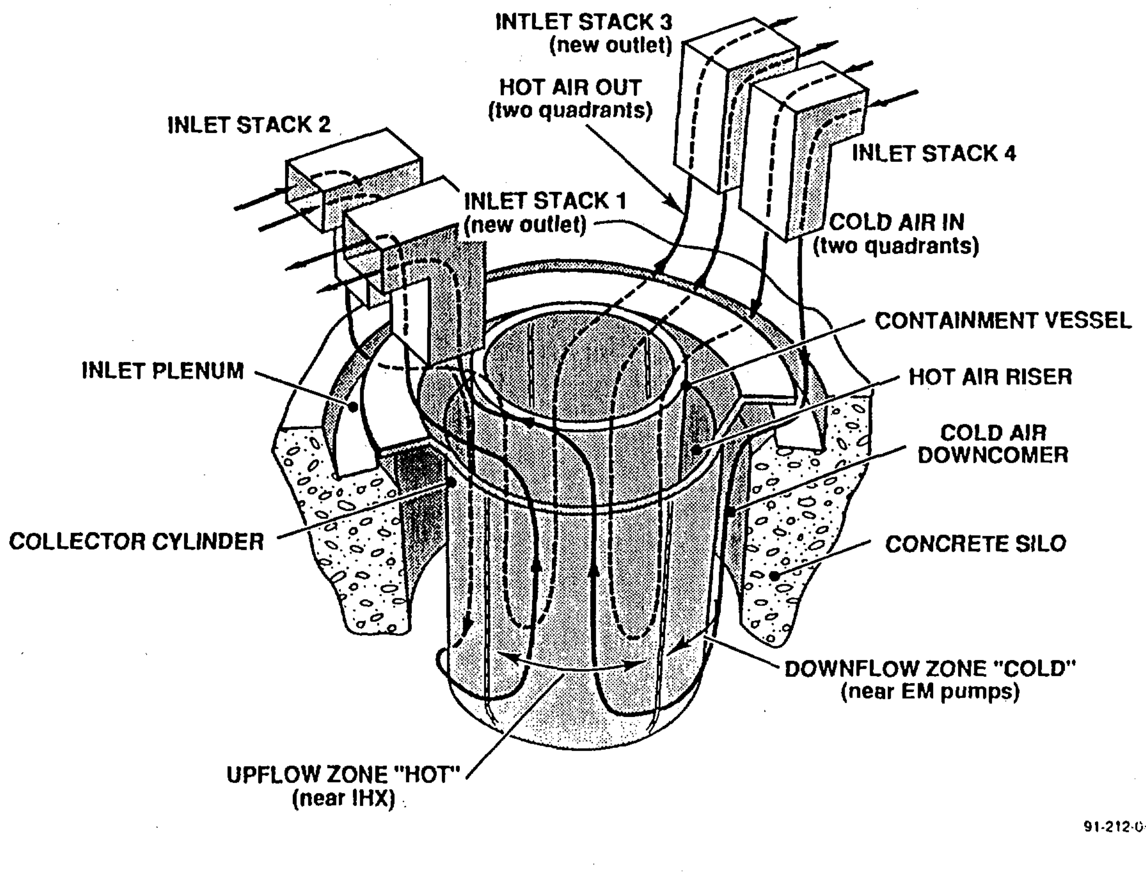

Figure 5 U-AIR FLOW MODEL FOR NATURAL CONVECTION FLOW PATTERN IN RVACS COLD AIR DOWNCOMER WITH TOTAL BLOCKAGE OF AIR OUTLETS

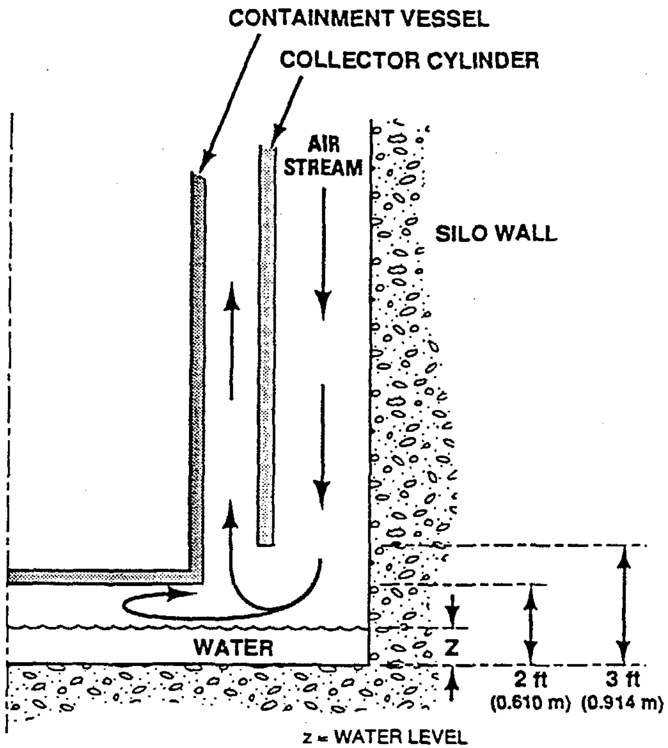

Figure 6 RVACS AIR FLOW PATH AND CONFIGURATION FOR FLOODING ANALYSIS

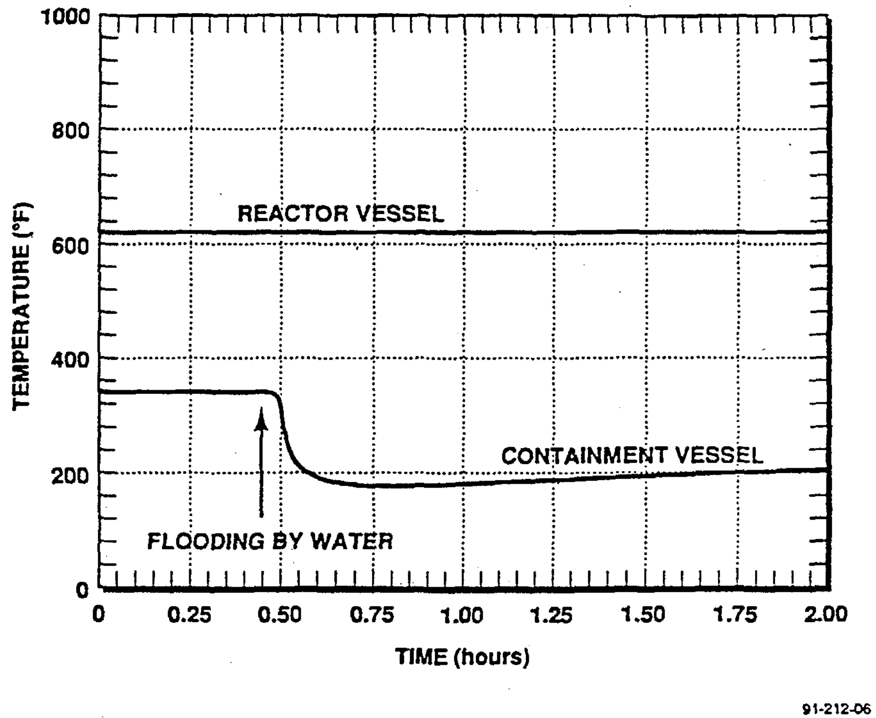

Figure 7 REACTOR AND CONTAINMENT VESSEL TEMPERATURES RESULTING FROM FLOODING EVENT