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**EXPERIMENTAL AND ANALYTICAL STUDY OF A
LOSS OF COOLANT ACCIDENT
WITH A SIMULATED CANDU PASSIVE CONTAINMENT**

by

MICHAEL ROBERTSON CAMPBELL, B.E.Sc.

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Engineering

**The Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering**

**Department of Mechanical and Aerospace Engineering
Carleton University**

April, 1998

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submitted by Michael Robertson Campbell, B.E.Sc.
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April 29, 1998

Abstract

The CANDU passive containment concept relies on a buoyancy induced recirculating flow of the containment atmosphere following a Loss of Coolant Accident (LOCA) to remove energy, limiting the pressure rise, via water cooled condenser coils located at the top of the containment. An experimental apparatus has been designed and constructed to simulate the important thermalhydraulic mechanisms present in a passive containment. A simple computer program, PASSCON, has been developed to predict and interpret the experimental results. The results demonstrate that a recirculating flow of the containment atmosphere is induced, and that the elevated condenser coils provide an effective means of limiting the pressure rise. The PASSCON program provides reasonably good agreement with the experimental results, and provides insight into the mechanisms which affect the behaviour of the containment atmosphere.

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Nomenclature

C	a constant, or specific heat, J/kg K
C_p	specific heat at constant pressure, J/kg K
D_h	hydraulic diameter, m
D	diameter, m
D_o	outer diameter, m
D_v	Diffusivity, m^2/s
f^*	Fanning friction factor
g	acceleration due to gravity, m/s^2
G	mass flux, kg/m^2s
G_{max}	mass flux through minimum flow area, kg/m^2s
Gr	Grashof number
h	height, m
h_{cond}	condensation heat transfer coefficient, W/m^2K
h_{mt}	mass transfer heat transfer coefficient, W/m^2K
h_{nc}	natural convection heat transfer coefficient, W/m^2K
h_r	radiation heat transfer coefficient, W/m^2K

k	thermal conductivity, W/mK
K	loss coefficient
K_c	Fanning friction factor
K_{ent}	entrance loss coefficient
K_{exit}	exit loss coefficient
K_{fc}	mass transfer coefficient, forced convection
K_{nc}	mass transfer coefficient, natural convection
L	characteristic length, m
m	mass, kg
M	molecular weight
N	number of tubes in crossflow
P	pressure, Pa
ΔP_B	buoyant pressure difference, Pa
ΔP_F	friction pressure difference, Pa
Pr	Prandtl number
Q	energy added or removed, J
Q_{in}	energy added by steam injection, J
Q_{out}	energy removed by condensation and heat transfer, J
R	universal gas constant, J/kgK
Re	Reynolds number
Sc	Schmidt number

Sh	Sherwood number
S_T	transverse distance between tubes in condenser coil, m
t	time (s)
T	Temperature, K
T_{ref}	reference temperature, K
u_t	total internal energy of steam and air, J
u_f	Specific internal energy of liquid water, J/kg
u_g	specific internal energy of steam, J/kg
U	overall heat transfer coefficient, $\text{W/m}^2\text{K}$
V	tank volume, m^3
x^+	non-dimensional length
X	mass fraction

Greek Symbols

β	thermal expansion coefficient, $1/\text{K}$
ϵ	emissivity
λ	latent heat, J/kg
ρ	density, kg/m^3
σ	Stefan-Boltzmann constant,
μ	viscosity, kg/m s

Subscripts

b, ∞	Bulk conditions
i	Interface conditions
g	noncondensable (air)
v	condensable (steam)
f	liquid
a	air
s	steam
w, W	Wall
r, R	riser

Chapter 1

Introduction

1.1 CANDU Passive Containment Design

The CANDU reactor concept incorporates a large, horizontally mounted cylindrical vessel, called the calandria, which contains the heavy water moderator. A schematic of the CANDU design is shown in Figure 1. Several hundred horizontal fuel channels, containing uranium oxide fuel pass through the calandria. The high pressure heavy water coolant flows through the fuel channels and removes the heat energy from the fuel. The fuel channels are connected by feeders to inlet or outlet headers. Coolant flow passes from the outlet headers to the steam generators, where the heat energy is transferred to boiling light water. The generated steam flows to a series of turbines. The exhaust from the turbines is condensed in a condenser, and the condensate is returned to the steam generator. The cooled heavy water coolant is pumped from the steam generator outlet into the inlet headers, and the cycle repeats.

Current CANDU nuclear generating stations rely on a mix of both active and passive safety systems to reduce the frequency and severity of accidents [1]. Active safety systems rely on mechanical and/or electrical equipment. Passive systems rely on natural processes, well established material properties or stored internal energy for their operation. Passive systems offer

improved reliability and less operator involvement. Passive safety systems can also reduce the capital costs for new generating stations due to the reduction in the amount of required mechanical equipment. Another advantage of passive safety systems becomes apparent during probabilistic risk assessments required by nuclear regulators for licensing purposes. The reliability of safety systems is an important factor in these assessments.

A Loss of Coolant Accident (LOCA) occurs when any of the components carrying the coolant ruptures. Fuel failures can result due to overheating, resulting in the release of fission products into discharging coolant and thus into the containment structure. Radioactive material may then escape the building. This can result in radiation exposure to workers and the general public.

The primary heat transport circuit (carrying the heavy water coolant) is designed and fabricated to very high standards. The probability of a serious failure is low. Nevertheless, the severe consequences of such an accident require that safety systems be incorporated into the design of stations to reduce the severity of such accidents.

CANDU reactors are housed in containment buildings which contain released fission products in order to limit radiation exposure to workers and the public following accidents. As such, the containment atmosphere is isolated from the surrounding environment. The large amounts of steam released during LOCAs cause a rapid rise of the internal pressure of the containment building. The containment building is designed to withstand this pressure rise, and

to limit leakage from the building to a specific (low) value at a given pressure. To ensure that the pressure does not increase to a level that could damage the building, resulting in large leaks, containment buildings are equipped with systems that are designed to reduce pressure by condensing the steam. Existing containment buildings are equipped with a dousing system as shown in Figure 2. A large tank at the top of the containment feeds the dousing system. The system is activated by a pressure difference. Once activated, the water is sprayed into the containment atmosphere, condensing the steam. Thus, this system is “passive”, in that it relies on natural processes, and is activated automatically. While this system can remove the energy from the initial discharge of steam from the reactor, it is only effective for short-term heat removal.

Passive safety systems incorporated in current CANDU designs include, in addition to the dousing system described earlier [1] :

- spring assisted gravity drop of absorber rods to shut down the reactor in an emergency
- injection of neutron-absorbing poison by stored compressed gas into the moderator to shut down the reactor in an emergency
- natural thermosyphoning cooling of the core during loss of coolant flow accidents
- injection of emergency coolant driven by a stored compressed gas following a LOCA
- cooling of the fuel and fuel channels by heat transfer to the moderator following a LOCA coupled with a Loss of Emergency Core Cooling (LOECC)

Designs for future CANDU nuclear generating stations incorporate additional passive safety systems. Among these are:

- natural circulation cooling of the moderator and shield tanks to cope more reliably with LOCAs coupled with Loss of Emergency Core Cooling (LOECC)
- the use of self-starting hydrogen recombiners to reduce the amount of hydrogen in the containment atmosphere during accidents (hydrogen is the product of a high-temperature reaction between zirconium reactor components and steam/water)
- natural circulation of the containment atmosphere to provide long-term cooling and energy removal following a LOCA

The present work focusses on this last passive safety feature.

The proposed CANDU passive containment design is shown in Figure 3, taken from Reference [2]. During a LOCA, steam released from the break mixes with the containment atmosphere air, creating a hot, buoyant mixture. This mixture rises to the top of the containment, where heat exchangers cooled by gravity-fed water condense the steam and cool the air. The cooled air sinks to the bottom of the containment and recirculates. Thus, a buoyancy governed recirculating flow of the containment atmosphere is induced, which removes the energy of the steam discharged into the containment via the heat exchangers. The removal of energy from the containment atmosphere arrests the pressure rise and cools the containment atmosphere.

The present work is part of a study funded by Atomic Energy of Canada Limited (AECL). The objective of the study is to demonstrate that a recirculating buoyancy-driven flow of the containment atmosphere can be induced, and that water cooled condenser coils can provide an effective means for removing energy from the containment. Further objectives of the study are to gain insight into the thermalhydraulics of the natural circulation flows induced in passive containments, and to help validate the GOTHIC code used by AECL[3]. The GOTHIC program is a large, complex three-dimensional finite volume code. As such, it is inappropriate for interpreting the results from the present study. A simple program, PASSCON, was developed for the present study, and incorporates analytical models discussed in the following sections.

Although a study investigating the failure pressure of a 1/5th scale model of a CANDU containment has been undertaken at the University of Alberta [4], no integrated experimental studies have been published investigating the thermohydraulic behaviour relevant to the passive CANDU containment. The current study includes an experimental program using a simulated passive containment. The experimental apparatus designed and built for an earlier study was modified for this study. This will be discussed in the following sections.

1.2 Previous Relevant Studies

1.2.1 Buoyancy Driven Flow

The program LOPWAT2.1, written by Slaby and Rogers [5,6], was developed for an earlier study on SLOWPOKE reactor behaviour during Loss of Pool Water Accidents (LOPWA). The SLOWPOKE is a pool-type reactor which uses light water as a coolant and moderator, as shown in Figure 4, taken from reference [7]. A large tank is surrounded by an air gap, which is in turn surrounded by a concrete wall. The reactor core is located near the bottom of the tank. The uranium fuel heats the water, which rises inside a riser to heat exchangers. Once the water is cooled, it sinks to the bottom of the tank and recirculates. During a LOPWA accident, it is assumed that all the coolant water is lost, and buoyancy driven air circulates within the tank.

The program LOPWAT2.1 calculates natural circulation flows, peak fuel temperatures, air temperatures at various points, and riser, tank wall and concrete temperatures at various points during LOPWA conditions. The program is a simple one-dimensional transient model that iterates to find air flow based on a balance between friction and buoyancy (gravity) forces. First, a mass flowrate is guessed, and temperatures around the flow circuit are calculated based on this flowrate from closed-form equations, and an energy balance between the power input from the decay heat generated in the core and the heat loss rate to the concrete walls. The buoyant pressure difference is determined from density differences within the tank, calculated from the temperatures of the flow circuit. The friction pressure difference is calculated from pressure loss

terms determined from accepted correlations for hydraulic resistances. If the buoyant and friction pressure terms do not balance, a new guess for the air mass flowrate is made and the iteration proceeds.

An apparatus was designed and built by Slaby to validate the models used in the LOPWAT2.1 program [8]. A schematic of the apparatus is shown in Figure 5, taken from reference [8]. The main components of the apparatus are a cylindrical stainless steel tank surrounded by an air gap, in turn surrounded by a concrete wall. The apparatus employed electric heaters to simulate the reactor core decay heat. The recirculating air mass flowrate was measured by an energy balance method, using the measured temperature rise across the simulated core. The program LOPWAT2.1 was modified to match the conditions in the apparatus. The modified program, LOPWATEX, was used to interpret the results from the experiments. Very good agreement between the experimental results and the LOPWATEX predictions was obtained [6,8,9]. The program LOPWATEX forms the basis for the PASSCON program developed for this study.

1.2.2 Condensation of Steam in the Presence of Air

Condensation of steam in the presence of air is one of the dominant heat transfer mechanisms during containment building pressure transients [10]. Condensation heat transfer in the presence of noncondensibles is governed by diffusion [11]. Diffusion is the transfer of mass,

driven by concentration differences, in the same sense that heat transfer is driven by temperature differences. When steam condensation begins on the heat transfer surface, a steam-depleted layer develops between the mixture and the condensate, as shown in Figure 6. In order for any more steam to condense on the surface, it must diffuse across this layer.

Green and Almenas [10] outlined the important parameters that require consideration in an analytical determination of the heat and mass transfer coefficients. They determined that the primary parameters are the ratio of noncondensable to condensable species, the velocity of the mixture, the temperature difference, and the pressure. Other secondary parameters can also affect the heat and mass transfer rates, such as surface conditions, whether the condensation is dropwise or filmwise, etc.

Correlations based on experimental data are available. Of these, a widely used and accepted correlation is the Uchida correlation [12]. Uchida performed experiments investigating condensation rates on the external surface of metal cylinders. The data have been formulated as a correlation which considers only the noncondensable to condensable ratio and thus provides only an approximate prediction.

The similarity of the equations governing diffusion mass transfer and those governing heat transfer has led to the development of a heat to mass transfer analogy (HMT), as described by Collier [13]. A model of this type can be formulated to include all of the primary parameters discussed by Green and Almenas. The widely used CONTAIN code [14] developed by the

Nuclear Regulatory Commission in the United States uses a HMT analogy to calculate heat and mass transfer rates. The approach is similar to that given by Collier. This approach was used in the present work.

1.2.3 Containment Pressurization

The program BLDG was developed to calculate containment building pressures following a LOCA in a CANDU reactor [15]. The program uses a simple one-node model, in which the pressure is calculated using an energy balance. The energy added to the containment is equal to the total enthalpy of the steam released in the accident, while the energy removed is equal to that removed by the appropriate heat sinks. The mixture conditions in the containment are iterated on the basis of temperature, equating the total internal energy of the steam and air in the containment to the net energy added. The building pressure is determined by adding the steam and air partial pressures, as per Dalton's law. Due to the low pressures present, the ideal gas law is valid for the calculation of the air and steam partial pressures. This type of calculation is standard procedure, and is used in programs such as CONTAIN and GOTHIC. A one-node model was used for the present case.

1.3 Present Study

The purpose of the present study is to gain insight into the natural circulation flowrates, pressures and temperatures occurring in a passive CANDU containment building during a LOCA. Chapter 2 describes an experimental apparatus designed to simulate the important thermalhydraulic processes present in a passive containment during a LOCA. Chapter 3 describes the instrumentation used to collect the experimental data. Chapter 4 describes the computer program, PASSCON, developed to analyze and interpret the results from the experimental apparatus. PASSCON makes use of the buoyancy flow calculation from the program LOPWATEX, a HMT analogy heat transfer correlation, and a pressurization calculation similar to that in the BLDG program as well as other important features. Chapter 5 presents the experimental results, and compares them with the predictions from the PASSCON program. Chapter 6 presents the conclusions drawn from the experiments and the numerical models, and offers some recommendations for future work.

Chapter 2

Experimental Apparatus

2.1 Introduction

A schematic diagram of the apparatus is shown in Figure 7. Steam produced by a small electric steam generator is injected near the bottom of a cylindrical riser, which is housed inside a cylindrical tank, serving to simulate the containment. The steam mixes with air creating a buoyant mixture which rises inside the riser to the top of the tank. There, the steam is condensed and the air cooled by small condenser coils fed by water from the university water supply. Condensation occurs also on the surfaces of the riser, wall and other surfaces. The cooled air sinks to the bottom of the tank. Before re-mixing with the injected steam, the air flows through a flow-measuring unit just below the point of steam injection. Small cartridge heaters installed in the flow-measuring unit heat the flowing air to allow for a measurement of the induced mass flow rate by an energy balance based on the measured temperature rise of the air through the unit. A photograph of the experimental apparatus is given in Figure 8. The tank and stand were built for the earlier study on SLOWPOKE accidents [8].

No attempt was made to design a scale model of any passive containment design. The aim of the experimental program was to reproduce the important thermalhydraulic and heat

transfer mechanisms present in passive containments during accidents.

The components of the apparatus are described in the following sections.

2.2 Steam Generator

The steam generator used in the experiments is a Chromalox CMB-3/120 electrically powered compact steam generator. A photograph of the steam generator is given in Figure 9. The steam generator can produce up to 1 g/s of dry steam at pressures from 0 to 690 kPa (0 to 100 psi). The steam generator pressure is controlled by setting the temperature controller corresponding to the desired saturation pressure. A 3/8" copper tube carries the steam into the tank. A heating tape with a percentage controller (Omega model HTWC 101-006) is wrapped around the steam line to minimize the heat loss from the line. The controller can be set so that the temperature of the line is maintained at the desired steam temperature. Control of the steam flow will be discussed in Section 3.5.

2.3 Riser, Stand and Flow-Measuring Unit

The cylindrical riser is constructed from 1/32" AISI 304 stainless steel. It has a diameter of 220 mm and a height of 1048 mm. Twelve slots with width 30 mm and length 120 mm near the bottom of the riser allow for air flow into the flow-measuring unit. Four slots are cut into the bottom of the riser to allow it to fit over the square base plate of the stand. A circular top plate is

bolted to the top of the riser. It covers the area of the downcomer except for two rectangular holes for the condenser coils. A photograph of the riser is shown in Figure 10.

The stand consists of an AISI 304 stainless steel base plate. Four legs made from angled AISI stainless steel are welded to the base plate. The base plate is bolted to a circular centering plate with four drilled holes which fit into alignment pins on the bottom of the outer tank. A photograph of the stand is shown in Figure 11.

The flow-measuring unit is a 30 mm square tube made from AISI 304 stainless steel. It is bolted on top of the four legs attached to the base plate. A circular plate which centers the riser on the stand is also bolted to the top of the legs. Four cartridge heaters Omega CIR-1026/120 are mounted in a 2 by 2 array inside the flow-measuring unit. The heaters are 50 mm (2") long with a diameter of 6 mm (approx. 1/4"). Each heater has a capacity of 100 W. The heaters are mounted to the flow-measuring unit with 3/16" bolts with ceramic bushings to minimize conductive heat loss. The outside of the flow-measuring unit is insulated with a 2 cm thick Kaowool blanket to minimize heat losses.

2.4 Condensers

A schematic of the condensers used in the apparatus is shown in Figure 12, and a photograph in Figure 13. The coils were constructed using sections of 1/2" copper tubing and 1/2" ninety-degree elbows. Water is supplied to the two condenser coils in parallel, with the

inlets connected together and supplied by the university water supply. The two outlets are connected together and drain into a sump. The outer heat transfer area of each coil is 0.052 m^2 .

A shroud, with a rectangular cross-section, and open at both ends, surrounds each of the condenser coils. This is to constrain the flowing steam/air mixture to flow over the condenser coils, and to provide a more easily established flow path. The minimum flow area over the condenser coils in each shroud is 0.012 m^2 .

2.5 Tank

The tank serves as the pressure boundary for the apparatus. The cylindrical tank has a diameter of 447 mm and an inside height of 1219 mm. The tank is constructed of 3.2 mm thick AISI 304 stainless steel. The bottom of the tank is welded to the cylindrical body. The top lid is bolted to the flange on the top of the tank with 16 1/4" bolts. The interface between the lid and the flange is sealed with a 1/8" thick Neoprene gasket. Lid removal allows for inspection and adjustment of the internal components. Three anemometer pass-throughs on the side of the tank used in the previous study were sealed for the present study.

To maintain the pressure boundary, thermocouple wires pass through the lid through hollow 3/4" brass fittings which are filled with Omegabond OB-700 high temperature cement. The tops of the fittings are sealed with epoxy. The lines for cooling water flow to the condenser coils pass through the tank lid through Swagelok 1/2" bulkhead union fittings sealed by rubber

O-rings. The lines for steam injection and condensate removal pass through the tank lid through O-ring sealed Swagelok bulkhead union fittings with nominal sizes of 3/8" and 1/4" respectively.

2.6 Peristaltic Pump

A peristaltic pump Omega FPU-255 is used to remove the condensate from the tank without removing the lid. The condensate can be collected and its volume measured.

Chapter 3

Instrumentation

3.1 Introduction

Tank pressure, air mass flowrate and temperature data were collected and stored by a data acquisition system. The cooling water flowrate and cartridge heater power were measured separately. The following sections describe the instrumentation and methods used to obtain the measurements. An error analysis is presented in Appendix D.

3.2 Temperature Measurement

Type K (chromel-alumel) thermocouples are used for all temperature measurements in the present experiments. Thermocouple wires (AWG no. 24) were insulated by fibreglass. The error for the thermocouples is 2.2 C or 0.75%, whichever is higher [16].

Temperature measurements are taken at various locations shown in Figure 14. The tank wall temperature is measured at six different elevations. Duplicate tank wall temperatures are made at two of these elevations at positions directly opposite each other to check for symmetry. The steam/air mixture temperature is measured at the riser bottom (near the point of steam

injection), riser top (or exit), downcomer (just below the condenser coils) and flow-measuring unit inlet and outlet. The coil surface, riser wall and coolant water temperatures are also measured. The tank wall, coil and riser surface thermocouples are cemented in place with Omegabond 101 thermally conductive epoxy to reduce errors due to thermal resistance.

All thermocouples measuring steam/air mixture temperatures are protected by a radiation shield from possible radiation heat exchange error. The shields are constructed from stainless steel tube (O.D. 1/4", I.D. 1/8"). Radiation error is reduced since the shield surrounding the thermocouple is much closer to the mixture temperature than to the temperature of the surrounding surfaces. The shield is open at both ends so that the steam/air mixture may flow freely over the thermocouple.

The thermocouples are connected to an Omega EXP-16 data acquisition board. The board amplifies the low thermocouple voltage and performs cold-junction compensation. The conversion from voltage to temperature is done by the data acquisition program PASSIVE using a look-up table provided by the manufacturer [16].

3.3 Pressure Measurement

Tank pressure is measured using an Omega PX603-060G5V pressure transducer. The transducer is connected to the tank lid with a 1/4" nominal steel pipe. The transducer requires a

voltage input from 10 to 30 V. It produces a linearized output from 1 to 5 V. It has a range from 0 to 60 psi (0 to 413.7 kPa). The output is connected directly to the DAS-8 analog to digital converter. The transducer was calibrated using a dead weight tester using the procedure contained in Reference [18].

3.4 Cooling Water Flowrate Measurement

The cooling water flowrate supplied to the condenser coils is measured using an Omega FL-755 rotameter. Water from the University water supply was used in the experiments.

3.5 Steam Injection Rate

The steam injection rate depends on the steam generator pressure. For an ideal gas discharging from a vessel through a nozzle, there exists a ratio of the backpressure to the vessel pressure below which the flowrate is independent of the backpressure. This ratio is called the critical pressure ratio. At this pressure ratio, the steam velocity is equal to the sonic velocity. For steam, the ratio is 0.5405 [18]. Thus, the flowrate is dependent solely on the steam generator pressure and the flow area.

To control the flowrate, four brass nozzles with known opening diameters corresponding to four different steam generator pressures were designed and constructed. To calibrate the steam generator, the outlet was connected to a condenser coil constructed from two lengths of 3/8"

copper tube. The coil was immersed in cold water. The steam generator temperature was set to the corresponding pressure of the nozzle being calibrated. The steam was first discharged into the open room in order for the flow to reach steady state. The steam was then condensed in the condenser coils. The condensate was collected and measured. The nozzle diameters, corresponding steam generator pressures and measured mass flowrates are presented in Table 1. Note that, in principal, for critical flow, assuming steam as a perfect gas and saturation conditions, the value of

$$\frac{\dot{m}\sqrt{T}}{AP} \quad (1)$$

where $\dot{m}$ is the mass flowrate, T is the temperature in Kelvin, A is the nozzle throat area, and P is the pressure, should be approximately constant. This is not the case. This calculation assumes that the nozzle is isentropic, and that no pressure losses exist elsewhere in the flow. The nozzles used in this work cannot be assumed to be isentropic, and losses occur in the line carrying the steam both before and after the nozzle. Also, the line is not insulated in the 75 mm length between the steam outlet from the steam generator and the nozzle. The mass flowrate measured using the 2 mm diameter nozzle is lower than that using the 1.5 mm nozzle, even though the flowrate in the other three nozzles increased with nozzle opening area. This is due to the fact that critical flow was not achieved using this nozzle.

After each experiment, the condensate was collected and its volume measured. Knowing the amount collected and the duration of steam injection, the average steam injection rate could be calculated.

3.6 Air Mass Flowrate Measurement

The air mass flowrate is determined by performing a heat balance on the air flowing through the flow-measuring unit. This method was selected because the very low air mass flowrates make hot-wire anemometer calibration extremely difficult with uncertain results. Four cartridge heaters, Omega CIR-1026/120, are mounted in the flow-measuring unit in a 2 by 2 array. The heaters are powered by a variac, and the supplied power is measured by a wattmeter. The heaters produce a temperature rise in the air flowing through the flow-measuring unit. The flowrate is calculated from the input power and the measured temperature rise. The data acquisition program PASSIVE performs the calculation assuming that the flow through the flow-measuring unit is composed entirely of air. The average thickness of the Kaowool blanket surrounding the flow-measuring unit is 1 cm. The thermal conductivity of Kaowool is 0.052 W/mK. Using these values, the heat loss from the flow measuring unit is approximately 5% for typical experimental conditions. Therefore, PASSIVE calculates the air mass flowrate assuming 95% of the power input heats the air.

The flow through the unit is allowed to reach steady state with the cartridge heater power on before any steam is injected. The temperature of the air flowing through the flow-measuring unit remains relatively constant, and the temperature of the cartridge heater remains constant, even after steam injection, as will be demonstrated in Chapter 5. Therefore, the measured flow rate during tests will not be affected by thermal transients in the apparatus.

3.7 Data Acquisition System

A computerized data acquisition system is used to collect and store temperature and pressure data, and to calculate the air mass flowrate. The system consists of a Zenith IBM XT-8088 compatible computer, a DAS-8 analog to digital converter, and three EXP-16 multiplexer boards. The data acquisition system was constructed for the SLOWPOKE apparatus [8].

3.8 Data Acquisition Program PASSIVE

The data acquisition program PASSIVE is based on the program SLOWPOKE used for data acquisition in the earlier simulation of SLOWPOKE reactor accidents. The program PASSIVE was developed to collect and store the experimental data produced by the passive containment experimental apparatus. The program is written in the QuickBASIC language. A listing of the program is given in Appendix A.

The program PASSIVE uses subroutines provided by the manufacturer of the DAS-8 board [16]. The DAS-8 and EXP-16 boards are controlled by sending data to the subroutine DAS8. Four different DAS-8 modes are used in the program: mode 0 initializes the board, mode 1 locks the board to the desired DAS-8 channel, mode 3 verifies that the board is locked to the appropriate channel, and mode 14 selects the desired EXP-16 channel.

The main calling routine PASSIVE loads the thermocouple voltage to temperature look-up table provided by the manufacturer. It opens the output files and creates table headlines. The calling routine proceeds to TEMPGET, where voltages are read and converted to degrees Celsius. TEMPGET¹ reads ten values for each thermocouple, and averages them. CJCGET is then called to perform cold-junction compensation. PRESGET reads the pressure transducer voltage and converts it to kilopascals. The program returns to PASSIVE to calculate the air mass flowrate. SCROUT outputs the data to the screen while DATAOUT writes data to the output files. Measurements are taken every ten seconds.

An error analysis for measurements made by PASSIVE is presented in Appendix D.

¹ TEMPGET is also the name of a subroutine in the program LOPWATEX, and is not to be confused with the subroutine discussed here.

Chapter 4

Analytical Model

4.1 Introduction

This chapter describes the program PASSCON which was developed to predict and interpret the experimental results from the passive containment apparatus. The program PASSCON is made up of four key analytical elements: a buoyancy driven flowrate calculation based on the earlier program LOPWATEX [8], an energy-balance calculation of temperatures and mixture conditions (including pressure), a heat-mass transfer analogy for determining condensation heat transfer to the condenser and tank surfaces, and property value correlations for steam and air mixtures. A listing of the PASSCON program is shown in Appendix B, and a flowchart of the program is included in Appendix C.

4.2 Flowrate Calculation

4.2.1 Analytical Model

The air mass flowrate is determined by an iterative method. A basic assumption of the method is that the net buoyant pressure difference caused by the creation of the hot steam/air

mixture by the injection of steam and the cooled air in the downcomer, is balanced by friction pressure losses caused by the mixture flowing around the flow circuit. An assumption of this method is that quasi steady-state conditions exist, and that transient effects can be ignored. As shown by Rogers [19] for recirculating flows in SLOWPOKE reactors, the transient terms remain several orders of magnitude lower than the steady terms, even in the initial part of the transient. The buoyant pressure difference is calculated from the simple relation:

$$\Delta P_B = \sum_i \rho_{ave,i} g \Delta h_i - \sum_j \rho_{ave,j} g \Delta h_j \quad (2)$$

where ΔP_B is the buoyant pressure difference, ρ_{ave} is the average density, g is the acceleration due to gravity, Δh is the difference in vertical height and the subscripts i and j correspond to the riser and downcomer regions respectively. The total buoyant pressure difference is determined by adding the buoyant pressure differences around the flow circuit. A schematic of the analytical model of the flow circuit is shown in Figure 15. The densities are calculated using the ideal gas law. To calculate the densities, the temperatures of the flow circuit must first be calculated. This will be discussed in section 4.4.

The friction pressure difference is calculated using the following equation:

$$\Delta P_F = \sum_m K_m \frac{G_m^2}{2\rho_{ave,m}} \quad (3)$$

where K is the loss coefficient, and G is the mass flux. The mass flux is equal to the mass flowrate divided by the flow area. The loss coefficients are discussed in the section describing the PASSCON subroutine FBAL. Loss coefficients can be from losses, such as those for flow expansion or contraction, or due to friction caused by flow through a duct. In this case, the Fanning friction factor, f (or K_c), is used, and is converted to the loss coefficient, K , using the following:

$$K = 4fL / D_h \quad (4)$$

where L is the length of the duct and D_h is the hydraulic diameter. The correlations used to find the friction factors and loss coefficients will be discussed in Section 4.2.3.

To find the total mass flowrate, the steam flowrate must be determined. It is assumed that the upwards velocity of the steam at the point of injection (at the bottom of the riser) is equal to the upwards velocity of the air at that point. Knowing the density of the steam and the cross-sectional area of the riser, the steam mass flowrate at this point can be calculated. However, the flowrate of the steam will decrease in the flow loop, due to the removal of steam from the mixture by condensation. A series of mass conservation equations can be written to account for

this effect.

Firstly, it is assumed that all the steam present in the riser, plus the steam injected during the time step under consideration, fills the entire riser region. Properties of the mixture based on this condition are calculated using the energy balance method which will be discussed in section 4.3.3. The condensation heat transfer rate to the riser wall is then determined using the heat-mass transfer analogy which will be discussed in section 4.3.4. The mass flowrate of the steam *leaving* the riser is then the ratio of the mass of steam present in the riser after condensation to the mass of steam present before condensation multiplied by the initial steam mass flowrate at the riser bottom. Thus, the mass of steam present in the riser region is updated at each time step using the following equation:

$$m_{s,2} = m_{s,1} + \dot{m}_{inj} \Delta t - \dot{m}_{cond} \Delta t - \dot{m}_{exiting} \Delta t \quad (5)$$

where $m_{s,2}$ is the amount of steam present in the region at the end of the time step, $m_{s,1}$ is the amount of steam present at the beginning of the time step, $\dot{m}_{inj}$ is the rate of steam injection, $\dot{m}_{cond}$ is the rate of condensation, $\dot{m}_{exiting}$ is the mass flowrate of steam exiting the riser, and Δt is the time step size.

Similarly, the amount of steam in the downcomer region is updated using the following equation:

$$m_{s,2} = m_{s,1} + \dot{m}_{entering} \Delta t - \dot{m}_{cond,d} \Delta t \quad (6)$$

where $m_{s,1}$ is the mass of steam in the downcomer region at the start of the time step, $m_{s,2}$ is the mass of steam present at the end of the time step, $\dot{m}_{entering}$ is the mass flowrate of steam entering the the downcomer region from the riser region (which is equal to $\dot{m}_{exiting}$) and $\dot{m}_{cond,d}$ is the rate of condensation to the tank wall and the condenser coils.

4.2.2 PASSCON Main Calling Routine

Variable declaration, time stepping, flowrate iteration, and variable initialization are performed by the main calling routine in the program PASSCON. After the variables defining geometry and initial tank atmosphere conditions are initialized, high and low guesses for the air mass flowrate are calculated, using the iteration method found in LOPWATEX. The subroutine CHECKROOT is called to ensure that the interval between the guesses contains a root. PASSCON then calls subroutine FBAL to determine the temperatures around the flow loop and to calculate the buoyant and friction forces based on the flowrate guesses. Mixture properties are calculated in various subroutines, as discussed in section 4.3.7. PASSCON then decides if the iteration is complete or if new guesses are needed. New guesses are calculated using a bisection method. Once the flowrate is found, variables are updated and PASSCON proceeds to the next time step.

The main calling routine also accepts user input data. The user inputs the time to the end of the analysis, the time at which the cooling water supply to the condenser coils is turned on, the steam injection rate and enthalpy, and the ambient temperature. The size of the time step is also set in PASSCON, and is currently five seconds. The initial relative humidity can be set in the main calling routine, and is currently 30%.

4.2.3 Subroutine FBAL

Subroutine FBAL calculates the balance between the buoyancy pressure difference and flow loss pressure differences. FBAL first calculates the steam mass flowrate assuming the upwards velocity of the steam at the point of injection is equal to the upwards velocity of the air, as discussed earlier. FBAL then calls the subroutine TEMPGET, to be discussed in section 4.3.2, to determine the temperatures around the flow loop based on the steam and air flowrate guesses. The buoyancy force is determined by calculating the density differences in the steam/air mixture around the flow loop based on the temperatures found in TEMPGET. The friction force is calculated by determining the hydraulic resistances of the flow-measuring unit and the cooling coils. All other hydraulic resistances are ignored since they are much lower elsewhere in the flow loop. Shah's correlation [20] for the Fanning friction factor in developing laminar flow was selected for the determination of the pressure drop in the flow-measuring unit:

$$K_c = \frac{3.44 x_+^{-0.5} + \frac{\frac{K}{4 x_+} + fRe - 3.44 x_+^{-0.5}}{(1 + C x_+^{-2})}}{Re} \quad (7)$$

where K , fRe and C are geometry dependent coefficients given by Shah. The coefficients for a square duct are:

$$K = 1.43$$

$$fRe = 14.227$$

$$C = 0.00029$$

and

$$x_+ = \frac{L}{D_h Re} \quad (8)$$

Where L is the duct length, D_h is the hydraulic diameter, and Re is the Reynolds number in the duct:

$$Re = \frac{\rho V D_h}{\mu} \quad (9)$$

where ρ is the density, V is the velocity through the duct, and μ is the viscosity.

Entrance and exit pressure loss coefficients for the flow-measuring unit are also found from Shah [20]. They are calculated on the basis of the ratio of cross-sectional areas. For the

entrance, the ratio is the flow-measuring duct area to the tank area. For the exit, the ratio is the duct area to the riser area.

$$K_{ent}=0.55$$

$$K_{exit}=0.7$$

These last two coefficients are valid for fully developed flow (before and after the area change), and for higher Reynolds numbers. For the low Reynolds numbers in the present case, and due to the fact that the flow is not fully developed, large uncertainties exist in these coefficients. Compensation for these uncertainties will be discussed later.

The pressure loss over the condenser coil is determined using a correlation by Grimason taken from [21]:

$$\Delta P = \frac{f' G_{\max}^2 N}{\rho} \left(\frac{\mu_w}{\mu_B} \right)^{0.14} \quad (10)$$

where $G_{\max}$ is the maximum mass flux (ie. where the flow area is a minimum), N is the number of tube rows in crossflow, μ_B and μ_w are the viscosities for the bulk and wall conditions respectively, ρ is the local density found using the ideal gas law (note that these properties are those of the steam/air mixture flowing over the coils), and f' is the friction factor determined using the following [21]:

$$f = [0.25 + \frac{0.118}{(\frac{S_T}{D_o} - 1)^{1.08}}] (\frac{G_{\max} D_o}{\mu_B})^{-0.16} \quad (11)$$

where D_o is the tube outer diameter and S_T is the transverse distance between tube center lines.

These pressure drop correlations were derived for flows with much higher Reynolds numbers than those in the present case. As such, large uncertainties will exist. An empirical correction factor will be deduced based on the experimental results to compensate for the uncertainty. This will be discussed in Chapter 5.

4.3 Temperature Calculation

4.3.1 Analytical Model

A schematic of the analytical model used to find temperatures of the flow circuit is shown in Figure 15. The steam/air mixture temperatures, T_A , T_B , T_C , T_D and T_E are found using an energy balance method discussed in Sections 4.3.3 and 4.3.4. The cover is insulated by a 6 mm thick layer of Neoprene, therefore it is assumed that no heat is lost to the tank cover. Thus, T_C is equal to T_B .

Assuming that the tank wall temperature is uniform over its height, and that the

temperature drop across the wall is uniform (reasonable due to the relatively thin metal wall), a one-dimensional transient heat balance applied to the wall, T_w , yields:

$$dT_w = \frac{Q_{w,1} - Q_{w,2}}{m_w C_w} dt \quad (12)$$

where t is time, m is the mass, C is the specific heat, $Q_{w,1}$ is the heat transfer rate to the inside surface of the wall, which is dominated by the condensation of steam onto the wall surface in the presence of air, and $Q_{w,2}$ is the heat transfer rate from the outside surface of the wall to the surroundings, which includes a term to account for natural convection to the surrounding air as well as a term to account for radiation heat transfer to the surroundings. Note that the heat capacity of the wall is small, and can be neglected for this analysis, but since its addition does not complicate the model, it is included. The convection coefficient, h , is defined as:

$$h = \frac{Q}{A\Delta T} \quad (13)$$

where Q is the rate of transfer of energy, A is the heat transfer area, and ΔT is the difference in temperature between the heat transfer surface and the surroundings.

Thus, the heat transfer rates, Q , are defined by:

$$\begin{aligned}
 Q_{w,1} &= A_w h_{mt,w} (T_{D,MN} - T_w) \\
 Q_{w,2} &= A_w h_{nc,w} (T_w - T_\infty) + A_w h_{r,w} (T_w - T_\infty)
 \end{aligned}
 \tag{14}$$

where A_w is the heat transfer area of the tank wall, $T_{D,MN}$ is the average mixture temperature in the downcomer, T_∞ is the ambient temperature, assumed to be constant, $h_{mt,w}$ is the condensation heat transfer coefficient to inside of the tank wall, and $h_{nc,w}$ is the natural convection heat transfer coefficient from the outside surface of the tank wall.

Similarly, a transient heat balance applied to the riser wall, assuming that the riser wall has negligible heat capacity, yields:

$$Q_{R,1} = Q_{R,2} \tag{15}$$

where $Q_{R,1}$ is the heat transfer rate to the inside surface of the riser wall, which again is dominated by condensation in the presence of air, and $Q_{R,2}$ is the heat transfer rate from the outside surface of the riser wall, which includes a convection and a radiation term. These are defined by:

$$\begin{aligned}
 Q_{R,1} &= A_R h_{mt,R} (T_{R,MN} - T_R) \\
 Q_{R,2} &= A_R h_{nc,R} (T_R - T_{D,MN}) + \sigma A_R F_{RW} (T_R^4 - T_w^4)
 \end{aligned}
 \tag{16}$$

where A_R is the heat transfer surface area of the riser, $T_{R,MN}$ is the average temperature of the mixture in the riser region, T_R is the temperature of the riser, $h_{mt,R}$ is the condensation heat transfer coefficient to the inside surface of the riser wall, $h_{nc,R}$ is the natural convection heat transfer coefficient from the outside surface of the riser wall, σ is the Stefan-Boltzmann constant, and F_{RW} is the radiation interchange factor between the riser wall and tank wall. The value of T_R is determined using an iterative method, whereby the values of $Q_{R,1}$ and $Q_{R,2}$ are equal. The interchange factor is determined using the following equation:

$$F_{RW} = \frac{1}{\frac{1}{\epsilon_R} + \frac{D_R}{D_W} \left(\frac{1}{\epsilon_W} - 1 \right)} \quad (17)$$

where D_R is the diameter of the riser, D_W is the diameter of the wall, ϵ_R is the emissivity of the riser, and ϵ_W is the emissivity of the tank wall. This equation ignores radiation to the lid and tank bottom; the resulting error is small.

The determination of the condensation heat transfer coefficients, $h_{mt,W}$ and $h_{mt,R}$ involves the calculation of condensation rates of steam in the presence of air and will be discussed later, in Section 4.3.5.

Since the surroundings outside the tank can be treated as a black body, the heat transfer coefficient due to radiation, $h_{r,W}$, from the tank wall to the surroundings, is given by the

following equation:

$$\begin{aligned} h_{r,w} &= 4\sigma\epsilon_T \bar{T}^3 \\ \bar{T} &= \frac{T_w + T_\infty}{2} \end{aligned} \quad (18)$$

where T_w is the surface temperature of the wall, T_∞ is the ambient temperature, σ is the Stefan-Boltzmann constant, and ϵ_T is the emissivity of the tank.

The natural convection heat transfer coefficients, $h_{nc,w}$ and $h_{nc,R}$ are found using the following correlation for natural convection on a vertical surface (from Holman) [22]:

$$Nu = C(GrPr)^n \quad (19)$$

where Nu is the Nusselt number, Gr is the Grashof number, Pr is the Prandtl number, and C and n are constants which depend on geometry and whether the conditions are laminar or turbulent.

The Nusselt number is defined as follows:

$$Nu = h_{nc}L / k \quad (20)$$

where h_{nc} is the heat transfer coefficient for natural convection, L is the height of the wall, and k is the thermal conductivity of the steam/air mixture.

The Grashof number is defined as follows:

$$Gr = g\beta(T_w - T_\infty)L^3\rho^2/\mu^2 \quad (21)$$

where β is the coefficient of thermal expansion, μ is the viscosity, T_w is the temperature of the surface (wall or riser) and T_∞ is the temperature of the steam/air mixture.

The Prandtl number is defined as follows:

$$Pr = C_p\mu/k \quad (22)$$

where C_p is the specific heat of the steam/air mixture at constant pressure.

For the case of forced convection, the following is used:

$$Nu = \frac{h_{fc}L}{k} = 0.037 Re^{4/5} Pr^{1/3} \quad (23)$$

4.3.2 Subroutine TEMPGET

Subroutine TEMPGET calculates the steam/air mixture temperatures of the flow loop based on the current guesses of the air and steam mass flowrates. The tank volume is broken up into two regions, the riser region and the downcomer region. Mass balances for the steam and air, as well as energy balances for the steam/air mixture, are performed separately for each region. The mass balance equations were presented in section 4.2.1. The riser region includes the volume inside the riser as well as the volume above the condenser coils. The downcomer region includes the volume outside the riser below the condenser coils, including the small volume below the flow-measuring unit. Average conditions, including steam concentrations and mixture temperature, are determined by iterative methods for each of these two regions.

First, subroutine MIXGET is called to determine the initial steam/air mixture conditions in the riser. As discussed earlier, the injected steam is assumed to fill the entire riser region. An average riser mixture condition is calculated between these conditions and the riser exit conditions from the previous time step. UNCCOND is then called to calculate the heat transfer coefficient and condensation rate on the inside surface of the riser, $h_{mL,R}$, based on the current average conditions of the mixture in the riser. MIXGET is then called to determine the conditions of the steam/air mixture exiting the riser, based on the initial conditions in the riser and the amount of energy and steam removed from the mixture by heat-mass transfer to the riser wall. A new average riser mixture temperature is calculated and compared to the old one. Iteration

proceeds until the average riser mixture temperature converges on a solution. The value of T_R is determined using an iterative method, using the equations discussed previously. A similar method is used to determine conditions in the downcomer allowing for heat transfer to the coil, tank outer wall and from the riser wall. The heat transfer rate from the outside of the riser surface is calculated in the subroutine RISER, which uses accepted correlations for natural (or forced) convection on a vertical surface as discussed in Section 4.3.1. The heat transfer from the outer tank wall to the surroundings is calculated in subroutine WALL, which uses the natural convection correlations discussed in Section 4.3.1. Experience with the program indicates that, because of the very low flowrates, natural convection conditions always prevail.

4.3.3 Subroutine MIXGET

Subroutine MIXGET determines the steam/air mixture conditions in the various regions of the flow loop using an energy balance method. The routine determines the energy of the mixture based on the initial internal energies of the steam and air present in the region of interest and the energy losses and gains in the time step:

$$u_t = m_{s,in} u_g [T_{in}] + m_a C_{v,a} (T_{in} - T_{ref}) + Q_{in} - Q_{out} \quad (24)$$

where u_t is the total internal energy of the mixture, $m_{s,in}$ is the mass of steam present in the region at the beginning of the time step, m_a is the mass of air, $u_g[T_{in}]$ is the specific internal energy of

the steam at the temperature at the initial steam/air mixture temperature. C_{va} is the heat capacity of the air at constant volume. T_{ref} is the reference temperature (273 K). Q_{in} is the energy added by steam injection, and Q_{out} is the energy removed by heat transfer to the tank wall, riser wall or condenser coils.

The final conditions of the mixture are found by iterating on the basis of temperature. A temperature, T_{out} , is guessed, and the energy is calculated based on this temperature. This energy includes the internal energy of the steam in the region plus any injected steam, the internal energy of the air, plus the energy of any condensate formed:

$$u_t = m_{s,out} u_g [T_{out}] + m_{mist} u_f [T_{out}] + m_a C_{va} (T_{out} - T_{ref}) \quad (25)$$

Where $m_{s,out}$ is the mass of the steam in the region at the end of the time step, accounting for condensation and steam injection, m_{mist} is the mass of water droplets formed in the region (as described below), $u_g[T_{out}]$ is the specific internal energy of the steam at the guessed mixture temperature, $u_f[T_{out}]$ is the specific internal energy of liquid water at the guessed mixture temperature. If the final calculated energy of the mixture is higher than the initial energy and the energy losses and gains in the time step, then the temperature guess, T_{out} is lowered, and vice versa. Iteration proceeds until the energies are balanced.

Mist can form if the steam partial pressure in any region is higher than the corresponding

saturation pressure. MIXGET determines if mist forms in the region of interest by calculating the partial pressure of steam using the ideal gas law and comparing it to the saturation pressure.

MIXGET calculates the amount of mist if necessary. If the saturation pressure is exceeded, the routine increases the amount of condensed steam to compensate, and re-calculates the energy.

This mist formation or “pressure condensation” can have a significant effect on the overall pressure.

4.3.4 Subroutine UNCCOND

Subroutine UNCCOND calculates the condensation rate and equivalent heat transfer coefficient for the condensation of steam on surfaces in the presence of air. It uses the heat to mass transfer analogy presented by Collier [13]. As shown in Figure 6, heat transfer is governed by mass transfer across the steam depleted layer to the condensate layer, and then to the heat transfer surface. Thus, the overall heat transfer coefficient for condensation of steam in the presence of air, accounting for the thermal resistances of these processes in series, has the following form:

$$\frac{1}{U} = \frac{1}{h_{mi}} + \frac{1}{h_{cond}} \quad (26)$$

where h_{cond} is the heat transfer coefficient of the condensate layer, and h_{mt} is the mass transfer-heat transfer coefficient (which is the heat transfer coefficient of sensible heat transfer in parallel with the mass transfer across the steam-depleted layer). Since the heat transfer coefficient across the condensate layer will be much greater than the mass transfer-heat transfer coefficient for the present conditions:

$$\frac{l}{U} \approx \frac{l}{h_{\text{mt}}} \quad (27)$$

Therefore, the overall heat transfer coefficient can be assumed to be equivalent to h_{mt} , which has the following form (from Collier [13]):

$$h_{\text{mt}} = h_{\text{nc}} + K_{\text{nc}} \lambda \rho_g \frac{P_{\infty} - P_i}{(T_{\infty} - T_i) P_{\text{a,mean}}} \quad (28)$$

where h_{nc} is the natural convection heat transfer coefficient for sensible heat transfer from the steam/air mixture to the surface, determined by the methods described in Section 4.3.1, K_{nc} is the mass transfer coefficient for steam diffusing through the air to the surface for natural convection conditions, λ is the latent heat of steam, ρ_g is the density of liquid water, P_{∞} , T_{∞} and P_i , T_i are the partial pressures and temperatures of the steam in the mixture and the vapour-liquid interface respectively, and $P_{\text{a,mean}}$ is the log mean pressure of the air in the steam depleted layer, defined by the following equation:

$$P_{a,mean} = \frac{P_{a,i} - P_{a,b}}{\ln(P_{a,i} - P_{a,b})} \quad (29)$$

where $P_{a,i}$ is the air partial pressure at condensate film/steam depleted layer interface, and $P_{a,b}$ is the air partial pressure in the steam/air mixture. Consistent with the approximation of equation (26), P_i and T_i can be replaced by P_w and T_w . Also, if forced convection conditions are determined to prevail, then the natural convection heat transfer coefficient, h_{nc} , and the mass transfer coefficient, K_{nc} , can be replaced by their forced convection equivalents, h_{fc} and K_{fc} .

In the heat-mass transfer analogy, the Sherwood number is analogous to the Nusselt number in convective heat transfer. The Sherwood number is defined as follows:

$$Sh = K_{nc} (or K_{fc}) \frac{L}{D_v} \quad (30)$$

where L is the characteristic length and D_v is the diffusivity of the steam in air. To account for the effect of bulk motion, UNCCOND calculates Sherwood numbers for both natural and forced convection conditions using the following equations:

For natural convection:

$$Sh = C_n (Gr Sc)^n \quad (31)$$

For forced convection:

$$Sh = C_f Re^m Sc^{1/3} \quad (32)$$

where Gr is the Grashof number, Sc is the Schmidt number, Re is the Reynolds number, Pr is the Prandtl number, and C_f , C_n , m and n are constants which depend on the geometry, and whether laminar or turbulent conditions exist. UNCCOND chooses the higher of the two Sherwood numbers, reflecting actual behaviour.

The formulation for the Grashof number used in UNCCOND includes a term to account for density variations resulting from concentration variations as well as temperature variations, as suggested by Green and Almenas [10]:

$$Gr = \frac{gL^3}{\mu^2} [\beta(T_b - T_i) + \gamma(X_{q,i} - X_{q,\infty})] \rho^2 \quad (33)$$

$$\frac{l}{\gamma} = \frac{M_q}{M_q - M_v} X_b$$

where β is the coefficient of thermal expansion, X is the mass fraction of steam, and M is the

molecular weight. The subscripts g, v, b, and i correspond to the air, steam, and bulk and interface conditions respectively. The Schmidt number, which is analogous to the Prandtl number, is defined as:

$$Sc = \frac{\mu}{\rho D_v} \quad (34)$$

where D_v is the diffusivity of steam in air.

The diffusivity of steam in air is calculated using the Geankopolis correlation [21]:

$$D_v = 2.2 \times 10^{-5} \left(\frac{T}{273} \right)^{1.75} \left(\frac{101350}{P} \right) \quad (35)$$

where D_v is the diffusivity in m^2/s , P is the pressure in Pa.

The calculated heat-mass transfer coefficient is multiplied by a factor of 1.4 to take into account film waviness, as suggested by Sun et al [23].

4.3.5 Subroutine COIL

Subroutine COIL calculates the condensation rate of the steam/air mixture on the

condenser coils. A heat to mass transfer analogy similar to that used in UNCCOND is used. The following correlation for forced convection heat transfer over tubes, from Zukauskas [22], is used instead of the correlations for vertical walls:

$$Nu = C Re_{\max}^n Pr^{0.36} \quad (36)$$

where Nu is the Nusselt number, Re is the Reynolds number through the minimum flow area, and C and n are constants. The Nusselt number is used to find the appropriate h_{fc} , which is converted into K_{fc} using the heat-mass transfer analogy, as discussed in the previous section. For the current four-row tube arrangement, the constants used are:

$$C = 0.89$$

$$n = 0.4$$

4.4 Pressure Calculation

Due to the small volume involved, tank pressure is assumed to be uniform. It is also assumed that the steam and air present in each of the two regions of the tank (riser and downcomer) are distributed homogeneously through the region. Due to the low pressures involved, the steam partial pressure for each region can be calculated using the ideal gas law

[24]:

$$P_s = m_s R_s T_{ave} / V \quad (37)$$

where P_s is the steam partial pressure, m_s is the mass of steam present in the region, R_s is the steam gas constant, V is the volume of the region in question, and T_{ave} is the average absolute temperature in the region. If the mixture is saturated, P_s corresponds to the saturation pressure of steam at the temperature in question. If P_s is lower than the saturation pressure, then P_s is equal to the saturation pressure multiplied by the relative humidity.

The air partial pressure is also calculated using the ideal gas law, as follows:

$$P_a = m_a R_a T_{ave} / V \quad (38)$$

where P_a is the air partial pressure, m_a is the mass of air present in the region in question and R_a is the air gas constant. The total pressure in each region is determined by adding the steam and air partial pressures, according to Dalton's Law [24]:

$$P_T = P_a + P_s \quad (39)$$

The overall pressure in the tank is determined by calculating a weighted average of the total pressures in each region. The average is weighted using the ratio of the volumes of each region.

These calculations are performed by the TEMPGET subroutine in the PASSCON program.

4.5 Property Values

Property values are determined in various subroutines which contain correlations of tabulated data. The correlations for air property values were taken from the program LOPWATEX [8]. Correlations for the values of thermal conductivity, viscosity, specific heat, and thermal expansion coefficient for steam were determined from data tabulated in References [13,24]. The saturated steam properties of specific volume, saturation pressure, internal energies and enthalpies were found from correlations of standard steam tables published by Irvine and Liley [25].

Chapter 5

Experimental Results and Discussion

5.1 Introduction

This chapter presents the experimental results as well as predictions from the PASSCON program. Table 2 contains a summary of all the tests performed using the apparatus. The first tests (1-10) were performed without the condenser coils in place, and were meant to find leaks, loose connections and other problems with the apparatus. Following these tests the condenser coils were installed and tests (11-19) were performed with and without cooling water supplied to the condenser coils. Tests were also performed during which the water supply was turned on after the apparatus had been preheated by steam injection. Following these tests, the heating tape was added to the steam injection line, and the condenser coil shrouds were added. The final tests (20-25) are used in the final analyses.

5.2 Overall Performance of the Experimental Apparatus

The apparatus performed well and produced useful results for a wide range of tests. The apparatus demonstrated quite clearly that buoyancy driven flows are induced in passive containments, and are strongly affected by the presence of elevated condenser coils. The

following sections will demonstrate these observations.

As the apparatus was not designed initially for pressurization, some difficulties with leaks were encountered in early tests. These leaks were readily observed, and repairs were made to prevent further leaks.

Figure 16 presents the measured tank pressure with time for tests 14 and 20, to compare the results before and after the addition of the coil shrouds. These tests were performed with the same conditions (no cooling water flow, steam injection rate 1 g/s) with the exception of a longer duration of steam injection for test 20. Note the sudden drop in pressure near the end of the tests. This corresponds to the time at which the steam injection was shut off. The measured pressures are very close to one another, within 2 kPa. This gives confidence that the apparatus was pressurizing consistently, and demonstrates that measured results are repeatable.

Figure 17 presents two measured tank wall temperatures at the same elevation (near the top) and directly opposite each other, taken during Test 22. They are within 2 degrees Celsius of each other throughout most of the transient. This demonstrates that the behaviour of the flowing mixture in the apparatus is symmetrical about the vertical axis.

Figure 18 presents typical temperature measurements of the flow measuring unit inlet and outlet temperatures, and the surface temperature of the cartridge heaters, taken during Test 24. The heater surface temperature remains fairly constant (± 1 °C), demonstrating that the behaviour

of the flow-measuring unit is consistent, and that heat storage effects can be neglected. The small oscillations in the outlet temperature may be due to secondary flows, which are commonly induced in square ducts, particularly with flows with low Reynolds numbers. Note that there is a gradual downward trend in the flow-measuring unit outlet temperature. This corresponds to a gradual upwards trend in the calculated flowrate. There is also a slight upward trend in the measured inlet temperature. Figure 19 shows the air mass flowrate calculated by the PASSIVE data acquisition program using the data from Test 24. Note that the air mass flowrate increases with time. Figure 19 also presents measured air mass flowrates from a test with similar conditions before the coil shrouds were installed (Test 13). The air mass flowrate is much higher in Test 13. This is to be expected, since the flow is forced over the condenser coils when the shrouds are in place, resulting in higher friction forces.

5.3 Tests with No Cooling Water Supplied to the Condenser Coils

5.3.1 Air Mass Flowrate Results

Figure 20 presents the measured air mass flowrate with time from Test 25. The conditions of the test were a 900 second (15 minute) duration for the injection of steam, no cooling water supplied to the condenser coils, and a steam injection rate of 1 g/s. Note that the measured flowrate rises during the test, reaching a quasi steady state value of approximately 0.22 g/s. Figure 20 also presents the PASSCON program prediction given the same conditions. PASSCON underpredicts the flowrate by about 30-40%. The large difference between the

experimental results and the PASSCON prediction is due to the large uncertainty in theoretical pressure loss coefficients and friction factors used in the flowrate calculation in the PASSCON program. As discussed in Chapter 4, the flow loss correlations used in PASSCON were determined using flows with much higher Reynolds numbers than are present in the flow-measuring unit and the condenser coils. A correction factor, based on the experimental data, can be applied to the friction pressure difference calculated in the PASSCON program to improve the agreement with experimental data. This correction factor is simply a multiplier applied to the total friction pressure difference found using equation 3. A similar approach was used by Slaby [8] in the program LOPWATEX, which resulted in excellent agreement with measured flowrates. For the LOPWATEX program, a correction factor of 0.71 was determined. The correction factor used in the LOPWATEX program is, however, not valid in the present case due to different geometry. After trial and error, it was found that using a correction factor of 0.6 in the PASSCON program gives good agreement with experimental flowrate data in the quasi-steady state region, as shown in Figure 20. Further PASSCON flowrate predictions presented in this work will include this empirical correction factor.

Figure 20 also presents a new PASSCON prediction of the air mass flowrate, using the empirical correction factor, and shows good agreement with the measured values in the quasi steady-state region. The overprediction in the initial part of the transient is due to heat storage effects. Components in the apparatus store heat, and remove energy from the steam/air mixture flowing in the tank. The flowrate is strongly dependent on the difference in temperature between the mixture in the riser and that in the downcomer. Due to heat storage effects, this temperature

difference will take longer to develop than if there were no heat storage in the components.

PASSCON does not take heat storage into account, except for that of the tank wall.

5.3.2 Pressure Results

Figure 21 presents the measured tank pressures from Test 25 (no cooling water, 1 g/s steam injection and 900s duration), and the predicted pressures using PASSCON. The agreement is reasonably good (156 kPa after 900 s measured vs. 143 kPa predicted). PASSCON overpredicts the pressure in the initial part of the transient. This is due to heat storage effects, as discussed previously, and to the dominance of dropwise condensation in the initial part of the transient. The PASSCON program assumes that the dominant condensation mechanism is filmwise condensation. However, early in the transient, there is not enough liquid water present to develop a liquid film on the condensation surfaces. Thus, dropwise condensation will occur. A characteristic of the dropwise condensation mechanism is a higher condensation rate than that for a filmwise mechanism. Later in the transient, PASSCON underpredicts the pressure. This could be due to an overprediction of condensation heat transfer rates on the surfaces in the apparatus. Green and Almenas [10] observed that HMT analogies consistently *underpredict* heat transfer rates, which contradicts the current observation. To investigate the accuracy of the heat-mass transfer analogy used in the PASSCON program, the more widely-used and accepted Uchida correlation [12] was substituted, with the resulting pressure transient shown in Figure 21. The Uchida correlation results in an even greater underprediction of the pressure. At its greatest, the pressure difference between the PASSCON prediction using the Uchida correlation and that

using the HMT analogy is 15 kPa. This demonstrates that the HMT analogy does predict lower heat transfer rates than the Uchida correlation. A possible explanation for the observed pressure underprediction is the uniform wall temperature assumption. PASSCON assumes that the wall and riser temperatures are uniform with height, and that condensation occurs evenly over their surfaces. In reality, the wall temperature varies significantly over its height, which will result in varying condensation heat transfer rates over the wall.

5.3.3 Temperature Results

Figure 22 presents the experimental temperature results for the steam/air mixture at the exit of the riser for Test 25 (no cooling water, 900s duration), the downcomer just below the condenser coils, and at the entrance of the flow-measuring unit. Figure 25 also presents the PASSCON predictions for a test with the same conditions. Figure 23 presents the measured surface temperatures of the riser wall, tank wall and condenser coil, along with PASSCON predictions. The results give credence to the assumptions made in the PASSCON program. As the temperature of the riser wall increases towards the riser mixture temperature, the mixture temperature at the exit approaches the riser wall temperature, indicating that the heat transfer rate to the riser wall is very low.

The temperature of the top of the tank wall increases significantly, with the tank wall bottom remaining cool. This indicates that most of the steam is condensed near the top of the

tank, and the mixture re-entering the entrance unit is mostly air, which validates the assumption made for the flowrate calculation in the data acquisition program PASSIVE. The large difference between the tank wall top and bottom temperatures indicates that the uniform wall temperature assumption in PASSCON is an approximation. The uniform wall temperature assumption results in a predicted wall temperature which lies between the measure temperatures of the tank wall top and bottom. Thus, the calculated temperature of the air at the bottom of the downcomer will be higher than the measured quantity.

5.4 Tests With Cooling Water Flow Supplied to the Condenser Coils

5.4.1 Air Mass Flowrates

Figure 24 presents the air mass flowrate measurements for Test 24 (with cooling water, 1 g/s steam injection and 900s duration), and the PASSCON prediction. The air mass flowrates for tests with the cooling water supply turned on are higher than those with no cooling water. This is due to the increased buoyancy pressure difference, which is caused by a decrease in the average temperature in the downcomer region. The PASSCON program overestimates the flowrate (by about 25% in the quasi steady-state region) due to an overestimation of the condensation heat transfer rate, which will be discussed in the next section.

5.4.2 Pressure Results

Figure 25 presents the pressure results for Test 24. The pressure is lower than that observed during the test with no cooling water supply, as expected (about 131 kPa after 900 seconds). The PASSCON program underpredicts the pressure (120 kPa after 900 s, about 8% difference). This is due to an overprediction of the condensation heat transfer rate to the condenser coils. PASSCON assumes that forced convection conditions exist in the condenser coils. Most likely, there are mixed force/natural convection conditions in the condenser coils, resulting in lower condensation rates.

5.4.3 Temperature Results

Figure 26 presents the steam/air mixture temperatures at the riser exit, downcomer below the coils and entrance to the flow-measuring unit for Test 24, and the PASSCON predictions. Figure 27 shows the comparison of the riser wall, tank wall and condenser coil temperatures with the PASSCON predictions. The downcomer mixture temperature shows reasonably good agreement with the PASSCON prediction. The temperatures at the riser exit are very similar to the results from the test with no cooling water supplied, as expected, as shown in Figure 27a. The downcomer mixture temperature remains low and fairly constant, compared to the test without cooling water, which reaches a much higher value. This indicates that the mixture is being cooled effectively by the condenser coils, and that little steam is being recirculated.

5.5 Tests With Cooling Water Supply Delayed After Steam Injection

5.5.1 Air Mass Flowrates

The cooling effect of the condenser coils is demonstrated more dramatically for tests of this type. Figure 28 presents the measured and predicted air mass flowrates from Test 23, in which the cooling water supply was turned on after steam injection (1 g/s) has been occurring for 900 seconds (15 minutes). The measured and predicted flowrates rise significantly after cooling water has begun to flow through the condenser coils. This is due to an increased buoyancy pressure difference between the riser and downcomer regions, as the downcomer region will be cooler than if there was no water flowing through the condenser coils. The measured air flow rate increases more gradually than the predicted value since the PASSCON program ignores heat capacity effects, as stated earlier. The circulation time for air in the apparatus, based on a flowrate of 0.3 g/s, is approximately 640 seconds. Thus, a long lag time between the removal of heat in one region and changes in temperature around the flow circuit, and thus in buoyant force and flowrate, can be expected.

5.5.2 Pressure Results

Figure 29 presents the experimental and predicted pressure results for Test 23, in which the cooling water supply was turned on after 900 seconds (15 minutes). The first 900 s of the test are thus the same as for test 25. After the water supply was turned on the pressure dropped quite quickly and reached a new quasi steady-state. This indicates that pressure results do not experience the same lag as the air mass flowrate and temperatures. This is to be expected since pressure waves propagate very quickly [18]. This drop in pressure indicates that the coils are condensing steam effectively.

5.5.3 Temperature Results

Figure 30 presents the steam/air mixture temperature results from Test 23, as well as predictions from the PASSCON program. The downcomer mixture temperature drops quite rapidly after the cooling water is turned on. The riser exit temperature also drops, but the change is slower than in the downcomer. This is due to the lag caused by the long recirculation time. Since the downcomer temperature is lower, heat transfer to the riser wall increases, and the riser exit and riser wall temperatures eventually decrease. The surface temperature measurements and predictions are presented in Figure 31. The predicted riser wall temperatures agrees reasonably well with the measured values, considering the simplicity of the uniform temperature assumption in PASSCON. Note that the measured tank wall top temperature increases suddenly when the cooling water supply is turned on. The tank wall top temperature can be expected to increase even after the water is turned on due to the long lag time, however this does not explain the suddenness and magnitude of the rise.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

An experimental apparatus used to simulate the important thermalhydraulic processes present in a CANDU passive containment during a LOCA has been designed and constructed. Experimental results have been obtained. The following conclusions may be made from the experience with the apparatus and the program, PASSCON:

- the apparatus demonstrated that a buoyancy driven recirculating flow is induced using elevated cooling coils
- the results demonstrate that elevated condenser coils provide an effective means of removing containment atmosphere energy and a means of arresting the pressure rise
- the apparatus demonstrated that cooling caused by heat transfer to the tank wall also results in a smaller induced buoyancy driven flow
- the apparatus demonstrated good pressure retention when kept in good repair
- the apparatus provided confidence in the flowrate calculation method, and provided an empirical correction factor for the flow losses used in the PASSCON program

- the apparatus gave confidence in the assumption that all steam is condensed in the downcomer region, and that air only recirculates through the flow-measuring unit

The following conclusions were drawn from the experience with the program, PASSCON:

- the predictions demonstrated that a simple one-node pressure calculation provides fairly accurate predictions of containment pressure for quasi steady-state conditions
- force-balance determined air mass flowrate predictions are accurate provided an experimentally determined empirical correction factor is applied to the flow loss buoyancy difference
- the uniform wall temperature assumption provides approximate agreement with experimental results; however, a nodalized solution of the wall would yield better agreement
- a uniform downcomer temperature is a poor assumption for the case with no cooling water supplied to the condenser coils, but is more reasonable for the case with cooling water supplied
- the predictions during the initial part of the transient are poor, due to heat storage effects in the apparatus

6.2 Suggested Improvements

The following are recommendations for improvements to the program PASSCON:

- Integrate the density of the air in the riser and downcomer, instead of using average values, to improve the accuracy of the buoyancy force calculation.
- Divide the downcomer region into three separate regions: the region above the condenser coils, the region occupied by the coils, and the region below the coils, in order to improve the accuracy of the downcomer mixture and tank wall temperatures.

OR

- Use a nodalized solution for the wall, to determine the temperature profile
- Adopt a more physically reasonable method of updating the riser wall temperature, perhaps by nodalizing the riser wall to establish a temperature profile

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TABLES

Table 1. Steam Generator Nozzle Diameter, Flowrate and Pressure

Orifice Diameter (mm)	Flowrate (g/s)	Steam Generator Pressure (kPa-abs)
0.8	0.7	550
1.2	0.9	500
1.5	1.0	410
2.0	0.7	270

Table 2. Summary of Tests Performed Using the Passive Containment Apparatus

Test No.	Cooling Water Flow (L/s)	Duration of Steam Injection (s)	Steam Injection Rate (g/s)	Peak Pressure (kPa)	Coils, Shrouds Present	Comments
1	-		1.0	115.8		Leakage from gasket - replaced
2	-		1.0	120.2		Leakage from thermocouple fittings - sealed
3	-		1.0	119.3		Leakage from Water supply fitting - repaired
4	-		1.0	118.1		Leakage from various fittings
5	-		1.0	118.6		..
6	-		1.0	119.7		..
7	-		1.0	115.2		..
8	-		1.0	115.1		..
9	-		1.0	113.1		Water supply re-soldered, coils attached, all O-rings replaced, all cover bolts replaced
10	none	420	1.0	131.3	C	No leakage
11	9.5	420	1.0	127.3	C	No leakage
12	none	420	1.0	117.3	C	O-ring failed - replaced
13	9.5	420	1.0	121.5	C	Leakage from

						transducer port - repaired
14	none	420	1.0	131.4	C	No leakage
15	9.5	420	1.0	128.4	C	No leakage
16	9.5 @ 600 s	900	1.0	138.6	C	No leakage
17	9.5 @ 1500 s	2500	1.0	175.9	C	Water supply hosed fitting failed - replaced
18	9.5 @ 1500 s	2500	1.0	179.4	C	No leakage
19	none	480	1.0	120.3	C,S	Coil shrouds installed, gasket leakage detected - repaired
20	none	600	1.0	133.0	C,S	No leakage
21	none	600	1.0	141.3	C,S	No leakage
22	9.5	600	1.0	123.9	C,S	No leakage
23	9.5 @ 900 s	1500	1.0	153.1	C,S	No leakage
24	9.5	900	1.0	131.5	C,S	No leakage
25	none	900	1.0	157.2	C,S	No leakage
26	none	-	none	-	C,S	Determine steady-state behaviour of FMU

C - coils present, S - shrouds present

FIGURES

Figure 1: Schematic of CANDU Reactor

Figure 2: Schematic of Current CANDU Containment Building Design

- Primary Heat Transport System
- Passive Emergency Water System
- Steam Generator Heat Rejection
- Moderator Heat Rejection
- Hydrogen Recombiner

Figure 3: Schematic of CANDU Passive Containment Design

SLOWPOKE ENERGY SYSTEM

Figure 4: Schematic of SLOWPOKE SES-10 Reactor

Figure 5: Schematic of SLOWPOKE Simulation Apparatus

Figure 6: Condensation in the Presence of Non-condensibles

Figure 7: Schematic of Passive Containment Simulation Apparatus

Figure 8: Photograph of Apparatus

Figure 9: Photograph of Chromalox CMB-3 120 Compact Steam Generator

Figure 10: Photograph of Riser

Figure 11: Photograph of Stand Flow-Measuring Unit

Figure 12: Schematic of Condenser Coil (Side View)

Figure 13: Photograph of Condenser Coil

Figure 14: Location of Thermocouples

Figure 15: Schematic of Analytical Model

Figure 16: Pressures; Comparison of Tests 20 & 14

Figure 17: Wall Temperatures; Test 21; Same Elevation; Opposite Sides

Figure 18: Temperatures; Test 24; Flow-Measuring Unit

Figure 19: Air Mass Flowrates; Effect of Condenser Shrouds

Figure 20: Air Mass Flowrates; No Cooling Water

Figure 21: Pressures; No Cooling Water

Figure 22: Mixture Temperatures; No Cooling Water

Figure 23: Surface Temperatures; No Cooling Water

Figure 24: Air Mass Flowrates; With Cooling Water

Figure 25: Pressures; With Cooling Water

Figure 26: Mixture Temperatures; With Cooling Water

Figure 27: Surface Temperatures; With Cooling Water

Figure 27a: Mixture Temps; Comparison of tests with & without water

Figure 28: Air Mass Flowrates; Cooling Water on @ 15 min.

Figure 29: Pressures, Cooling Water on @ 15 min.

Figure 30: Mixture Temperatures; Cooling Water on @ 15 min.

Figure 31: Surface Temperatures; Cooling Water on @ 15 min.

APPENDIX A

This appendix contains a listing of the data acquisition program PASSIVE:

```
'DATA ACQUISITION PROGRAM "PASSIVE"
'
'This program has been developed for data acquisition
'of data measured in the experiments with the Passive
'Containment Building simulator.
'Used references are:
' 1. DAS-8PGA A/D interface board - Operator's manual,
'    published by Omega Engineering, Inc.
' 2. Microsoft QuickBASIC Version 4.5, Microsoft
'    Corporation, 1990.
'
'Declare variables and subroutines.
'
DIM SHARED T(7, 15), HW(2), TR(15), TS(15), VEL(15)
DIM LT%(15), D%(100), TK(320), AV(15)
COMMON SHARED CH%, DAT%(), AV(), CJC
COMMON SHARED LT%(), D%(), v, NK, SIK, SVK, TK()
'
DECLARE SUB ADCONV (CH%, NC!, VALUE!)
DECLARE SUB CJCGET (NC, CJC)
DECLARE SUB DAS8 (MD%, BYVAL dummy%, FLAG%)
DECLARE SUB DATAOUT (A, T!(), P1, P2, MDOT)
DECLARE SUB ERRCODES (FLAG%)
DECLARE SUB HEADLINE ()
DECLARE SUB INITIALIZE ()
DECLARE SUB LOCKCHAN (CH%)
DECLARE SUB SCROUT (CJC, T(), P1, P2, MDOT)
DECLARE SUB PRESGET (NC!, P1!, P2!)
DECLARE SUB TEMPGET (NC, CJC, T())
DECLARE SUB TEMPINTRP (v!, CJC, TC!)
'
CLS
LOCATE 12, 1
INPUT "Your old output files will be lost. Proceed anyway? (Y or N):", D$
IF D$ = "N" THEN END
CLS
LOCATE 25, 1: COLOR 0, 7: PRINT "-PLEASE WAIT-"; : COLOR 7, 0:
PRINT "  Creating titles of output files.": LOCATE 1, 1
CALL HEADLINE
LOCATE 25, 1: COLOR 0, 7: PRINT "-PLEASE WAIT-"; : COLOR 7, 0:
PRINT "  Loading DAS-8 I/O address and thermocouple";
```



```

PRINT " lookup table data.": LOCATE 1, 1
'
'Initialize data acquisition board DAS-8.
CALL INITIALIZE
'
'Load thermocouple linearizing look up data.
GOSUB 50000
'
'Set gain settings for each expansion multiplexer EXP-16.
AV(0) = 50
AV(1) = 1000
AV(2) = 1000
'
'Set number of A/D conversions (NC) for each data.
NC = 5
CLS
LOCATE 12, 26
PRINT "TO START, PRESS ANY KEY."
30  IF INKEYS = "" THEN GOTO 30
    CLS
    TIMES = "00:00:00"
    COLOR 0, 7
    LOCATE 1, 1
    PRINT USING " ELAPSED TIME = #####.##"; TIMER / 60
    COLOR 7, 0
10  LOCATE 1, 32
    A = TIMER / 60
    AS = TIMES
    PRINT USING "TIME OF THE LAST MEASUREMENT = #####.##"; A
'
'Make thermocouple readings.
CALL TEMPGET(NC, CJC, T())
'
'Make pressure transducer readings.
CALL PRESGET(NC, P1, P2)
IF TIMES < "00:00:30" THEN GOTO 17
'
'Print measured data on the screen.
17  TAVE = 273 + (T(2, 2) + T(2, 2)) / 2
    CPA = 975.62 + .05003 * TAVE + .0001267 * TAVE ^ 2
    P = 10
    IF (T(2, 1) - T(2, 2)) = 0 THEN GOTO 18
    MDOT = 0.95 * P / (CPA * (T(2, 2) - T(2, 1)))

```

```

18  CALL SCROUT(CJC, T(), P1, P2, MDOT)
,
'Store data in the output files.
CALL DATAOUT(A, T(), P1, P2, MDOT)
,
'The following commands control data collection period.
SELECT CASE TIMES
CASE "00:00:00" TO "00:01:00"
    DELT = 10
CASE IS > "00:01:01"
    DELT = 10
CASE IS < "00:00:00"
    PRINT "Wrong value of TIMES.", TIMES
END SELECT
TAKE = TAKE + DELT
20  COLOR 0, 7
    LOCATE 1, 1
    PRINT USING " ELAPSED TIME = #####.##"; TIMER / 60
    COLOR 7, 0
    IF TAKE > TIMER THEN GOTO 20
,
'Repeat scan of channels.
GOTO 10
'*****
50000 '----- Table lookup data for K type thermocouple -----
'Run this subroutine only in the initialization section of the program
'The following variables are: Number of points, voltage step
'interval (mV), starting voltage (mV)
DATA 309 , .2 , -6.6
READ NK, SIK, SVK
'Temperature at -6.6mv, -6.4mV, -6.2mV etc.
DATA -353.5,-249.3,-224.0,-207.6,-194.3,-182.8,-172.3,-162.8,-153.8,-145.4
DATA -137.3,-129.6,-122.3,-115.2,-108.3,-101.6, -95.1, -88.7, -82.5, -76.4
DATA -70.4, -64.6, -58.8, -53.1, -47.5, -42.0, -36.6, -31.2, -25.9, -20.6
DATA -15.4, -10.2, -5.1, -0.0, 5.0, 10.1, 15.1, 20.0, 25.0, 29.9
DATA 34.8, 39.7, 44.6, 49.5, 54.3, 59.1, 64.0, 68.8, 73.6, 78.4
DATA 83.2, 88.0, 92.9, 97.7, 102.5, 107.4, 112.2, 117.1, 122.0, 126.9
DATA 131.8, 136.7, 141.7, 146.6, 151.6, 156.5, 161.5, 166.5, 171.5, 176.5
DATA 181.6, 186.6, 191.6, 196.6, 201.6, 206.6, 211.6, 216.6, 221.5, 226.5
DATA 231.5, 236.4, 241.4, 246.3, 251.2, 256.1, 261.0, 265.9, 270.8, 275.6
DATA 280.5, 285.3, 290.2, 295.0, 299.8, 304.6, 309.4, 314.3, 319.1, 323.9
DATA 328.7, 333.4, 338.2, 343.0, 347.8, 352.6, 357.3, 362.1, 366.9, 371.6
DATA 376.4, 381.1, 385.9, 390.6, 395.4, 400.1, 404.8, 409.6, 414.3, 419.0

```

```

DATA 423.8, 428.5, 433.2, 437.9, 442.6, 447.3, 452.0, 456.8, 461.5, 466.2
DATA 470.9, 475.6, 480.3, 485.0, 489.7, 494.4, 499.1, 503.8, 508.5, 513.1
DATA 517.8, 522.5, 527.2, 531.9, 536.6, 541.3, 546.0, 550.7, 555.4, 560.0
DATA 564.7, 569.4, 574.1, 578.8, 583.5, 588.2, 592.9, 597.6, 602.3, 607.0
DATA 611.7, 616.4, 621.2, 625.9, 630.6, 635.3, 640.0, 644.8, 649.5, 654.2
DATA 658.9, 663.7, 668.4, 673.2, 677.9, 682.7, 687.4, 692.2, 696.9, 701.7
DATA 706.5, 711.3, 716.1, 720.8, 725.6, 730.4, 735.2, 740.0, 744.8, 749.7
DATA 754.5, 759.3, 764.1, 769.0, 773.8, 778.7, 783.5, 788.4, 793.3, 798.1
DATA 803.0, 807.9, 812.8, 817.7, 822.6, 827.5, 832.4, 837.3, 842.2, 847.2
DATA 852.1, 857.1, 862.0, 867.0, 872.0, 876.9, 881.9, 886.9, 891.9, 896.9
DATA 901.9, 906.9, 911.9, 916.9, 922.0, 927.0, 932.0, 937.1, 942.2, 947.2
DATA 952.3, 957.4, 962.5, 967.6, 972.7, 977.8, 982.9, 988.0, 993.1, 998.2
DATA 1003.4, 1008.5, 1013.7, 1018.8, 1024.0, 1029.2, 1034.4, 1039.6, 1044.8, 1050.0
DATA 1055.2, 1060.4, 1065.6, 1070.8, 1076.1, 1081.3, 1086.6, 1091.9, 1097.2, 1102.4
DATA 1107.7, 1113.0, 1118.3, 1123.7, 1129.0, 1134.3, 1139.7, 1145.0, 1150.4, 1155.8
DATA 1161.2, 1166.6, 1172.0, 1177.4, 1182.9, 1188.3, 1193.8, 1199.2, 1204.7, 1210.2
DATA 1215.7, 1221.2, 1226.8, 1232.3, 1237.9, 1243.5, 1249.1, 1254.7, 1260.3, 1265.9
DATA 1271.6, 1277.3, 1282.9, 1288.6, 1294.3, 1300.1, 1305.8, 1311.5, 1317.3, 1323.1
DATA 1328.9, 1334.7, 1340.5, 1346.4, 1352.2, 1358.1, 1363.9, 1369.8, 1375.7

```

```

FOR i = 0 TO NK - 1: READ TK(i): NEXT i
RETURN

```

```

'*****

```

```

SUB ADCONV (CH%, NC, VALUE) STATIC

```

```

' This subroutine performs A/D conversion.

```

```

DIM DAT(1000)

```

```

' Perform NC A/D conversions. NC is defined in the main calling
' routine of the program.

```

```

FOR i = 1 TO NC

```

```

' Do A/D conversion using mode 4.

```

```

MD% = 4

```

```

CALL DAS8(MD%, VARPTR(D%(CH%)), FLAG%)

```

```

IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)

```

```

DAT(i) = D%(CH%)

```

```

NEXT i

```

```

' Average the values read from the channel.

```

```

SUM = 0!
FOR i = 1 TO NC
  SUM = SUM + DAT(i)
NEXT i

```

```

VALUE = SUM / NC
END SUB

```

```

'*****

```

```

SUB CJCGET (NC, CJC)

```

```

' This subroutine gets cold junction compensation temperature.

```

```

' Output of CJC channel is scaled at 24.4mV/deg.C. This corresponds to

```

```

' 0.1 deg.C/bit. Dividing output in bits by 10 yields degrees C.

```

```

' Lock DAS-8 to channel #7 (CJC channel) using mode 1.

```

```

CH% = 7

```

```

CALL LOCKCHAN(CH%)

```

```

' get CJC data from this channel using subroutine ADCONV.

```

```

CALL ADCONV(CH%, NC, VALUE)

```

```

' Change output in bits to real temperature

```

```

CJ% = VALUE

```

```

CJC = CJ% / 10

```

```

END SUB

```

```

'*****

```

```

SUB DATAOUT (A, T(), P1, P2, MDOT)

```

```

' This subroutine stores measured data in output files for later

```

```

' analysis.

```

```

SEC = A * 60

```

```

' Temperatures of the concrete at the lower level.

```

```

OPEN "TEMPLEV1.OUT" FOR APPEND AS #1

```

```

FORMAT$ = " #####.## #####.### #####.### #####.### #####.### #####.### "

```

```

PRINT #1, USING FORMAT$; SEC; T(1, 0); T(1, 1); T(1, 2); T(1, 3); T(1, 4)

```

```

CLOSE #1

```

,

'Temperatures of the concrete at the middle level.

OPEN "TEMPLEV2.OUT" FOR APPEND AS #2

FORMAT\$ = "#####.## #####.### #####.### #####.### #####.### #####.### "

PRINT #2, USING FORMAT\$; SEC; T(1, 5); T(1, 6); T(1, 7); T(1, 8); T(1, 9)

CLOSE #2

,

'Temperatures of the concrete at the top level.

OPEN "TEMPLEV3.OUT" FOR APPEND AS #3

FORMAT\$ = "#####.## #####.### #####.### #####.### #####.### #####.### "

PRINT #3, USING FORMAT\$; SEC; T(1, 10); T(1, 11); T(1, 12); T(1, 13); T(1, 14)

CLOSE #3

,

'Temperatures of the mixture.

OPEN "TAIR.OUT" FOR APPEND AS #5

FORMAT\$ = "#####.## #####.### #####.### #####.### #####.### #####.### "

PRINT #5, USING FORMAT\$; SEC; T(0, 10); T(0, 6); T(0, 8); T(0, 9); T(0, 7)

CLOSE #5

,

'Flowrate through velocity duct and temperatures.

OPEN "MDOT.OUT" FOR APPEND AS #6

FORMAT\$ = "#####.## #.##### #####.## #####.##"

PRINT #6, USING FORMAT\$; SEC; MDOT; T(3, 1); T(3, 2)

CLOSE #6

,

'Temperatures along the tank wall.

OPEN "TTANK2.OUT" FOR APPEND AS #7

FORMAT\$ = "#####.## #####.### #####.### #####.### #####.### #####.### "

#####.###"

PRINT #7, USING FORMAT\$; SEC; T(2, 8); T(2, 9); T(2, 10); T(2, 11); T(2, 12); T(2, 13)

CLOSE #7

,

'Temperatures of the concrete across the bottom.

OPEN "TBOTTOM.OUT" FOR APPEND AS #8

FORMAT\$ = "#####.## #####.### #####.### #####.### "

PRINT #8, USING FORMAT\$; SEC; T(2, 14); T(2, 6); T(2, 7)

CLOSE #8

,

'Temperature of the outside air.

OPEN "TOUTAIR.OUT" FOR APPEND AS #9

FORMAT\$ = "#####.## #####.### "

PRINT #9, USING FORMAT\$; SEC; T(0, 14)

CLOSE #9

```
,
'Pressure in the tank.
OPEN "PTANK.OUT" FOR APPEND AS #11
FORMAT$ = " #####.## #####.## #####.##"
PRINT #11, USING FORMAT$; SEC; (P1 + 101.35); (P2 + 101.35)
CLOSE #11
,
```

```
'Temperatures of the cooling water.
OPEN "TWATER.OUT" FOR APPEND AS #12
FORMAT$ = " #####.## #####.## #####.## "
PRINT #12, USING FORMAT$; SEC; T(2, 14); T(2, 15)
CLOSE #12
,
```

```
'Temperatures of the lid and of the insulation on the lid.
OPEN "TLID.OUT" FOR APPEND AS #13
FORMAT$ = " #####.## #####.## #####.## #####.##"
PRINT #13, USING FORMAT$; SEC; T(0, 11); T(0, 12); T(0, 13)
CLOSE #13
,
```

```
END SUB
```

```
*****
```

```
,
SUB ERRCODES (FLAG%) STATIC
,
```

```
' This subroutine checks error codes obtained from DAS-8,
' prints them on the screen and stops the program in the case
' of any error is encountered.
,
```

```
PRINT " The returned FLAG% = "; FLAG%
SELECT CASE FLAG%
CASE 1
  PRINT "Base address unknown. (I/O location not initialized)": END
CASE 2
  PRINT "Mode number <0 or >22.": END
CASE 3
  PRINT "Invalid Base Address, <256 or >1016.": END
CASE 4
  PRINT "Mux scan limits out of range or reversed order,";
  PRINT "<0 or >7.": END
CASE 5
  PRINT "Channel number out of range, <2 or >7.": END
CASE 6
```

```

    PRINT "A/D timeout. Incorrect busy signal from A/D.": END
CASE 7
    PRINT "Interrupt level out of range, <2 or >7.": END
CASE 8
    PRINT "Mode 8 data transfer parameters out of range.": END
CASE 9
    PRINT "Mode 9 data transfer parameters out of range.": END
CASE 10
    PRINT "Counter number out of range, <0 or >2.": END
CASE 11
    PRINT "Counter configuration number out of range, <0 or >5.": END
CASE 12
    PRINT "Digital output data out of range, <0 or >15.": END
CASE 13
    PRINT "Mode 18 Trigger channel number out of range, <0 or >7.": END
CASE 14
    PRINT "Mode 18 Trigger level out of range, <2048 or >2047.": END
CASE 15
    PRINT "Mode 18 Trigger slope not 0 or 1.": END
CASE 16
    PRINT "PGA gain codes illegal, <0 or >3.": END
CASE 17
    PRINT "PGA function not available (no DAS-8PGA).": END
CASE 18
    PRINT "Mode # unavailable for this language.": END
CASE 19
    PRINT "Mode 21 not initialized.": END
CASE IS > 19
    PRINT "Flag% > 19 - Error type not specified.": END
END SELECT
END SUB

'*****
'
SUB HEADLINE
'
'This subroutine creates headlines of output files.
'
OPEN "TEMPLEV1.OUT" FOR OUTPUT AS #1
PRINT #1,
PRINT #1, "Temperatures of the concrete at the lower level."
PRINT #1,
PRINT #1,

```

```

PRINT #1, " TIME    T(0,1)  T(0,2)  T(0,3)  T(0,4)  T(0,5)"
PRINT #1,
CLOSE #1
OPEN "TEMPLEV2.OUT" FOR OUTPUT AS #2
PRINT #2,
PRINT #2, "Temperatures of the concrete at the middle level."
PRINT #2,
PRINT #2,
PRINT #2, " TIME    T(0,1)  T(0,2)  T(0,3)  T(0,4)  T(0,5)"
PRINT #2,
CLOSE #2
OPEN "TEMPLEV3.OUT" FOR OUTPUT AS #3
PRINT #3,
PRINT #3, "Temperatures of the concrete at the top level."
PRINT #3,
PRINT #3,
PRINT #3, " TIME    T(0,1)  T(0,2)  T(0,3)  T(0,4)  T(0,5)"
PRINT #3,
CLOSE #3
OPEN "TAIR.OUT" FOR OUTPUT AS #5
PRINT #5,
PRINT #5, "Temperatures of the air."
PRINT #5,
PRINT #5,
PRINT #5, " TIME  Riser Exit  Riser Bottom  Downcomer  Coil  Riser Wall"
PRINT #5,
CLOSE #5
OPEN "MDOT.OUT" FOR OUTPUT AS #6
PRINT #6,
PRINT #6, "Air Flowrate through the entrance unit."
PRINT #6,
PRINT #6,
PRINT #6, " TIME    MDOT    TIN    TOUT"
PRINT #6,
CLOSE #6
OPEN "TTANK2.OUT" FOR OUTPUT AS #7
PRINT #7,
PRINT #7, "Temperatures along the tank wall."
PRINT #7,
PRINT #7,
PRINT #7, " TIME    T(0,1)  T(0,2)  T(0,3)  T(0,4)  T(0,5)  T(0,6)"
PRINT #7,
CLOSE #7

```



```
OPEN "TBOTTOM.OUT" FOR OUTPUT AS #8
PRINT #8,
PRINT #8, "Temperatures of the concrete across the bottom."
PRINT #8,
PRINT #8,
PRINT #8, " TIME    T(2,6)  T(2,7)  T(1,15)"
PRINT #8,
CLOSE #8
OPEN "TOUTAIR.OUT" FOR OUTPUT AS #9
PRINT #9,
PRINT #9, "Temperature of the outside air."
PRINT #9,
PRINT #9,
PRINT #9, " TIME    T(0,13)"
PRINT #9,
CLOSE #9
OPEN "PTANK.OUT" FOR OUTPUT AS #11
PRINT #11,
PRINT #11, "Pressure in the tank (kPa)."
PRINT #11,
PRINT #11,
PRINT #11, " TIME    P1    P2    "
PRINT #11,
CLOSE #11
OPEN "TWATER.OUT" FOR OUTPUT AS #12
PRINT #12,
PRINT #12, "Temperatures of the cooling water."
PRINT #12,
PRINT #12,
PRINT #12, " TIME    T(2,14)  T(2,15)"
PRINT #12,
CLOSE #12
OPEN "TLID.OUT" FOR OUTPUT AS #13
PRINT #13,
PRINT #13, "Temperatures of the lid and of insulation on the lid."
PRINT #13,
PRINT #13,
PRINT #13, " TIME    T(0,11)  T(0,12)  T(0,13)"
PRINT #13,
CLOSE #13

END SUB
```

```
*****
```

```
,
```

```
  SUB INITIALIZE STATIC
```

```
,
```

```
'This subroutine initializes DAS-8. Address is stored  
'in DAS8.ADR file.
```

```
,
```

```
  OPEN "DAS8.ADR" FOR INPUT AS #1
```

```
  INPUT #1, BASADR% 'initialize & declare CALL parameters
```

```
  CLOSE #1
```

```
  FLAG% = 0
```

```
  MD% = 0 'Mode 0 = initialization
```

```
  CALL DAS8(MD%, VARPTR(BASADR%), FLAG%)
```

```
  IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
```

```
,
```

```
END SUB
```

```
*****
```

```
,
```

```
  SUB LOCKCHAN (CH%) STATIC
```

```
,
```

```
'This subroutine locks DAS-8 to channel # using mode 1.
```

```
,
```

```
  MD% = 1: LT%(0) = CH%: LT%(1) = CH%
```

```
  CALL DAS8(MD%, VARPTR(LT%(0)), FLAG%)
```

```
  IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
```

```
,
```

```
'Verify if the multiplexer channel is locked to the specified channel.
```

```
  MD% = 3: D%(0) = 1
```

```
  CALL DAS8(MD%, VARPTR(D%(0)), FLAG%)
```

```
  IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
```

```
  IF D%(0) <> CH% THEN PRINT "Mux channel is different from channel #.": END
```

```
,
```

```
END SUB
```

```
*****
```

```
  SUB PRESGET (NC, P1, P2)
```

```
,
```

```
'Read and convert value from pressure transducer P1
```

```
'Pressure in Kilopascals
```

```
  CH% = 3
```

```
  CALL LOCKCHAN(CH%)
```

```
  CALL ADCONV(CH%, NC, VALUE)
```

```

PV1 = VALUE * 5 / 2048
P1 = 103.37 * (PV1 - 1)
'
'Read and convert value from P2
CH% = 4
CALL LOCKCHAN(CH%)
CALL ADCONV(CH%, NC, VALUE)
PV2 = VALUE * 5 / 2048
P2 = 103.37 * (PV2 - 1)
PRINT USING "PV1: ###.##, PV2: ###.##"; PV1; PV2
'
END SUB

```

```

*****

```

```

'

```

```

SUB SCROUT (CJC, T(), P1, P2, MDOT)

```

```

'

```

```

'This subroutine displays measured data on the screen.

```

```

'

```

```

LOCATE 4, 1

```

```

i = 0

```

```

'FOR J = 0 TO 15

```

```

FOR J = 0 TO 15

```

```

  PRINT USING "CH## M## = #####.# C."; i; J; T(i, J)

```

```

NEXT J

```

```

i = 1

```

```

FOR J = 0 TO 15

```

```

  LOCATE J + 4, 24

```

```

  PRINT USING "CH## M## = #####.# C."; i; J; T(i, J)

```

```

NEXT J

```

```

i = 2

```

```

FOR J = 0 TO 15

```

```

  LOCATE J + 4, 48

```

```

  PRINT USING "CH## M## = #####.# C."; i; J; T(i, J)

```

```

NEXT J

```

```

PRINT

```

```

PRINT USING "Cold junction temperature (CJC) = ###.# deg. C."; CJC

```

```

PRINT USING "P1 = ###.##, P2 = ###.###"; P1; P2

```

```

PRINT USING "MDOT = #.#####"; MDOT

```

```

'

```

```

END SUB

```

```

*****

```

```

',
SUB TEMPGET (NC, CJC, T())
',
'This subroutine converts and evaluates measured temperatures.
',
'Get cold junction compensation temperature.
CALL CJCGET(NC, CJC)
',
FOR CH% = 0 TO 2
',
'Lock DAS-8 on the one channel that EXP-16 is connected to.
CALL LOCKCHAN(CH%)
',
'Select each EXP-16 channel in and convert it.
'Digital outputs OP1-4 drive the EXP-16 sub-multiplexer address, so use
'mode 14 to set up the sub-multiplexer channel.
FOR MUX% = 0 TO 15
MD% = 14
CALL DAS8(MD%, VARPTR(MUX%), FLAG%) 'address set
IF FLAG% <> 0 THEN CALL ERRCODES(FLAG%)
',
'Now that channel is selected, perform A/D conversion using mode 4.
'Then transfer data to corresponding array element T(CH%,mux%).
CALL ADCONV(MUX%, NC, VALUE)
v = (VALUE * 5) / (AV(CH%) * 2048)
',
'Interpolate measured voltages to find K-type thermocouple
'temperatures.
CALL TEMPINTRP(v, CJC, TC)
T(CH%, MUX%) = TC
',
'Now repeat sequence for all other DAS-8 and EXP-16 channels.
NEXT MUX%
NEXT CH%
END SUB

'*****
',
SUB TEMPINTRP (v, CJC, TC)
'This subroutine interpolates measured voltages to find K-type
'thermocouple temperature.
',
'Entry variables:-

```

```

' CJC = cold junction compensator temperature in deg. C.
' V = thermocouple voltage in volts
Exit variables:-
' TC = temperature in degrees Centigrade
' TF = temperature in degrees Fahrenheit
Perform CJC compensation for K type
VK = 1000 * v + 1! + (CJC - 25) * .0405'VK in mV
'

Find look-up element
EK = INT((VK - SVK) / SIK)
IF EK < 0 THEN TC = TK(0): GOTO 51170'Out of bounds, round to lower limit
IF EK > NK - 2 THEN TC = TK(NK - 1): GOTO 51170'Out of bounds,round to upper limit
Do interpolation
TC = TK(EK) + (TK(EK + 1) - TK(EK)) * (VK - EK * SIK - SVK) / SIK'Centigrade
51170 TF = TC * 9 / 5 + 32'Fahrenheit
END SUB

```

APPENDIX B

This Appendix contains a listing of the program PASSCON.

PROGRAM PASSCON

```
*
*
*   This program simulates the natural circulation of a steam/air
*   mixture in the passive containment/slowpoke rig.
*
*
*   The following is the main calling routine.
*   It initializes and defines all the reference parameters
*   and performs the bisection algorithm to find a root
*   of the force balance equation.
*
  DIMENSION ZERO(3),FRIC(3),BUOY(3)
  DOUBLE PRECISION MDOT(3)
*
  INTEGER FNOD,K,M,NE,NEB,NOD,L,II
  INTEGER NODA,NODB,TIMEA,TIMEB,SS,FLAG,FLAG0,FLAG1,FLAG2
*
*
  REAL A,B,C,D,E,ACMIN,ADC,ADCWALL,AHT,AR,AW
  REAL DELTAIR,DIN,DL,DLID,DR,DT,DX,EPSS,FDCS,FINT,HGO
  REAL FRDC,G,HMT,HR,ID,KA,KC,KENT,KEXIT,LCOIL,LDC,LDCC,LR,LTP
  REAL
LW,MA,MS,MDOUT,MDA,MDS,MDT,MDSOLD,MSF,MSG,MDW,MDST,OD,PI,PA
  REAL MARIS,MSRIS,MSOLD,PS,PT,PWDC,RA,RS,ROC,ROS,RHO,SB,SHC,SHS
  REAL
MADOWN,MSDOWN,T,TAMB,TA,TB,TC,TD,TE,TH2O,THE,THL,TIME,TINF,TTANK
  REAL TAO,TBO,TCO,TDO,TEO,TLIDO,TRO,TWO,PTOLD,ERRP,MAXERP
  REAL TR,TW,V,VRIS,VDOWN,W,X,RHOA,RHOB,RHOC,RHOD,RHOE
  REAL MSROLD,MSDOLD,MRIS,MWAL,TCOOL
*
*   Definition of variables used in main calling routine:
*
*   B    = distance from tank bottom to riser exit (m)
*   C    = tank wall height (m)
*   D    = distance from tank bottom to coil bottom (m)
*   E    = distance from tank bottom to velocity duct outlet (m)
*   ACPIN = minimum flow area for both cooling coils (m^2)
*   ADC   = flow area of the downcomer (m**2)
*   ADCWALL = heat exchange area for the downcomer to surroundings
*           heat flow path (based on concrete wall I.D.) (m**2)
*   AHT   = Heat transfer area. (m**2)
```

- * AR = riser outer area (m**2)
- * AW = tank wall area (m**2)
- * DELT = Time step. (minutes)
- * DELTAIR = thickness of the air gap between the steel
liner and the concrete wall (m)
- * DIN = concrete wall diameter
- * DL = inside diameter of the tank
- * DLID = diameter of lid (m)
- * DR = diameter of riser (m)
- * DT = time step
- * DX = node distance (concrete)
- * EPSS = emissivity of stainless steel
- * ERRP = % change in pressure from last pressure iteration
- * FDCS = radiation interchange factor from the steel liner
wall to the surroundings
- * FINT = final time
- * FLAG1 = flag to turn on condenser coils calculation
- * FRDC = radiation interchange factor from the riser wall
to the stainless steel liner
- * G = acceleration due to gravity (m/s**2)
- * HGO = enthalpy of injected steam (J/kg.K)
- * HMT = cooling coil heat transfer coefficient (w/m^2 K)
- * HR = radiation heat trasnfer coefficient riser-tank
- * KA = Thermal conductivity of air at TF. (W/m.k)
- * KC = thermal conductivity of concrete
- * KENT = loss coefficient to account for entrance losses
to the core
- * KEXIT = loss coefficient to account for exit losses
from the core
- * LCOIL = total length of tubing in BOTH cooling coils (m)
- * LDC = length of downcomer wall through which heat
transfer occurs to the surroundings (m)
- * LR = length of riser through which heat flows (m)
- * LTP = length of the downcomer wall above the riser top (m)
- * LW = total length of wall (m)
- * M = counts time steps
- * MA = initial mass of air in volume (kg)
- * MARIS = mass of air in riser region (kg)
- * MADOWN = mass of air in downcomer (kg)
- * MAXERP = maximum error in pressure for pressure iteration
- * MDW = mass flowrate of cooling coil water (kg/s)
- * MLID = mass of lid (kg)
- * MS = mass of steam in volume (kg)
- * MSRIS = mass of steam in riser region (kg)
- * MSDOWN = mass of steam in downcomer (kg)

- * MSF = mass of water (kg)
- * MSG = mass of vapour (kg)
- * MD = Mass flow-rate. (kg/s)
- * MDST = steam injection rate (kg/s)
- * MRIS = mass of riser (kg)
- * MWAL = mass of tank wall (kg)
- * NOD = nod number
- * PI = 3.141593
- * PA = partial pressure of air (Pa)
- * PS = partial pressure of steam (Pa)
- * PT = total tank pressure (Pa)
- * PTOLD = pressure from previous iteration
- * PWDC = inside perimeter of downcomer
- * RA = air constant 287 J/kg*K
- * RS = steam constant 462 J/kg*K
- * ROC = concrete density (kg/m**3)
- * ROS = stainless steel density (kg/m**3)
- * RHO = initial relative humidity
- * SB = Stefan Boltzmann constant 5.699e-8 (W/m**2 K**4)
- * SHC = specific heat of concrete (J/m.K)
- * SHS = specific heat of 304 stainless steel (J/m.K)
- * SS = flag to set initial guesses at temperatures
- * TVOL = average temperature in tank, used in PRESSGET
- * TVOL = average tank temperature from previous time step
- * TAMB = ambient temperature
- * TA = temperature after steam injection in mixing node
- * TB = temperature at outlet of riser
- * TC = temperature at top of condenser coils
- * TD = temperature at bottom of condenser coils
- * TE = temperature at inlet to velocity duct
- * TAO,TBO, etc. = temperatures from previous time step.
- * TH2O = temperature of cooling coil water (K)
- * THE = thickness of tank wall (m)
- * THL = thickness of lid (m)
- * TIME = time
- * TCOOL = time at which the cooling water supply is turned on (s)
- * TINF = surface temperature of the concrete wall (K)
- * TR = temperature of the riser wall (K)
- * TTANK = temperature in riser pressure region, used in PRESSGET (K)
- * TW = temperature of the tank wall (K)
- * V = volume of tank (m^3)
- * VRIS = volume of riser and region above riser (m^3)
- * VDOWN = volume of downcomer region (m^3)
- * W = width of the riser
- * XVOL = cumulative fraction of injected steam condensed

* XA,XB,ETC. = fraction of steam condensed at various points

* -----

*

```
COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,PSR,PSSR
COMMON /DC/ LDCC,LDC,ADC,DELTAIR,ADCWALL,FDCS,LTP
COMMON /PROPS/ G,SB,PI
COMMON /INJEC/ MDST,HGO
COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR
COMMON /EXES/ RHOA,RHOB,RHOC,RHOD,RHOE
COMMON /COIL/ MDW,ACMIN,LCOIL,TH2O,ID,OD,HMT
COMMON /TEMPS/ TA,TB,TC,TD,TE,TW,TR,TAMB,TLID
COMMON /OLDTEMP/ TAO,TBO,TCO,TDO,TEO,TRO,TWO,TLIDO,TVOLD,XVOLD
COMMON /OLDMASS/ MSOLD,MSDOLD,MSROLD
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
COMMON /CONTR2/ ROC,SHC,KC,DX,DIN,SHS,MLID,MRIS,MWAL
COMMON /HTCS/ HTCOIL,HTCWAL,HTCRIS,HTCRIS2
COMMON /FLAGS/ FLAG0,FLAG1
COMMON /EMISS/ EPSS
```

*

* Set input data.

*

* Constants

ACMIN=0.024

A=.2

B=1.048

C=1.22555

D=0.85

E=0.1

CP=1010.

DIN=0.54

DL=0.44

DLID=0.7

DR=0.229

EPSC=0.9

EPSS=0.95

FLAG0=0

FLAG1=0

FNOD=11

G = 9.8

ID=0.01

KC=1.4

KENT = 0.5

KEXIT = 1.0

LCOIL=2.6

LW=1.22555

M=1
 MD=0.00045
 MAXERP=0.01
 N=20
 OD=0.0125
 PI=3.141593
 RA=462
 RS=287
 ROC=2500
 ROS=5000
 SB = 5.669E-8
 SHC=880
 SHS=450
 SS=1
 STIME = 0.
 THE=0.002
 THL=0.0097
 TIME=0
 V=0.186

*

PA=101350.
 PS=0.

*

*

LDC = D
 LTP = C-B
 LDCC = LDC
 $ADC = \pi(DL^2)/4 - \pi(DR^2)/4$
 $PWDC = \pi DL$
 $DELTAIR = (DIN - (DL + 2*THE))/2$

*

$ADCWALL = \pi DIN LDCC$

*

LR = B-E
 $AR = \pi DR LR$
 LW = D
 $AW = \pi DL LW + \pi(DL/2)^2$
 $VRIS = (\pi/4) DR^2 LR + (\pi/4) DL^2 LTP$
 $VDOWN = V - VRIS$
 $MLID = ROS \pi DLID THL$
 $MRIS = ROS 0.0005 DR \pi LR$
 $MWAL = ROS THE DL \pi LW$

*

* Get radiation interchange factors, calculated in sub-routine RINTRF

*

```

CALL RINTRF(FDCS,FRDC)
*
*
WRITE(*,*) 'ENTER UPPER LIMIT OF TIME INTERVAL (SEC): '
READ(*,*) FINT
*
*
WRITE (*,*) 'ENTER TIME TO TURN ON COOLING WATER (SEC): '
READ (*,*) TCOOL
*
*
WRITE (*,*) 'ENTER AN AMBIENT TEMPERATURE: (C)'
READ (*,*) TAMBC
*
TAMB = TAMBC+273.
*
WRITE (*,*) 'ENTER STEAM PRODUCTION RATE IN KG/S: '
READ (*,*) MDST
*
WRITE (*,*) 'ENTER THE ENTHALPY OF THE STEAM KJ/KG: '
READ (*,*) HGO
HGO=HGO*1000.

L=N+1
*
*   II is counter of readjustments of mass flow rate initial guess.
II=1
*
*   Input temperature of the concrete.
*
TINF=TAMB
TINFC=TINF-273.
*
*   -----
*
WRITE (11,799)
799 FORMAT (' TIME   AIR PP   STEAM PP   TOTAL P   PSAT',/)
WRITE (12,798)
798 FORMAT (' TIME   MDA     MDS     MDT   ',
1  'MS',/)
WRITE (14,797)
797 FORMAT (' TIME   MSRIS   MSDOWN   MDOUT   PSR   ',
1  'PSSR',/)
WRITE (15,796)
796 FORMAT (' TIME   HTCOIL   HTCWAL   HTCRIS',/)
WRITE (16,795)

```

```
795 FORMAT (' TIME   TA      TB      TC      TD   ',  
1   'TE   TR   TW'./)
```

*

* The following are initial values for temperatures in K.

*

TAO=TAMB

TA=TAO

TBO=TAMB

TB=TBO

TCO=TAMB

TC=TCO

TDO=TAMB

TD=TDO

TEO=TAMB

TE=TEO

TW=TAMB

TWO=TW

TLIDO=TAMB

TRO=TAMB

TR=TRO

MDW=1.

TH2O=293

HTCRIS2=0.

MDS=0.

XVOL=1.

TVOL=TAO

MDSOLD=MDS

QOUT=0.

MDOUT=0.

PT=PA+PS

MDT=MDA+MDS

HMT=0.

*

* Time step control here, time step = 5 seconds

*

DT=5.

*

* Calculate initial partial pressures of steam and air.

*

RHO=0.3

MA=PA*V/(RA*TAMB)

```

CALL PSAT(PSSO,TAMB)
PS=RHO*PSSO
MS=PS*V/(RS*TAMB)
MARIS=MA*(VRIS/V)
MSRIS=MS*(VRIS/V)
MSDOWN=MS-MSRIS
MSG=MS
MSF=0.
PTOLD=PA+PS
TVOLD=TAMB
MSOLD=MS
MSDOLD=MSDOWN
MSROLD=MSRIS
XVOLD=XVOL
XEOLD=0.

```

```

*
WRITE (11,800) TIME,PA/1000.,PS/1000.,PT/1000.,PSSO/1000.
WRITE (12,801) TIME,MDA,MDS,MDT,MS
WRITE (14,802) TIME,MSRIS,MSDOWN,MDOUT,PSR,PSSR
WRITE (15,803) TIME,HTCOIL,HTCWAL,HTCRIS
WRITE (16,804) TIME,TA-273.,TB-273.,TC-273.,TD-273.,
1  TE-273.,TR-273.,TW-273.

```

```

*
*
*****
444  CONTINUE

```

```

FLAG0=FLAG0+1
IF (FLAG0.GT.2) THEN
  FLAG0=5
ENDIF

```

```

*
* Initialization of guesses for mixture mass flow rate. MDOT(1) and
* MDOT(3) represent the high and low limits of the interval
* that contains a root of the force balance. For each guess
* a call is made to subroutine FBAL to calculate the value of
* the force balance at the guess. The residues are then stored
* in ZERO(1) and ZERO(3) respectively.

```

```

IF (I.LEQ.1) THEN
99  MDOT(2)=0.0001
    MDOT(1)=0.8*MDOT(2)
    MDOT(3)=5.00*MDOT(2)

```

```

ELSE
MDOT(2)=0.0001+(II-1)*0.0001
MDOT(1)=0.8*MDOT(2)
MDOT(3)=5.0*MDOT(2)
ENDIF

```

*

```

CALL FBAL(MDOT(1),MDS,FRIC(1),BUOY(1),ZERO(1),QOUT,MDOUT)
CALL FBAL(MDOT(3),MDS,FRIC(3),BUOY(3),ZERO(3),QOUT,MDOUT)

```

*

* Check to make sure that the interval contains a root
 * using subroutine CHECKROOT. This subroutine adjusts
 * mixture mass flow rate if the root is not found.

*

```

CALL CHECKROOT(MDOT(1),MDOT(3),MDS,ZERO(1),ZERO(3),QOUT,MDOUT,
1      FRIC(1),FRIC(3),BUOY(1),BUOY(3),II)

```

*

* Begin the iteration procedure. The new guess, MDOT(2),
 * is the midpoint of the interval.

*

```

WRITE (13,*) 'START MIXTURE FLOWRATE ITERATION'
1 MDOT(2) = (MDOT(1) + MDOT(3))/2
CALL FBAL(MDOT(2),MDS,FRIC(2),BUOY(2),ZERO(2),QOUT,MDOUT)

```

*

* A guess for mixture mass flow that is too high makes frictional
 * effects greater than the buoyant ones. This makes the
 * residue of the force balance negative. Of course, the
 * opposite is true if the guess is too low. In the next
 * segment, either the high or low end of the interval is
 * replaced with the value of the current guess. Thus, the
 * size of the interval is decreased with each iteration.

*

```

IF (ZERO(2) .LT. 0) THEN
MDOT(3) = MDOT(2)
ZERO(3) = ZERO(2)
ELSE
MDOT(1) = MDOT(2)
ZERO(1) = ZERO(2)
ENDIF

```

*

* Check to see if the tolerance for a root is met.

*

```

IF (ABS(MDOT(3)-MDOT(1)) .GT. 0.00000001) THEN
GOTO 1
ELSE
ENDIF

```

```

MDA=MDOT(1)
*
*   Once this point is reached the force balance has been
*   satisfied.
*
WRITE (13,*) 'END FLOWRATE ITERATION'
WRITE (13,*)
II=1
*
PT=PA+PS

*   Update time.

189 M=M+1
TIME=TIME+DT
*
*   Update temperatures, steam flowrate

WRITE (13,*) 'PROCEED TO NEXT TIME STEP'
WRITE (13,*) 'TIME: ',TIME
WRITE (13,*)
WRITE (13,*) '----->'
WRITE (13,*)
28 WRITE(*,*) 'M-----> ',M,TIME
IF (TIME.GE.TCOOL) THEN
  FLAG1=FLAG1+1
ENDIF
IF (FLAG1.GT.7) THEN
  FLAG1=7
ENDIF
TAO=TA
TBO=TB
TCO=TC
TDO=TD
TEO=TE
TLDO=TLID
TRO=TR
TWO=TW
XVOLD=XVOL
TVOLD=TVOL
MSROLD=MSRIS
MSDOLD=MSDOWN
MSOLD=MS
*

```


* Output the results of each time step.

```
MDT=MDA+MDS
CALL PSAT(PSSO,TA)
WRITE (11,800) TIME,PA/1000.,PS/1000.,PT/1000.,PSSO/1000.
800 FORMAT (F8.2,2X,F8.1,2X,F8.1,2X,F8.1,2X,F8.1)
WRITE (12,801) TIME,MDA,MDS,MDT,MS
801 FORMAT (F8.2,2X,F8.6,2X,F8.6,2X,F8.6,2X,F8.6)
WRITE (14,802) TIME,MSRIS,MSDOWN,MDOUT,PSR,PSSR
802 FORMAT (F8.2,2X,F8.6,2X,F8.6,2X,F8.6,2X,F8.2,2X,F8.2)
WRITE (15,803) TIME,HTCOIL,HTCWAL,HTCRIS
803 FORMAT (F8.2,2X,F8.2,2X,F8.2,2X,F8.2)
WRITE (16,804) TIME,TA-273.,TB-273.,TC-273.,TD-273.,
1 TE-273.,TR-273.,TW-273.
804 FORMAT (F8.2,2X,F8.2,2X,F8.2,2X,F8.2,2X,F8.2,2X,F8.2,
1 2X,F8.2)
```

* Check if final time has elapsed; continue loop

```
IF (TIME.LE.FINT) THEN
  GOTO 444
ENDIF
```

```
*
899 FORMAT(/)
```

*

```
END
```

*

```
* *****
```

```
* SUBROUTINES :
```

```
* *****
```

```
* *****
```

```
SUBROUTINE CHECKROOT(ML,MH,MDS,ZL,ZH,QOUT,MDOUT,FRL,FRH,
1 BOYL,BOYH,I)
```

*

* This subroutine is used to check that a root of the force
* balance equation exists within the interval ML to MH. If
* the root does not exist in the interval, the subroutine
* adjusts the initial guess.
* Variables passed are:

*

* BOYL,BOYH = value of the buoyant pressure term at ML
* and MH respectively (Pa)

* FRL,FRH = value of the frictional pressure term at

```

*      ML and MH respectively (Pa)
*      MDS = steam flow rate (kg/s)
*      ML,MH = low and high ends of the interval (kg/s)
*      TH,TR = core outlet and inlet temperatures respectively (K)
*      ZL,ZH = residues of the force balance at ML and MH (Pa)
*
IMPLICIT LOGICAL (A-Z)
*
INTEGER I
DOUBLE PRECISION ML,MH,MDOT
*
REAL BOYH,BOYL,FRH,FRL,ZH,ZL,QOUT,MDOUT
*
10 IF ((ZL/ZH) .LT. 0) THEN
  CONTINUE
ELSE
  WRITE(*,*) 'INTERVAL DOES NOT CONTAIN A ROOT'
  WRITE(*,*) 'CURRENT LOW END IS ',ML,' LOW RESIDUE IS ',ZL
  WRITE(*,*) 'CURRENT HIGH END IS ',MH,' HIGH RESIDUE IS ',ZH
  I=I+1
  MDOT=0.0001+(I-1)*0.0001
  ML=0.8*MDOT
  MH=5.0*MDOT
  CALL FBAL(ML,MDS,FRL,BOYL,ZL,QOUT,MDOUT)
  CALL FBAL(MH,MDS,FRH,BOYH,ZH,QOUT,MDOUT)
  GOTO 10
ENDIF
RETURN
END
*

* *****
* SUBROUTINE FBAL(MDA,MDS,FRD,BOY,BAL,QOUT,MDOUT)
*
* This subroutine is used to calculate the frictional and
* buoyant pressure terms for a given mass flow rate. These
* are then used in the force balance. The passed arguments
* are defined below:
*
* BAL = difference between BOY and FR. Yields zero
*       when the force balance is satisfied.
* BOY = buoyant pressure term (Pa)
* FRD = frictional pressure term (Pa)
* MDT = mixture mass flow rate (kg/s)
* MDS = steam mass flow rate (kg/s)

```

* QOUT = energy removed from system during time step.

*

*

* In addition, some variables are passed via COMMON blocks.

* These are defined in the main calling routine.

*

* Declarations and initializations

*

DOUBLE PRECISION MDA

REAL QOUT,MDOUT,BAL,BOY,FR,FRED,KINFD,LD,WD,DEMD

REAL AMD,MUA,MUS,MUM,DUMMY,RED,XPD,KCD,KEND,KEXID,RCD

REAL FRD,PA,ROAA,ROAS,ROBA,ROBS,VELS,VELA

REAL ROCA,ROCS,RODA,RODS,RHOA,RHOB,RHOC,RHOD,RHOE

REAL ROEA,ROES,TA,TB,TC,TD,TE,MOM,MDT,MDS,MDST

REAL MA,MS,RA,RS,PS,MSF,MSG,TVOL,XVOL

REAL TW,TR,TAMB,TLID,G,SB,PI,DT,DL,DR,ARIS,ADC

REAL MSRIS,MSDOWN,ACMIN,TH2O,OD,ST,N,GMAX,MUB,MUW

*

COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL

COMMON /TEMPS/ TA,TB,TC,TD,TE,TW,TR,TAMB,TLID

COMMON /PROPS/ G,SB,PI

COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2

COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR

COMMON /INJEC/ MDST,HGO

COMMON /COIL/ MDW,ACMIN,LCOIL,TH2O,ID,OD,HMT

*

* Preliminary evaluation of the temperatures required for the
* buoyant term is done in subroutine TEMPGET. Densities are
* calculated using the perfect gas relationship, which is
* installed in subroutine RHOGET.

*

* Calculate the flowrates of the air and steam, which are related
* by their partial pressures.

*

* $MDS = MDT / (1 + (RS/RA) * (PA/PS))$

* $MDA = MDT - MDS$

$RHOA = PA / (RA * TA)$

$VELA = MDA / (RHOA * (PI/4) * DR ** 2)$

$VELS = VELA$

$ROAS = MSRIS / VRIS$

$MDS = ROAS * (PI/4) * DR ** 2 * VELS$

$MDT = MDA + MDS$

WRITE (13,*) 'FBAL: GUESS AT MIXTURE FLOWRATE: ',MDT

*

50 CALL TEMPGET(MDA,MDS,QOUT,MDOUT)

*

*

PT=PA+PS

* Initialize constants for Shah's correlation.

*

FRED=14.227

KINFD=1.43

CD=0.00029

*

* Initialize dimensions of the velocity duct.

* LD = length

* WD = width

* DEMD = hydraulic diameter

* AMD = cross-sectional area

*

LD=0.1

WD=0.03

DEMD=0.03

AMD= 0.0009

*

RHOA=PA/(RA*TA)

RHOB=PA/(RA*TB)

RHOC=PA/(RA*TC)

RHOD=PA/(RA*TD)

RHOE=PA/(RA*TE)

* Calculate Reynold's Number for Velocity Duct

*

* Based on the value of Reynolds number, find the pressure

* loss coefficient representing frictional effects

* in the velocity duct KCD using Shah's correlation.

*

CALL MUGET (MUA,MUS,TE)

RED=MDA*DEMD/(AMD*MUA)

XPD=LD/(DEMD*RED)

KCD=(3.44*XPD**(-0.5)+(KINFD/(4*XPD)+FRED-3.44*XPD**(-0.5))

1/(1+CD*XPD**(-2)))/RED

*

*

* Find the pressure loss coefficient for the velocity duct.

*

KEND=0.55

```

KEXID=0.7
RCD=(KEND+KEXID+(4*KCD*LD/DEMD))/(AMD**2)
*
* Find the frictional pressure loss FRD for the duct
*
* WRITE (13,*) 'RCD: ',RCD,' MDA: ',MDA,' RHOE: ',RHOE
FRD=RCD*(MDA**2)/(2*RHOE)
*
* Find the friction factor for the condenser coils.
*
CALL MUGET (MUB,DUMMY,TC)
ST=0.03
GMAX=MDA/ACMIN
F=(0.25+(0.118/((ST/OD)-1)**1.08))*(GMAX*OD/MUB)**(-0.16)
*
* Find the loss for the coil.

N=4.
FRC=(F*GMAX**2*N/RHOC)*(MUW/MUB)**0.14

* Find the buoyant pressure gain, BOY.
*

BOY=(G/2)*(RHOD*(B-E)+RHOE*(D-A)-RHOB*(D-A)-RHOA*(B-E))
*
* Find the momentum pressure term
*

ADC=(PI/4)*(DL**2-DR**2)
ARIS=PI*DR**2/4
MOM = ((MDA)**2)*(1/RHOB - 1/RHOA)/(ARIS**2) +
1 ((MDA)**2)*(1/RHOC - 1/RHOE)/(ADC**2)
*

CC=.6
BAL = BOY - (CC*(FRD+FRC)) - MOM
WRITE (13,*) 'BOY: ',BOY,' FR: ',CC*(FRD+FRC),' MOM: ',MOM
*
RETURN
END
*
*
* *****

```

SUBROUTINE HRGET(T1,T2,FINT,HR)

This subroutine is used to find the radiation heat transfer coefficient to account for radiation heat losses from the steel liner to the surroundings. The passed variables are

FINT = radiation interchange factor between the bodies
HR = the radiation heat transfer coefficient (W/m**2 K)
T1 = temperature of body 1 (K)
T2 = temperature of body 2 (K)

REAL CP,FINT,G,HR,SB,T1,T2

COMMON /PROPS/ G,SB,PI

HR = SB*FINT*(T1 + T2)*(T1**2 + T2**2)

RETURN
END

SUBROUTINE CPGET(CPA,CPS,TEMP)

This subroutine is used to find the heat capacity at constant pressure for steam and air.

REAL TEMP,CPA,CPS

CPA=975.62+0.05033*TEMP+0.0001267*TEMP**2
CPS=3756-8.774*TEMP+0.01377*TEMP**2-6.619E-6*TEMP**3
RETURN
END

SUBROUTINE KGET(CONDA,CONDS,TEMP)

This subroutine is used to calculate the thermal conductivity of steam/air using a quadratic fit to tabulated data between 250 and 2000 K. Units are W/m K.

IMPLICIT LOGICAL (A-Z)

REAL TEMP,CONDA,CONDS

CONDA = 0.00963 + 6.102E-5*TEMP - 2.509E-9*TEMP**2

```
CONDS = 0.002434 + 0.0000507*TEMP + 2.542E-8*TEMP**2
RETURN
END
```

*

* *****

```
SUBROUTINE MUGET(VISCA,VISCS,TEMP)
```

*

* This subroutine is used to calculate the dynamic viscosity
* of steam/air using a quadratic fit to tabulated data between
* 250 and 2000 K. Units are kg/m s.

*

```
IMPLICIT LOGICAL (A-Z)
```

*

```
REAL TEMP,VISCA,VISCS
```

*

```
VISCA=(0.7664 + 0.004003*TEMP - 5.867E-7*TEMP**2)/1E5
```

```
VISCS=9.637E-7+3.596E-8*TEMP+1.343E-13*TEMP**2-4.06E-17*TEMP**3
```

```
RETURN
```

```
END
```

*

*

* *****

```
SUBROUTINE PRGET(PRA,PRS,TEMP)
```

*

* This subroutine is used to calculate the Prandtl number of
* air using a quadratic fit to tabulated data between 250 and
* 2000 K.

*

```
IMPLICIT LOGICAL (A-Z)
```

*

```
REAL TEMP,PRA,PRS,CPS,MUS,KS
```

*

```
CPS=3756-8.774*TEMP+0.01377*TEMP**2-6.619E-6*TEMP**3
```

```
MUS=9.637E-7+3.596E-8*TEMP+1.343E-13*TEMP**2-4.06E-17*TEMP**3
```

```
KS=.002434+0.0000507*TEMP+2.542E-8*TEMP**2
```

```
PRS=CPS*MUS/KS
```

```
PRA = 0.6962 - 1.086E-5*TEMP + 9.059E-9*TEMP**2
```

```
RETURN
```

```
END
```

*

* *****

```
SUBROUTINE RHOGET(DENSA,DENSS,TEMP,X)
```

*

* This subroutine calculates the density of the mixture assuming
* a constant total tank pressure.

```

*
*
*
  IMPLICIT LOGICAL (A-Z)
*
  REAL DENSA,DENSS,TEMP,MA,MS,RA,RS,PA,PS,DUMMY,SPVS
  REAL MSF,MSG,TVOL,XVOL,X,PAR,PSR,PT,VRIS
*
  COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL
  COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR

  PT=PA+PS
  PSR=X*MS*TEMP*RS/VRIS
  DENSS=PSR/(RS*TEMP)
  PAR=PT-PSR
  DENSA=PAR/(RA*TEMP)

  RETURN
  END
*
* *****
  SUBROUTINE SPVOLS(SPVOLF,SPVOLG,TEMP)
*
*   This subroutine calculates the specific volume of
*   saturated steam (m3/kg). The equations are from Irvine
*   & Liley. (1984)
*
  IMPLICIT LOGICAL (A-Z)
*
  REAL SPVOLF,SPVOLG,TEMP,PS1,PCR,TC,TCR
*
  TCR=647.3
  TC=(TCR-TEMP)/TCR
  CALL PSAT(PS1,TEMP)
  PCR=22089000

  SPVOLF=3.155E-3*(1.-1.915388*TC**(1./3)+12.0152*TC**(5./6)
1  -7.8464*TC**(7./8)-3.888614*TC+2.058224*TC**2
2  -2.082999*TC**3+0.8218*TC**4+0.475497*TC**5)

  SPVOLG=(69690.8/PS1)*(1.+1.6351*TC**(1./3)+52.58446*TC**(5./6)
1  -44.69465*TC**(7./8)-8.97511*TC-0.438455*TC**2
2  -19.17958*TC**3+36.7653*TC**4-19.46244*TC**5)

  RETURN

```


END

*

*

* *****

SUBROUTINE RHOG(DENSG,TEMP)

*

* This subroutine calculates the density of saturated steam
* in kg/m³ at a given temperature

*

IMPLICIT LOGICAL (A-Z)

*

REAL DENSG,TEMP,SPVG,DUMMY

*

CALL SPVOLS(DUMMY,SPVG,TEMP)

DENSG=1/SPVG

RETURN

END

*

* *****

SUBROUTINE PSAT(P,TEMP)

*

* This subroutine is used to calculate the saturation pressure
* of steam (Pa) at a given temperature. From Irvine & Liley (1984).

*

IMPLICIT LOGICAL (A-Z)

*

REAL P,TEMP

*

P=1.E6*EXP(-3892.7/(TEMP-42.6776)+9.48654)

RETURN

END

*

*

* *****

SUBROUTINE UGET(UF,UG,TEMP)

*

* This subroutine is used to calculate internal energies
* using U=E-Pv.

*

IMPLICIT LOGICAL (A-Z)

*

REAL UF,UG,TEMP,HF,HG,HFG,PST,SPVF,SPVG

*

CALL ENGET(HF,HG,HFG,TEMP)

CALL PSAT(PST,TEMP)

```

CALL SPVOLS(SPVF,SPVG,TEMP)
UF=HF-PST*SPVF
UG=HG-PST*SPVG
RETURN
END

```

*

* *****

```

SUBROUTINE ENGET(HF,HG,HFG,TEMP)

```

*

* This subroutine is used to calculate the enthalpies of steam
 * at a given temperature. Enthalpies in J/kg. Equations are
 * from Irvine & Liley (1984)

*

```

IMPLICIT LOGICAL (A-Z)

```

*

```

REAL TEMP,HF,HG,HFG,TC,TCR

```

*

```

TCR=647.3

```

```

TC=(TCR-TEMP)/TCR

```

```

HF=2.0993E6*(0.883923-2.67173*TC+6.2264*TC**2-13.179*TC**3
1 -1.91322*TC**4+68.79377*TC**5-124.8199*TC**6+72.144*TC**7)

```

```

HG=2.0993E6*(1.+457874*TC**(1./3.)+5.0844129*TC**(5./6.)
1 -1.485132*TC**(7./8.)-4.813519*TC+2.694118*TC**2
2 -7.390645*TC**3+10.496169*TC**4-5.4684*TC**5)

```

```

HFG=HG-HF

```

```

RETURN

```

```

END

```

*

* *****

```

SUBROUTINE BETA(BETAS,TEMP)

```

*

* This subroutine calculates the volume coefficient of
 * expansion of steam at different temperatures. The line
 * was fitted to data from WATERPRO property tables.

*

```

IMPLICIT LOGICAL (A-Z)

```

*

```

REAL BETAS,TEMP

```

*

```

BETAS=0.12416-2.19E-4*TEMP

```

```

RETURN

```

```

END

```

*

```

* *****
SUBROUTINE RHOWGET(ROW,TEMP)
*
*   This subroutine calculates the density of water. (kg/m^3)
*
IMPLICIT LOGICAL (A-Z)
*
REAL ROW,TEMP
*
ROW=997.4
RETURN
END
*
* *****
SUBROUTINE MUWGET(MUW,TEMP)
*
*   This subroutine calculates the viscosity of water.(KG/M.S)
*
IMPLICIT LOGICAL (A-Z)
*
REAL MUW,TEMP
*
MUW=9.8E-4
RETURN
END
*
* *****
SUBROUTINE KWGET(KW,TEMP)
*
*   This subroutine calculates the thermal conductivity
*   of water (W/mK)
*
IMPLICIT LOGICAL (A-Z)
*
REAL KW,TEMP
*
KW=0.604
RETURN
END
*
* *****
SUBROUTINE PRWGET(PRW,TEMP)
*
*   This subroutine calculates the Prandtl number of water.
*

```

IMPLICIT LOGICAL (A-Z)

*

REAL PRW,TEMP

*

PRW=6.78

RETURN

END

*

SUBROUTINE LAMCORE(RE,L,D,KFRIC)

*

* This subroutine is used to calculate the friction loss
* coefficient for a pipe of diameter D and length L
* under laminar flow conditions.

*

IMPLICIT LOGICAL (A-Z)

*

REAL D,KFRIC,L,RE

*

KFRIC = $64 * L / (D * RE)$

RETURN

END

*

*

*

*

SUBROUTINE UNCCOND(T,TWALL,LWALL,AWALL,MDT,AV,DC,MSU
1 ,MAU,VOL,U,MDC)

*

* This subroutine calculates the equivalent heat transfer
* coefficient for condensation of steam in the presence
* of air on a vertical wall. It assumes that the interface
* temperature equals the wall temperature.

*

* Tinf = temperature of mixture

* Ti = temperature of liquid/vapour interface

* Pvinf = pressure of steam in mixture

* Pvi = pressure of steam at interface (=saturation P)

* Pai = pressure of air at interface

* Pam = log mean of air pressure in mixture and interface

*

*

REAL T,TWALL,AWALL,PT,PA,X,TI,UNC,HCON,HMT,HNC,MDC,TINF
REAL PVINF,PVI,TV,TF,PVV,PAI,PAM,RHOGVV,RHOGA,RHOGV

```

REAL RGVINF,RHOGVI,CPA,CPS,CPV,MUA,MUS,MUV,KA,KS,KV
REAL PRV,BETAA,BETAS,GRV,C1,N,GRKV,DV,DT,SCV,SHV
REAL KNC,HFV,HGV,HFGV,HFF,HGF,HFGF,Q,LWALL,HMT1,HMT2
REAL MA,MADOWN,MS,RA,RS,PS,MSF,MSG,TVOL,XVOL,G,SB,PI
REAL V,DL,DR,A,B,C,D,E,LW,LR,AW,AR,MAU,MSU,VOL,FF
REAL XGB,XGI,MG,MV,GAMMA,MDT,AV,DC,HC,DELTAT

```

```

COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL
COMMON /PROPS/ G,SB,PI
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR

```

*

```

WRITE (13,*) 'SUBROUTINE UNCCOND'
TINF=T
TI=TWALL

```

*

```

PT=PA+MSU*RS*TINF/VOL
CALL PSAT(PVI,TI)

```

```

TV=(TI+TINF)/2

```

*

```

CALL PSAT(PVIN,TV)

```

*

```

WRITE (13,*) 'MSU: ',MSU,' VOL: ',VOL,' RS: ',RS
PVIN=MSU*RS*TINF/VOL
TF=TWALL+0.25*(TI-TWALL)
PVV=ABS((PVIN-PVI)/(LOG(PVIN/PVI)))
PAI=PT-PVI
PAM=(PAI-PA)/(LOG(PAI/PA))

```

*

```

determine mixture properties in steam depleted layer

```

*

```

CALL RHOG(RHOGVV,TV)
RHOGVV=PVV/(RS*TV)
RHOGA=PAM/(RA*TV)
RHOGV=RHOGA*(PAM/PT)+RHOGVV*((PT-PAM)/PT)
CALL RHOG(RGVINF,TINF)
CALL RHOG(RHOGVI,TI)
CALL CPGET(CPA,CPS,TV)
CPV=CPS*RHOGVV/RHOGV+CPA*RHOGA/RHOGV
CALL MUGET(MUA,MUS,TV)
MUV=MUS*RHOGVV/RHOGV+MUA*RHOGA/RHOGV
CALL KGET(KA,KS,TV)
KV=KS*RHOGVV/RHOGV+KA*RHOGA/RHOGV
PRV=CPV*MUV/KV
BETAA=1/TV

```

CALL BETA(BETAS,TV)
BETA V=BETAS*PVV/PT+BETAA*PAM/PT

- * calculate natural convection htc for air
- * Grashof number formulation from Green and Almenas.

XGB=MAU/(MAU+MSU)
XGI=PAI*RS/(PVI*RA+PAI*RS)
MG=29.
MV=18.
GAMMA=1/(MG/(MG-MV)-XGB)

GRV=G*LWALL**3*RHOGV**2*(BETA V*(TINF-TI)+GAMMA*(XGI-XGB))/MUV**2

IF (GRV.GE.1E9) THEN
C1=0.1
N=1./3.
ELSE
C1=0.59
N=1./4.
ENDIF
HNC=C1*(ABS(GRV*PRV))**N*KV/LWALL

- * calculate forced convection htc for air and compare with
- * HNC, choose higher value.

UV=MDT/(RHOGV*AV)
REV=RHOGV*UV*DC/MUV
HFC=0.037*REV**(4./5.)*PRV**(1./3.)*KV/DC
IF (HNC.GT.HFC) THEN
HC=HNC
ELSE
HC=HFC
ENDIF

- * determine mass transfer-heat transfer coefficient using
- * heat to mass transfer analogy, from Collier 10.3.4.
- * Geankopolis diffusivity

DV=(2.20*1E-5)*(101350/PT)*(TV/273.)**1.75
SCV=MUV/(RHOGV*DV)

```
KNC=(HC/(CPV*RHOGV))*(PRV/SCV)**(2./3.)
CALL ENGET(HFV,HGV,HFGV,TV)
```

```
* calculate overall htc
```

```
* WRITE (13,*) 'PVINF: ',PVINF,' PVI: ',PVI
HMT=HNC+KNC*HFGV*RHOGVV*(PVINF-PVI)/((TINF-TI)*PAM)
```

```
* Uchida correlation
```

```
* HMT=380.*(MAU/MSU)**(-0.7)
```

```
FF=1.4
UNC=FF*HMT
U=UNC
Q=UNC*(TINF-TWALL)*AWALL*DT
MDC=AWALL*DT*(TINF-TI)*(HMT-HNC)/HFGV
IF (MDC.LT.0.) THEN
  MDC=0.
ENDIF
```

```
WRITE (13,*) 'UNC: ',UNC,' MDC: ',MDC
```

```
*
```

```
57 RETURN
```

```
END
```

```
*
```

```
*****
```

```
SUBROUTINE RISER(TINF,TR,MSU,MAU,VOL,LR,AR,MDT,AV,DC,U)
```

```
*
```

```
* This subroutine calculates the heat transfer from the outside
* surface of the riser.
```

```
*
```

```
REAL TINF,TR,QR,TAVE,PC,PAI,PAM,CPA,CPS,KA,KS,C1
REAL MUA,MUS,RHOA,RHOS,RHOMIX,CPMIX,KMIX,MUMIX,N
REAL BETAA,BETAS,BETAM,PVV,MA,MS,RA,RS,PA,PS,PT
REAL MSF,MSG,TVOL,XVOL,PS1,G,SB,PI,DT,LR,AR
REAL GR,PRMIX,GRPR,HR,U,MSU,MAU,HFC,REV,UV
```

```
*
```

```
COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL
COMMON /PROPS/ G,SB,PI
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
```

```
*
```

```
WRITE (13,*) 'SUBROUTINE RISER'
```

```

*   WRITE (13,*) 'TINF: ',TINF,' TR: ',TR,' MSU: ',MSU
*   WRITE (13,*) 'MAU: ',MAU,' VOL: ',VOL,' LR: ',LR
*   WRITE (13,*) 'AR: ',AR

IF (TINF.EQ.TR) THEN
  U=0.
  GOTO 12
ENDIF

TAVE=(TINF+TR)/2.
PS=MSU*RS*TAVE/VOL
PT=PS+PA
CALL CPGET(CPA,CPS,TAVE)
CALL KGET(KA,KS,TAVE)
CALL MUGET(MUA,MUS,TAVE)
RHOA=MAU/VOL
RHOS=MSU/VOL
CALL BETA(BETAS,TAVE)
BETAA=1/TAVE
RHOMIX=RHOA*PA/PT+RHOS*PS/PT
CPMIX=(RHOA*CPA+RHOS*CPS)/RHOMIX
KMIX=(RHOA*KA+RHOS*KS)/RHOMIX
MUMIX=(RHOA*MUA+RHOS*MUS)/RHOMIX
BETAM=BETAS*PS/PT+BETAA*PA/PT
*
*   Find the Grashof number for the riser, GR, and the product of
*   GR and the Prandtl number, PRMEAN.
*
*   WRITE (13,*) 'G: ',G,' BETAM: ',BETAM,' RHOMIX: ',RHOMIX
*   WRITE (13,*) 'MUMIX: ',MUMIX,' CPMIX: ',CPMIX,' KMIX: ',KMIX

GR=G*BETAM*ABS(TR-TINF)*LR**3*RHOMIX**2/MUMIX**2
PRMIX=CPMIX*MUMIX/KMIX
GRPR = GR*PRMIX

IF (GR.GE.1E9) THEN
  C1=0.1
  N=1./3.
ELSE
  C1=0.59
  N=1./4.
ENDIF
HNC=C1*(GRPR)**N*KMIX/LR

```


* Calculate force convection coefficient, if higher than natural, replace

```
UV=MDT/(RHOMIX*AV)
REV=RHOMIX*UV*DC/MUMIX
HFC=0.037*REV**(4./5.)*PRMIX**(1./3.)*KMIX/DC
IF (HNC.GT.HFC) THEN
  HR=HNC
ELSE
  HR=HFC
ENDIF
QR=HR*AR*(TR-TINF)*DT
WRITE (13,*) 'HR: ',HR
U=HR
12 RETURN
END
```

*

```
SUBROUTINE WALL(TINF,TW,LW,AW,U)
```

*

* This subroutine calculates the heat transfer from the outside
* surface of the wall.

*

```
REAL TINF,TW,QW,TAVE,CPA,CPS,KA,KS,C1
REAL MUA,MUS,RHOA,N,PRA
REAL BETAA,MA,MS,RA,RS,PA,PS,PT
REAL MSF,MSG,TVOL,XVOL,PS1,G,SB,PI,DT,LW,AW
REAL GR,GRPR,HW,U
```

*

```
COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL
COMMON /PROPS/ G,SB,PI
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
```

*

```
WRITE (13,*) 'SUBROUTINE WALL'
```

```
* WRITE (13,*) 'TW: ',TW,' TINF: ',TINF,' AW: ',AW,' LW: ',LW
IF (TINF.EQ.TW) THEN
  U=0.
  GOTO 18
ENDIF
```

```
TAVE=(TINF+TW)/2
CALL CPGET(CPA,CPS,TAVE)
CALL KGET(KA,KS,TAVE)
CALL MUGET(MUA,MUS,TAVE)
CALL RHOGET(RHOA,RHOS,TAVE,X)
```

```
BETAA=1/TAVE
RHOA=101.35/(RA*TINF)
```

```
*
* Find the Grashof number for the riser, GR, and the product of
* GR and the Prandtl number, PRMEAN.
*
GR=G*BETAA*ABS(TW-TINF)*LW**3*RHOA**2/MUA**2
PRA=CPA*MUA/KA
* WRITE (13,*) 'GR: ',GR,' PRA: ',PRA
GRPR = GR*PRA
```

```
IF (GR.GE.1E9) THEN
  C1=0.1
  N=1./3.
ELSE
  C1=0.59
  N=1./4.
ENDIF
HW=C1*(GRPR)**N*KA/LW
QW=HW*AW*(TW-TINF)*DT
WRITE (13,*) 'HW: ',HW
U=HW
18 RETURN
END
```

```
*****
```

```
*
* SUBROUTINE COILS(TINF,MDA,MDS,MSU,MAU,VOL,Q,MDC)
*
* This subroutine calculates the heat and mass transfer of
* the steam/air mixture to the condenser coils.
*
* The iterative procedure is from Kern (Process Heat Transfer,
* p. 344-)
*
* ACMIN= minimum flow area for cooling coils (m^2)
* ACOIL= total surface area of cooling coil (m^2)
* LCOIL= total length of coil tubing (m)
* MDW = mass flowrate of cooling water (kg/s)
* ID = inner diameter of coil tubing (m)
* OD = outer diameter of coil tubing (m)
* MM = molecular mass of mixture
* KD = diffusivity, m^2/s
* PAM = log mean of PA and PAI=PT-PC pressure of air in
* condensate film
```

```

*
REAL MDA,MDS,X,TINF,TAVE,ACOIL,DELT,ARRT,MMA,MMS
REAL RHOW,MUW,KW,PRW,UW,REW,NUW,HW,TL,PVIN,PT
REAL PVI,PAC,PAI,PAM,PSC,CPA,CPS,KA,KS,MUA,MUS,RHOGA,RHOGVV
REAL RHOMIX,CPMIX,KMIX,MUMIX,MDAIR,MDSTE,MDMIX
REAL UMIX,REMIX,PRMIX,C4,C1,N,NUHO,HO,KD,MM,KNC
REAL KG,HF,HG,HFG,LHS,RHS,ERR1,Q,MDC,HEQ,VOL,MSU,MAU
REAL MA,MS,RA,RS,PA,PS,MSF,MSG,TVOL,XVOL,MDW
REAL ACPMIN,LCOIL,TH2O,ID,OD,G,SB,PI,DT,HTCOIL

*
COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,TVOL,XVOL
COMMON /COIL/ MDW,ACPMIN,LCOIL,TH2O,ID,OD,HMT
COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR
COMMON /PROPS/ G,SB,PI
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
COMMON /HTCS/ HTCOIL,HTCWAL,HTCRIS,HTCRIS2

*
WRITE (13,*) 'SUBROUTINE COILS: DETERMINE COIL HTC'
*   WRITE (13,*) 'MDA: ',MDA,' MDS: ',MDS
ACOIL=PI*OD*LCOIL

PT=PA+MSU*RS*TINF/VOL

TI=TH2O

*   Calculate mixture properties at average of film temp and
*   mixture temp away from wall

TAVE=(TI+TINF)/2
CALL PSAT(PVI,TI)
*   CALL PSAT(PVIN,TINF)
*   WRITE (13,*) 'MSU: ',MSU,' VOL: ',VOL,' RS: ',RS
PVIN=MSU*TINF*RS/VOL
PAI=PT-PVI
PAM=(PAI-PA)/(LOG(PAI/PA))

*   CALL RHOG(RHOGVV,TAVE)
RHOGVV=MSU/VOL
RHOGA=PAM/(RA*TAVE)
CALL CPGET(CPA,CPS,TAVE)
CALL KGET(KA,KS,TAVE)
CALL MUGET(MUA,MUS,TAVE)
RHOMIX=RHOGA*PAM/PT+RHOGVV*(PT-PAM)/PT
*   WRITE (13,*) 'RHOMIX: ',RHOMIX
CPMIX=(RHOGA*CPA+RHOGVV*CPS)/RHOMIX

```

```
KMIX=(RHOGA*KA+RHOGVV*KS)/RHOMIX
MUMIX=(RHOGA*MUA+RHOGVV*MUS)/RHOMIX
```

- * calculate mixture side HO, using Zukauskas for staggered tubes.
- * correction factor = 0.89 for four-row arrangement.

```
MDMIX=MDA+MDS
UMIX=MDMIX/(RHOMIX*ACMIN)
REMIX=RHOMIX*OD*UMIX/MUMIX
* WRITE (13,*) 'REMIX: ',REMIX
PRMIX=CPMIX*MUMIX/KMIX
C4=0.89
C1=0.9
N=0.4
NUHO=C4*C1*REMIX**N*PRMIX**0.36
HO=NUHO*KMIX/OD
WRITE (13,*) 'HO: ',HO
```

- * calculate diffusivity (m²/s) using Geankopolis

```
KD=((.22*(TAVE/273)**1.75)*(101350/PT))/10000
CALL ENGET(HF,HG,HFG,TINF)
```

- * calculate Schmidt and Sherwood numbers, analogous to Prandtl and
- * Nusselt numbers

```
SCV=MUMIX/(RHOMIX*KD)
* WRITE (13,*) 'SCV: ',SCV
SHV=C4*C1*REMIX**N*SCV**0.36
* WRITE (13,*) 'SHV: ',SHV
KNC=SHV*KD/OD
* WRITE (13,*) 'KNC: ',KNC
```

- * calculate overall htc

```
* WRITE (13,*) 'HFG: ',HFG,' RHOGVV: ',RHOGVV
* WRITE (13,*) 'PVINF: ',PVINF,' PVI: ',PVI
* WRITE (13,*) 'TINF: ',TINF,' TI: ',TI,' PAM: ',PAM
FF=1.
IF (PVINF.LT.PVI) THEN
  HMT=HO
  MDC=0.
ELSE
  HMT=FF*(HO+KNC*HFG*RHOGVV*(PVINF-PVI)/((TINF-TI)*PAM))
```

```

MDC=DT*ACOIL*(TINF-TI)*(HMT-HO)/HFG
ENDIF
WRITE (13,*) 'HMT: ',HMT

```

* calculate Q for cooling coil

```

HTCOIL=HMT
Q=HMT*ACOIL*DT*(TINF-TI)
RETURN
END

```

*

*

```

SUBROUTINE RINTRF(FRDC)

```

*

* This subroutine calculates the radiation interchange factors
 * between two co-axial surfaces.

* DL : S. steel tank inner diameter (m).

* EPSS: Is the emissivity of the stainless steel.
 * concrete wall.

* FRDC: Radiation interchange factor from the riser wall to the
 * stainless steel tank.

* DR : Riser diameter (m). Stainless steel.

* TH : S. steel tank thickness (1/8" = 0.003175 m)

*

```

REAL DC,DL,EPSC,EPSS
REAL FDCS,FRDC,DR,TH

```

*

```

EPSS=0.95
DL=0.44
TH=0.003175
DR=0.229

```

*

```

FRDC=(1/EPSS+(DR/DL)*(1/EPSS-1))**(-1)

```

*

```

RETURN
END

```

*

*

*

```

SUBROUTINE TEMPGET (MDA,MDS,QOUT,MDOUT)

```

*

* This subroutine is used to find the temperature at various
 * points in the steam/air mixture ignoring radiation effects. The

* passed variables are:

*

* MDS = steam flow rate

* MDOUT = mass of steam condensed during time step (kg)

* MDA = mass flow rate OF AIR (kg/s)

* QOUT = energy removed from tank during time step.

*

* In addition, some variables are passed via COMMON blocks.

* These are defined in the main calling routine.

*

REAL QOUT,MDA,MDS,DTR,QDOWN,OLDTR,OLDTD,ERRTR,ERRTD,QC,QRP

REAL DTW,ERQW,TA,TB,TC,TD,TE,TW,TR,TAMB,TLID,TRMN,TDMN

REAL AJ,LJ,ERRMAX,TRCOIL,TDCOIL,QR,VOL,VRIS,VDOWN,QR2

REAL XA,XB,XC,XD,XE,G,SB,PI,DT,MDST,MDST1,HGO,TR1,MSC,DELTAT

REAL V,DL,DR,A,B,C,D,E,LW,LR,AW,AR,UR,UD,UW,UT,UR2,UW2

REAL ROC,SHC,KC,DX,DIN,SHS,MSCLID,MSCRIS,MSCCOI,MSCWAL,MSCP

REAL

MDOUT,MDSOLD,XEOLD,MA,MARIS,MADOWN,MSRIS,MSDOWN,MRIS,MWAL

REAL MSROLD,MSDOLD,MSOLD,TVOLD,XVOLD,DUMMY1,DUMMY2,HFGR

REAL

MSRAVE,MSDAVE,MS,HTCOIL,HTCWAL,HTCRIS,ACDOWN,ACRIS,MDT,EPSS

REAL BALTR,FRDC,HTCRIS2

DOUBLE PRECISION TR2

INTEGER PARTS,LOOP,SS,FLAG,FLAG0,FLAG1,FLAG2,ICOUNT

*

COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,PSR,PSSR

COMMON /TEMPS/ TA,TB,TC,TD,TE,TW,TR,TAMB,TLID

COMMON /OLDTEMP/ TAO,TBO,TCO,TDO,TEO,TRO,TWO,TLIDO,TVOLD,XVOLD

COMMON /OLDMASS/ MSOLD,MSDOLD,MSROLD

COMMON /GEOM/ V,VRIS,VDOWN,DL,DR,A,B,C,D,E,LW,LR,AW,AR

COMMON /PROPS/ G,SB,PI

COMMON /INJEC/ MDST,HGO

COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2

COMMON /CONTR2/ ROC,SHC,KC,DX,DIN,SHS,MLID,MRIS,MWAL

COMMON /HTCS/ HTCOIL,HTCWAL,HTCRIS,HTCRIS2

COMMON /FLAGS/ FLAG0,FLAG1

COMMON /EMISS/ EPSS

WRITE (13,*) 'SUBROUTINE TEMPGET'

*

* Set temperatures to those from last time step

TA=TAO

TB=TBO

```

TC=TCO
TD=TDO
TE=TEO
TDMN=(TD+TE)/2.
TLID=TLIDO
TR=TRO
TW=TWO
MS=MSOLD
MSRIS=MSROLD
MSDOWN=MSDOLD
XVOL=XVOLD
TVOL=TVOLD
ERRMAX=0.0125
MDT=MDA+MDS
UR2=HTCRIS2

```

- * Calculate the conditions at the point of steam injection, assuming
- * injection fills the entire riser.

```

MARIS=MA*(VRIS/V)
FLAG=1
ICOUNT=0

```

- *


```

MDST1=MDST
CALL MIXGET(TE,MSRIS,MARIS,(MSRIS+MDST1*DT),
1 (MDST1*DT*HGO),0.,0.,VRIS,TA)
FLAG=0

```

- * Calculate the conditions inside the
- * riser.

```

WRITE (13,*) 'DETERMINE RISER CONDITIONS:'

```

```

ACRIS=PI*(DR/2)**2.

```

```

OLDTR=TA

```

```

TRMN=(TA+TB)/2.

```

```

MSRIS=MSRIS+MDST1*DT

```

```

MARIS=MA*(VRIS/V)

```

```

MSRAVE=MSRIS

```

```

WRITE (13,*) 'TR: ',TR

```

```

DELTAT=TRMN-TR

```

```

IF (DELTAT.LT.0.2) THEN

```

```

    TR=TRMN-0.2

```

```

ENDIF

```

```

77 CALL UNCCOND(TRMN,TR,LR,AR,MDT,ACRIS,DR,MSRAVE,MARIS,VRIS
1 ,UR,MSCRIS)

```

```

IF (ICOUNT.GE.5) THEN
  UR=0.
ENDIF
HTCRIS=UR
QR=UR*AR*(TRMN-TR)*DT
CALL MIXGET(TA.MSRIS.MARIS.(MSRIS-MSCRIS),
1  0.,QR,MSCRIS,VRIS,TB)
TRMN=(TA+TB)/2.
WRITE (13,*) 'TRMN: ',TRMN
ERRTR=ABS(OLDTR-TRMN)/TRMN
IF (ERRTR.LT.ERRMAX) THEN
  GOTO 78
ELSE
  OLDTR=TRMN
  MSRAVE=(MSRIS+(MSRIS-MSCRIS))/2.
  ICOUNT=ICOUNT+1
  GOTO 77
ENDIF

```

78 CONTINUE

```

MSRIS=MSRIS-MDS/(MSRIS/(MSRIS-MSCRIS))*DT-MSCRIS

```

*

* Assume no heat is transferred to the top of the tank.

*

```

QLID=0.

```

```

TC=TB

```

*

* Find the conditions in the Coil (Region D)

*

```

MADOWN=MA*(V-VRIS)/V

```

```

MSDOWN=MSDOWN+MDS/(MSRIS/(MSRIS-MSCRIS))*DT

```

*

```

IF (FLAG1.GE.1) THEN

```

```

  CALL COILS(TC,MDA,MDS/(MSRIS/(MSRIS-MSCRIS)),MSDOWN,

```

```

1  MADOWN,VDOWN,QCOIL,MSCCOI)

```

```

  WRITE (13,*) 'TC: ',TC,' MSCCOI: ',MSCCOI,' QCOIL: ',QCOIL

```

*

```

  MSCCOI=MSCCOI*(FLAG1/7.)

```

*

```

  QCOIL=QCOIL*(FLAG1/7.)

```

```

ELSE

```

```

  MSCCOI=0.

```

```

  QCOIL=0.

```

```

ENDIF

```

```

QC=QCOIL

```

```

TD=TC

```

*

* Find the conditions in the Downcomer (Region E).

*

WRITE (13,*) 'DETERMINE DOWNCOMER CONDITIONS: '

ACDOWN=PI*(DL/2)**2.-ACRIS

TDMN=TD

OLDTD=TDMN

MSDAVE=MSDOWN

92 CALL UNCCOND(TDMN,TW,LW,AW,MDT,ACDOWN,DL,MSDOWN,MADOWN

1 ,VDOWN,UW,MSCWAL)

HTCWAL=UW

QWALL=UW*AW*(TDMN-TW)*DT

CALL

RISER(TDMN,TR,MSDOWN,MADOWN,VDOWN,LR,AR,MDT,ACDOWN,DL,UR2)

IF (UR2.LT.0.) THEN

UR2=0.

ENDIF

QR2=UR2*AR*(TR-TDMN)*DT

CALL MIXGET(TD,MSDOWN,MADOWN,(MSDOWN-MSCWAL-MSCCOI),

1 0.,(QWALL+QCOIL-QR2),(MSCWAL+MSCCOI),VDOWN,TE)

TDMN=(TD+TE)/2.

ERRTD=ABS(TDMN-OLDTD)/TDMN

WRITE (13,*) 'TDMN: ',TDMN

IF (ERRTD.LT.ERRMAX) THEN

GOTO 94

ELSE

OLDTD=TDMN

MSDAVE=(MSDOWN+(MSDOWN-MSCWAL-MSCCOI))/2.

GOTO 92

ENDIF

94 CONTINUE

MSDOWN=MSDOWN-MSCWAL-MSCCOI

IF (MSDOWN.LT.0.) THEN

MSDOWN=0.

ENDIF

* Update riser temperature.

WRITE (13,*) 'RISER ITERATION:'

CALL RINTRF(FRDC)

```

WRITE (13,*) 'UR: ',UR,' UR2: ',UR2
WRITE (13,*) 'TRMN: ',TRMN,' TDMN: ',TDMN
TR2=TR
ICOUNT=0
96 BALTR=UR*(TRMN-TR2)-UR2*(TR2-TDMN)-SB*FRDC*(TR2**4-TW**4)
ERRTR=ABS(BALTR/(UR*(TRMN-TR2)))
*   WRITE (13,*) 'TR: ',TR,' BALTR: ',BALTR,' ERRTR: ',ERRTR
   IF (ERRTR.LT.ERRMAX) THEN
       TR=TR2
       GOTO 95
   ELSE
       TR2=TR2-BALTR/(-UR-UR2-4*SB*FRDC*TR2**3)
*   WRITE (13,*) 'TR: ',TR2,' ERRTR: ',ERRTR
   ENDIF
   ICOUNT=ICOUNT+1
   IF (ICOUNT.GT.1000) THEN
       TR=TRMN
       GOTO 95
   ENDIF
   GOTO 96
*   TR=TR+(QR-QR2)/(MRIS*SHS)

95 WRITE (13,*) 'TR: ',TR
   WRITE (13,*) 'TAMB: ',TAMB,' TW: ',TW
   HTCRIS2=UR2
   CALL WALL(TAMB,TW,LW,AW,UW2)
   TBAR=(TW+TAMB)/2
*   Find heat transfer coefficient to surroundings; including radiation.
   UW2=UW2+4*SB*EPSS*TBAR**3
   QW2=UW2*AW*(TW-TAMB)*DT
   WRITE (13,*) 'UW2: ',UW2
   TW=TW+(QWALL+SB*FRDC*(TR**4-TW**4)-QW2)/(MWAL*SHS)
   WRITE (13,*) 'TW: ',TW

*   PS=(MSRIS+MSDOWN)*RS*(TRMN+TDMN)/(2*V)
*   PA=MA*RA*(TRMN+TDMN)/(2*V)
   PARIS=MARIS*RA*TRMN/VRIS
   PADOWN=MADOWN*RA*TDMN/VDOWN

   PSRIS=MSRIS*RS*TRMN/VRIS
   PSDOWN=MSDOWN*RS*TDMN/VDOWN

   PA=(PARIS*VRIS+PADOWN*VDOWN)/V
   PS=(PSRIS*VRIS+PSDOWN*VDOWN)/V

```

```

WRITE (13,*) 'VRIS: ',VRIS,' VDOWN: ',VDOWN,' V: ',V
WRITE (13,*) 'PS: ',PS,' PA: ',PA
RETURN
END

```

*

* *****

```

SUBROUTINE MIXGET(TIN,MSIN,MAIN,MSOUT,QIN,QOUT,MSC,VOL,TOUT)

```

*

* This subroutine calculates the mixture conditions in various regions
 * of the tank using an energy balance method.

*

* Energy in equals the internal energy of the air and steam,
 * while energy out equals the energy added/removed by steam
 * injection, condensation on walls or coils or due to vapour
 * saturation, and convection.

*

* MSC=mass of steam condensed, kg
 * TIN, TOUT= T before and after calc, Kelvin
 * QIN = energy added
 * QOUT = energy removed
 * MSIN = mass of steam in
 * MSOUT = mass of steam out
 * MAIN = mass of air

*

```

DOUBLE PRECISION MDA

```

```

REAL MSIN,MSOUT,MAIN,TIN,TOUT,TW,DELT,QIN,QOUT
REAL UF,UG,UFG,UT,UTT,UTTP,ERRMAX,DELU,RDELUT,HGO
REAL G,SB,PL,DT,MA,MS,MSC,RA,RS,PA,PS,PS1,PSS
REAL TL,TH,THIGH,TM,FTL,FTM,FPRO,VOL,MMIST,MVAP
INTEGER ICOUNT,FLAG,FLAG2,JCOUNT
COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
COMMON /OLDTEMP/ TAO,TBO,TCO,TDO,TEO,TRO,TWO,TLIDO,TVOLD,XVOLD
COMMON /PRES/ MA,MS,RA,RS,PA,PS,MSRIS,MSDOWN,PSR,PSSR
COMMON /INJEC/ MDST,HGO

```

* Energy in:

```

ICOUNT=0
ERRMAX=0.01
DTEMP=0.1
TKREF=273.
CALL CPGET(CPA,CPS,TIN)

```

```

CVA=CPA-RA
TOUT=TIN
MVAP=MSOUT
MMIST=0.
CALL UGET(UF,UG,TIN)
UT=MSIN*UG+MAIN*CPA*(TIN-TKREF)

UTT=UT-QOUT+QIN
QABS=QIN-QOUT
WRITE (13,*) 'SUBROUTINE MIXGET:'
WRITE (13,*) 'QIN: ',QIN,' QOUT: ',QOUT
WRITE (13,*) 'UT: ',UT,' UTT: ',UTT
WRITE (13,*) 'MSIN: ',MSIN,' MSOUT: ',MSOUT,' MSC: ',MSC

```

* Begin iteration.

```

FLAG2=0
61 IF (QABS.EQ.0.) THEN
    DTEMP=0.
    TOUT=TIN
    GOTO 63
ENDIF
IF (UTT.LT.UT) THEN
    TOUT=TOUT-DTEMP
    FLAG2=1
ELSE
    TOUT=TOUT+DTEMP
ENDIF
64 CALL UGET(UF,UG,TOUT)
CALL CPGET(CPA,CPS,TOUT)
CVA=CPA-RA
UTTP=MVAP*UG+(MSC+MMIST)*UF+MAIN*CPA*(TOUT-TKREF)
*     WRITE (13,*) 'TOUT: ',TOUT,' UTT: ',UTT

```

```

DELU=UTTP-UTT
RDELUT=DELU/UTT
CALL PSAT(PSS,TOUT)
PS1=(MSOUT-MMIST)*RS*TOUT/VOL
IF (FLAG.EQ.1) THEN
    GOTO 62
ENDIF

```

```

*     WRITE (13,*) 'PS1: ',PS1,' PSS: ',PSS
IF (PS1.GT.PSS) THEN
    MVAP=PSS*VOL/(RS*TOUT)
    MMIST=MSOUT-MVAP

```

```

*      WRITE (13,*) 'Saturation Pressure Exceeded. Corrected.'
      ENDIF

62 IF (ABS(RDELUT).LT.ERRMAX) THEN
      GOTO 63
    ENDIF
    IF (ICOUNT.EQ.1) THEN
      IF (FLAG2.EQ.1) THEN
        IF (UTTP.LT.UTT) THEN
          GOTO 63
        ENDIF
      ENDIF
    ENDIF
    ICOUNT=ICOUNT+1
    IF (ICOUNT.EQ.2000) THEN
      WRITE (13,*) 'ITERATION LIMIT EXCEEDED'
      GOTO 63
    ENDIF

    GOTO 61

63 CONTINUE
    CALL PSAT(PSS,TOUT)
      WRITE (13,*) 'PS1: ',PSS,' P' ENDIF
    MSC=MSC+MMIST
    WRITE (13,*) 'TOUT: ',TOUT,' UTP: ',UTTP
    RETURN

  END

*      *****
  SUBROUTINE TINCRMT(DTC,GC1,GC2,ALFA)
*
*      This subroutine checks the time increment (DT) to insure
*      mathematical stability.
*
*      eometric parameter 2

    REAL ALFA,DT,DTC,DX,GC1,GC2

    COMMON /CONTR1/ DT,NOD,SS,FLAG,FLAG2
    COMMON /CONTR2/ ROC,SHC,KC,DX,DIN,SHS,MLID,MRIS,MWAL
*
    DTC=DX**2/(4*ALFA*(GC1+GC2)*60)
    IF (DTC.LT.DT) THEN
      DT=DTC

```

END IF

*

RETURN

END

Appendix C: Flowcharts of Program PASSCON

FIGURE B.1 MAIN CALLING ROUTINE

FIGURE B.2 Subroutine FBAL

FIGURE B.3 Subroutine TEMPGET

FIGURE B.4 Subroutine MIXGET

FIGURE B.5: Subroutine UNCCOND

APPENDIX D

Error Analysis

The procedure for the error analysis is from References [E1] and [E2].

1. **Pressure Transducer.** The quoted error for the pressure transducer is 0.4% of the full scale value, which is 430 kPa [E3]. This corresponds to a 3σ value of 1.65 kPa. Thus, the 1σ value is $w_p=0.55$ kPa, or 1.8% at 30 kPa (gauge).
2. **Thermocouples.** The quoted error of Type K thermocouples is ± 2.2 K [E3]. This corresponds to the 3σ value. Thus, the 1σ value is $w_T=0.7$ K.
3. **Power.** The observed maximum fluctuation in the applied power to the flow-measuring unit was $\pm 5\%$. For a power of 10 W, this corresponds to a 3σ value of 0.5 W, and a 1σ value of $w_P=0.167$ W.

4. **Specific Heat of Air.** The specific heat of the air in the flow-measuring unit is calculated from the measured temperature using the following correlation:

$$C_p = 975.62 + 5033 \cdot 10^{-3} T + 126.7 \cdot 10^{-6} T^2 \quad (\text{E.1})$$

Differentiating the equation with respect to T yields:

$$\frac{dC_p}{dT} = 5033 \cdot 10^{-3} + 2 \cdot 126.7 \cdot 10^{-6} T \quad (\text{E.2})$$

Thus, the uncertainty is:

$$w_{c_p} = \sqrt{\left(\frac{dC_p}{dT} w_T \right)^2} \quad (\text{E.3})$$

For a temperature of 323 K, $w_{c_p}=0.09$, or 0.009%. Since this value is small compared to the other uncertainties, it will be neglected in the following calculations.

5. **Air Mass Flowrate.** The equation for the determination of the air mass flowrate from the measure temperature difference in the flow-measuring unit is:

$$\dot{m} = \frac{Q}{c_p (T_{out} - T_{in})} \quad (E.4)$$

Differentiating this equation with respect to the various parameters, and assuming that c_p remains constant yields:

$$\frac{\partial \dot{m}}{\partial Q} = \frac{1}{c_p (T_{out} - T_{in})} \quad (E.5)$$

$$\frac{\partial \dot{m}}{\partial T_{out}} = \frac{Q}{c_p (T_{out} - T_{in})^2} \quad (E.6)$$

$$\frac{\partial \dot{m}}{\partial T_{in}} = \frac{Q}{c_p (T_{out} - T_{in})^2} \quad (E.7)$$

These are independent of each other and can be assumed to be reasonably small.

Thus, the following equation can be used to determine the uncertainty in the calculated air mass flowrate:

$$w_{\dot{m}} = \sqrt{\left(\frac{\partial \dot{m}}{\partial Q} w_P\right)^2 + \left(\frac{\partial \dot{m}}{\partial T_{out}} w_{T_{out}}\right)^2 + \left(\frac{\partial \dot{m}}{\partial T_{in}} w_{T_{in}}\right)^2} \quad (E.8)$$

Using typical values of the temperatures ($T_{out} = 333$ K and $T_{in} = 313$ K), yields $w_m = 2.7 \times 10^{-5}$ kg/s, or, for a flowrate of 0.0006 kg/s, 4.5%.

APPENDIX E

Experimental Procedure

1. Turn on the Zenith data acquisition computer. At the prompt, type 'QB /L DAS8' to load the Quickbasic environment and the DAS-8 board drivers.
2. Load the program PASSIVE into the Quickbasic environment.
3. Turn on the power supply to the flow-measuring unit. Adjust the power until a constant supply of 10 W is delivered to the flow-measuring unit.
4. Connect the pressure transducer to the DAS-8 board using the provided coaxial connector. Connect the DC power supply to the pressure transducer and adjust the voltage to 10 V (or higher).
5. Run the PASSIVE program and observe the air mass flowrate until it reaches steady state.
6. Plug the steam generator power cord into the wall outlet. Turn on the water supply to the steam generator and close the outlet valve. Adjust the temperature controller to the desired level. Observe the steam generator pressure guage until it reaches the desired level.
7. Re-start the PASSIVE program. Open the steam generator outlet valve. If needed, turn on the cooling water supply and adjust to the desired level.
8. To halt the data acquisition routine, press 'Ctrl-Break'.
9. Close the steam generator outlet valve. Turn the temperature controller to the 'OFF' position. Close the water supply.
10. The steam generator must be blown-down daily. Wait until the steam generator pressure drops below 20 psi. Make sure the water supply and outlet valves are closed. Securely attach a hose to the blow-down outlet and attach the other end to the sump. Open the blow-down

valve and wait until the pressure drops to zero. Close the blow-down valve, open the outlet and water supply valves. Wait until the level in the sighting-glass reaches a steady level.

IMAGE EVALUATION TEST TARGET (QA-3)

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