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Research Title: Investigation of forced convection (i.e., ventilation) and associated heat transfer processes in waste emplacement drifts.

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GW

OBJECTIVE:

The objective of this task is to test out the forced convection/diffusion elements within ABAQUS to investigate whether or not they could be utilized to simulate the ventilation of waste emplacement drifts and realistically incorporate the convective heat transfer into such elements, diffusion heat transfer into such elements, and radiation heat transfer across these elements to the drift wall. Both transient and steady state heat transfer simulations were to be conducted.

Research Type/Technical Approach:

This research activity was purely computational using ABAQUS version 5.8 (Standard Version) and Patran Version 9.0 to set up the computational models. All analyses were performed on Silicon Graphics SGI R10,000 workstations running UNIX. In addition to using the ABAQUS Standard, several user subroutines were written in FORTRAN to be included and compiled with the ABAQUS input decks. Such user subroutines are provided in this Scientific Notebook.

M.A
7/30/00

Development of input material properties for the ABAQUS forced ventilation / heat transfer analyses.

Thermodynamic Properties of Dry Air (A. Bejan, Convective Heat Transfer, 1995)

Temperature T (°C)	Density ρ (kg/m³)	Thermal Conductivity k, [W/m·K]	Thermal Diffusivity α [m²/s]	Specific Heat C_p [J/kg·K]
0.0	1.293	2.4×10^{-2}	0.184×10^{-4}	1008.8
10.0	1.247	2.5×10^{-2}	0.196×10^{-4}	1022.9
20.0	1.205	2.5×10^{-2}	0.208×10^{-4}	997.4
30.0	1.165	–	–	–
60.0	1.060	–	–	–
100.0	0.946	3.2×10^{-2}	0.328×10^{-4}	1031.3
200.0	0.746	–	–	–

Note: $\alpha = \dfrac{k}{\rho C_p} \Rightarrow C_p = \dfrac{k}{\rho \alpha}$

Tentative Volumetric Air Flow Rates To Investigate

a) $\dot{V} = 1.0$ m³/s.

b) $\dot{V} = 10.0$ m³/s.

c) $\dot{V} = 15.0$ m³/s.

ABAQUS Mass Flow Rates (Initial)

a) $(1.0 \ m^3/s)(1.205 \ Kg/m^3) = 1.205 \ Kg/s$

b) $(10.0 \ m^3/s)(1.205 \ Kg/m^3) = 12.05 \ Kg/s.$

c) $(15 \ m^3/s)(1.205 \ Kg/m^3) = 18.08 \ Kg/s.$

Note.
Mass flow rates calculated based on dry air density @ $T = 20°C$ (see page 5).

ABAQUS mass flowrates are required to be input as [Mass/time·Area]

Thus, the area of cross-section air flow space is required.

Assumptions

Drift diameter = 5.1 m

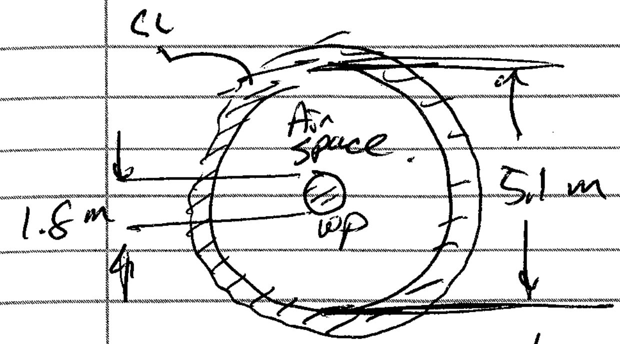
i.e. $[5.5 \ m - 2*(0.20 \ m)] = 5.1 \ m,$

diameter of initial rock excavation

Concrete liner thickness

Waste Package Diameter = 1.8 m.

[Manteufel, 1997, "Effects of Ventilation and backfill on a mined waste disposal facility" Nuclear Engineering and Design, 172, pp 205-219].



wp = waste package
cL = concrete liner

$A_{flow} = \frac{\pi}{4}[(5.1m)^2 - (1.8m)^2] = 17.9 \ m^2$

Calculate Mass Flow Rate per unit Area for ABAQUS Analysis.

Air Volumetric Flow Rate	ABAQUS Mass Flow Rate/unit Area.
a) $1.0 \ m^3/s$	$6.732 \times 10^{-2} \ Kg/m^2/s$
b) $10.0 \ m^3/s$	$0.6732 \ Kg/m^2/s$
c) $15.0 \ m^3/s$	$1.0101 \ Kg/m^2/s$

Note. For initial ABAQUS analyses the mass flow rate was assumed constant over entire cross-section. [rough approximation as velocity profile in fully-developed flow regime is parabolic].

Thermal material input parameters for TSwz, waste package, concrete liner. [Reference, DOE Ground Support Analysis for Viability Assessment].

Thermal properties for waste package Steel.

Density (ρ) = 8131 Kg/m^3
Thermal Conductivity (K) = 41.71 W/m.K.
Specific Heat (C_p) = 487.9 J/Kg.K.
Emissivity = 0.80

Thermal Properties for Concrete Liner

Density (ρ) = 2323 Kg/m^3
Thermal Conductivity (K) = 2.5 W/m.K
Specific Heat (C_p) = 1005 J/Kg.K
Emissivity = 0.90

Thermal Properties of TSwz (Repository Host Rock)

Density (ρ) = 2274 Kg/m^3
Thermal Conductivity (K) = 2.1 W/m.K
Specific Heat = 930 J/Kg.K.

Stefan-Boltzman Constant (σ) = 5.669×10^{-8} $\frac{W}{m^2 \cdot K^4}$
(needed for radiation heat transfer)

Temperature of Absolute Zero = −273.0 °C

Thermal Heat Generation Rate for Waste package. [Mantenfel, 1997]

Table 1.0

Time After Emplacement (Yr)	Time After Emplacement (s)	Thermal Output (W)	Volumetric Heat Flux (W/m^3)
0.0	0.0	8016.47	237.6
1.0	3.1536×10^7	7873.61	233.3
2.0	6.3072×10^7	7738.36	229.3
5.0	1.5768×10^8	7346.68	217.7
10.0	3.1536×10^8	6734.76	199.6
20.0	6.3072×10^8	5748.46	170.4
50.0	1.5768×10^9	3841.43	113.8
100.0	3.1536×10^9	2413.61	71.5
200.0	6.3072×10^9	1508.68	44.7
500.0	1.5768×10^{10}	890.15	26.4
1000.0	3.1536×10^{10}	516.46	15.3
2000.0	6.3072×10^{10}	270.60	8.0
5000.0	1.5768×10^{11}	172.04	5.1
10,000.0	3.1536×10^{11}	124.69	3.7

Volumetric Heat Flux (W/m^3) calculation

WP Diameter = 1.8 m.

Need to calculate Average waste package Spacing.

Assume:

Areal Mass Loading = 85 MTU/acre.
Drift Spacing = 28 m

Average Initial MTU / waste package = 8.94 MTU/package

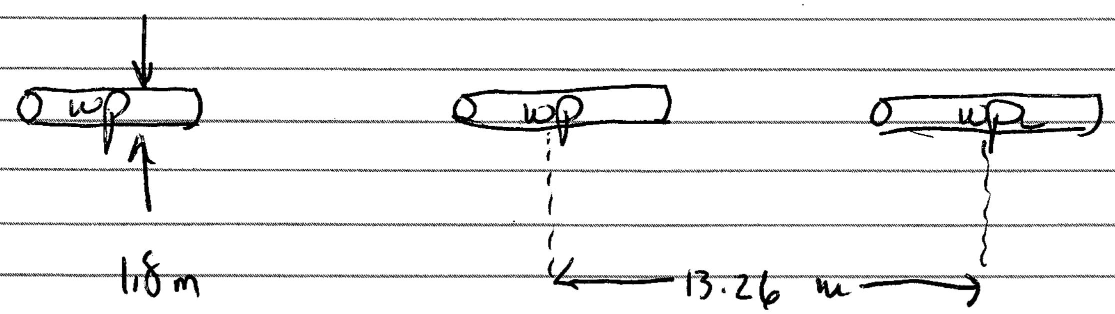
Conversions ⇒ 1 acre = 4047 m^2

Waste package Spacing = $\dfrac{\left(4047 \frac{m^2}{acre}\right) * \left(8.94 \frac{MTU}{package}\right)}{\left(85 \frac{MTU}{acre}\right)(28\ m)}$

≅ 15.2 m / waste package.

For an 85 MTU/acre Thermal load, Rui Chen used as waste package spacing of 13.26 m / waste packed.

This analyses opted to used value value of 13.26 m as derived by Rui Chen for the waste package spacing.



Assumption:
- Volumetric heat flux is smeared over the full length of waste package spacing to simulate a continuous heater.

Volume = $\dfrac{\pi (1.8 m)^2}{4} (13.26\ m) = 33.7\ m^3$

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equivalent volume / heater.

Thermal output per waste package (ie. Column 3, Table 1, pg 9), is divided by above Volume to obtain volumetric heat flux (Column 4, Table 1, pg 9).

Note. The volumetric heat flux is input into ABAQUS using using the AMPLITUDE option. [Time is input in seconds].

M.A.
8/10/00

Initial Temperature for ABAQUS Model:-

Ground Surface $T_0 = 18.7°C$ (Average).

$d = 311$ m

$T_{grad} = 0.1897$ °C/m

Emplacement Drift Horizon.

$$T^{i}_{Repository} = T_0 + T_{grad} * d = 24.6\,°C.$$

M.A.
8/10/00

The ABAQUS documentation (e.g. theory manual, user's manuals Vols I, II, and III were reviewed to identify element types needed for the forced convection / diffusion analyses, additional input commands needed, time step requirements, etc.

Some of the information obtained on the ABAQUS forced convection heat transfer elements was as follows from ABAQUS documentation:

Forced convection/heat Transfer Elements -

- allow for heat storage (specific heat) and heat conduction as well as convection of heat by fluid moving through the mesh (forced convection)

- forced convection heat transfer elements can be used in heat transfer analyses in conjunction w/ cavity radiation modeling.

- forced convection elements can be used in conjunction with the standard heat transfer diffusion elements

- both transient and steady-state heat transfer analyses can be performed w/ such elements.

Note: Transient analyses w/ the ABAQUS heat transfer convection/diffusion analyses must take in consideration restrictions on the Courant Number and Peclet Number in order to ~~make~~ maintain accuracy in calculations and a stable transient time step.

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Regarding the Peclet Number (γ) ABAQUS documentation recommends a value somewhere in the range of 1000 or less. The Peclet Number is a representation of the convective heat transfer to conductive heat transfer ratio. High Peclet No.'s indicate that the heat transfer is strongly convection dominated, and solution more difficult.

The Peclet No. (γ) was derived for ventilation air flow rates of 1.0 and 10.0 m^3/s.

(1) Volumetric Flow Rate ($\dot{V}$) = 10.0 m^3/s.

$A_{flow} = 17.9 \; m^2$

$v = \frac{\dot{V}}{A_{flow}} = 0.559 \; m/s$ (air velocity)

$\gamma = |v| \, \Delta l \, \frac{\rho c}{K}$

Fluid = Air (dry) @ T = 20°C

density (ρ) = 1.205 kg/m^3
thermal cond. (k) = 2.5×10^{-2} $W/m \cdot K$
Specific Heat (c_p) = 997.4 $J/kg \cdot K$.

where
Δl = typical element length along direction of flow.

For 2D-axisymmetric model (discussed later)

$\Delta l = 0.25 \; m.$

$\therefore \; \dot{V} = 10.0 \; m^3/s$

$$\gamma = (0.559 \; m/s)(0.25 \; m) \left(\frac{(1.205 \frac{kg}{m^3})(997.4 \frac{J}{kg \cdot K})}{2.5 \times 10^{-2} \frac{J}{s \cdot m \cdot K}} \right)$$

$\underline{\gamma = 6718.4 \; >> \; 1000}$

(2) Volumetric Flow Rate $\dot{V} = 1.0 \; m^3/s$.

$v = (1 \; m^3/s)/(17.9 \; m^2) = 0.0559 \; m/s$ (velocity)

$$\gamma = (0.0559 \; m/s)(0.25 \; m) \frac{(1.205 \; kg/m^3)(997.4 \frac{J}{kg \cdot K})}{(2.5 \times 10^{-2} \frac{W}{m \cdot K})}$$

$\dot{V} = 1.0 \; m^3/s$

$\underline{\gamma = 671.8 \; < \; 1000}$

Calculation of the Peclet No. indicates that for the element size chosen, the 1.0 m^3/s air flow rate is within limits of ABAQUS guidelines (i.e., < 1000)

however the 10.0 m^3/s air flow rate leads to a Peclet No. somewhat greater than 1000 indicating a transient solution would likely be more difficult to obtain accurate results.
Nevertheless an analyses will be performed to see what type of transient solution results can be obtained.

MA 8/10/00

As mentioned ~~of~~ on page 15, the other requirement in performing transient analyses w/ the forced convection / diffusion elements is the Courant Number (C) be less than 1.0. A value of $C > 1.0$ could lead to inaccurate results in a convection / diffusion ~~at~~ analyses.

mpa 9/5/00

ABAQUS ~~eg~~ example problems limit Courant No: $C = 0.8$

Courant No. defined as.

$$C = v \frac{\Delta t}{\Delta h}$$

where Δt is time step (transient).
Δh = element length along direction of flow.

Solve for Δt.

(a) Volumetric flow rate $= 1.0\ m^3/s$.

$v = 0.0559\ m/s$.
$\Delta h = 0.25\ m$

$$\Delta t = \frac{C \Delta h}{v} = \frac{0.8(0.25 m)}{0.0559\ m/s}$$

$\underline{\Delta t \cong 3.6 \text{ seconds.}}$

$\dot{V} = 0.559$ m/s w/ $A_{flow} = 17.9 m^2$

(b) Volumetric Flow Rate = 10.0 m^3/s.

$$\Delta t = \frac{C \Delta h}{v} = \frac{(0.8)(0.25 \text{ m})}{0.559 \text{ m/s}}$$

$\Delta t =$ 0.36 seconds

One can see that the Courant Condition places severe restrictions for a stable thermal time step in transient analysis w/ forced convection-diffusion elements.

This indicates that long ventilation time frames would be difficult to analyze (i.e. ventilating drift for several weeks/months). Without the addition of the air mass flow rates, the thermal timestep can be quite large if one were just to include the radiation heat transfer between wp and drift wall surfaces and only conduction heat transfer through the convection/diffusion elements between wp and drift wall surfaces.

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Note: ABAQUS has two different types of elements that can be used for forced convection/diffusion heat transfer. In the case of an 2D axisymmetric analysed the will be discussed next, these elements are.

DCCAX4
DCCAX4D

With the use of the DCCAX4D elements (which include dispersion control to minimize oscillations in solution), the ABAQUS Standard code will automatically adjust the thermal time step based on the Courant condition discussed on previous two pages to maintain a stable solution. Thus, for the 2D transient analyses conducted (in which the emplacement drift was first heated via radiation heat transfer and conduction heat transfer for a period of time (e.g. 1 month) w/ air mass flow rate $\dot{V} = 0.0$ the time step could be very large. Upon initiating the ventilation flow rate into the transient heat transfer analysis (say at t = 1 month), the thermal time step was reduced to around 0.36 sec for the $\dot{V} = 10.0 m^3/s$ flow rate.

The DCCAX4 element usage did not cause

ABAQUS to automatically reduce the thermal time step so dramatically, but it would appear (based on ABAQUS documentation) that the Peclet No. and Courant conditions should still be maintained for solution accuracy even though the transient thermal time step and stability requirements were not as strict with the the DCCAX4 elements versus the DCCAX4D elements.

MA
8/12/00

After initial analyses with the convection / diffusion elements, it was determined the ABAQUS FILM boundary conditions were required on both the waste package surface and drift wall surface to accurately account for the convective heat transfer into the air stream. In incorporation of FILM boundary conditions within a ABAQUS model both the film coeff (ie, heat transfer coeff.) and the air sink temperature must be defined. The approach for setting the sink temperature is discussed later as part of the model definition.

The heat transfer coefficient (approximation) was developed as follows:

Approximation for heat transfer Coeff. (h_m)

Reference: Mark's Standard HandBook for Mechanical Engineers.

Section: Turbulent flow of Gases inside Clean Tubes

Conditions to be met for this approx.

$$\frac{DG}{\mu_f} > 7000$$

where

D = diameter (ft)
G = mass velocity ($lb/hr \cdot ft^2$) of cross-section occupied by fluid

μ_f = viscosity of fluid $\left(\frac{lb_m}{hr\cdot ft}\right)$

Assume air (dry) @ $T = 20^\circ C$.

$D = 5.1\,m = 16.7\,ft.$

$\mu_f = 1.81\times10^{-4}\frac{g}{cm\cdot s} = \left(1.81\times10^{-4}\frac{g}{cm\cdot s}\right)\left(\frac{1\,kg}{10^3\,g}\right)\left(\frac{10^2\,cm}{m}\right)\left(\frac{3600\,s}{hr}\right)$

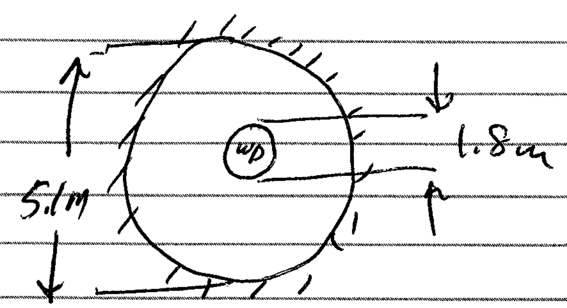
$= \left(6.516\times10^{-2}\frac{kg}{m\cdot hr}\right)\left(\frac{0.3048\,m}{ft}\right)\left(\frac{1\,lb_m}{0.4536\,kg}\right)$

$\mu_f = 4.378\times10^{-2}\frac{lb_m}{hr\cdot ft}.$

Assume Volumetric Flow Rate $= 10\,m^3/s$

$\rho_{air} = 1.205\,kg/m^3$ @ $20^\circ C$

$A_{flow} = 17.9\,m^2$



$A_{flow} = (17.9\,m^2)\left(\frac{1\,ft}{0.3048\,m}\right)^2 = 192.5\,ft^2$

Mass Flow Rate $= \left(12.05\frac{kg}{sec}\right)\left(\frac{1\,lb_m}{0.4536\,kg}\right)\left(\frac{3600\,s}{hr}\right)$

$= 9.5635\times10^4\frac{lb_m}{hr}.$

$\therefore\ G = \dfrac{9.5635\times10^4\,\frac{lb_m}{hr}}{192.5\,ft^2} = 496.8\,\frac{lb_m}{hr\cdot ft^2}$

✓ $\dfrac{DG}{\mu_f} = \dfrac{(16.7\,ft)\left(496.8\,\frac{lb_m}{hr\cdot ft^2}\right)}{4.378\times10^{-2}\,\frac{lb_m}{hr\cdot ft}} = 189{,}508 \gg 7000$

ok to use this method.

h_m = mean value of h for entire surface.

$$h_m = \frac{0.024\,C_p\,G^{0.8}}{(D_i)^{0.2}}$$

$D_i = 5.1\,m = 16.7\,ft$

$G = 496.8\,lb_m/hr\cdot ft^2$

C_p = Specific heat @ constant pressure $\frac{Btu}{lb\cdot ^\circ F}$.

@ $20^\circ C$ $\quad C_p = \left(997.4\frac{J}{kg\cdot K}\right)\left(\frac{1\,Btu}{1.05435\times10^3\,J}\right)\left(\frac{0.4536\,kg}{lb}\right)\frac{1}{\left(\frac{1.8^\circ F}{^\circ K}\right)}$

$C_p = 0.23822\,\frac{Btu}{lb\cdot ^\circ F}$

$$h_m = \frac{0.024\left(0.23822\ \frac{Btu}{lb\cdot°F}\right)\left(496.8\ \frac{lbm}{hr\cdot ft^2}\right)^{0.8}}{(16.7\ ft)^{0.2}}$$

$$h_m = 0.467\ \frac{Btu}{hr\cdot ft^2\cdot °F}$$

$$= \left(0.467\ \frac{Btu}{hr\cdot ft^2\cdot °F}\right)\left(\frac{0.2930711\ W}{Btu/hr}\right)\left(\frac{1\ ft}{0.3048\ m}\right)^2\left(\frac{1.8\ °F}{°K}\right)$$

$$\boxed{h_m = 2.652\ \frac{W}{m^2\cdot K}}$$

Value for h_m used on both the waste package surface and the drift wall surface for initial analyses.

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8/13/00

ABAQUS 2D axisymmetric models for the forced convection / diffusion heat transfer analyses w/ cavity radiation.

For this analyses, 2 separate ABAQUS models were developed. The first model did not include the forced convection elements within the air gap. This was done to get a handle on only the radiation heat transfer (i.e. ~~for~~ heat flux from waste package surface, heat flux into concrete liner, waste package an concrete wall liner surface temps after some duration of transient heat transfer analyses. This was done to make sure that the same radiation heat transfer was taking place between these two surfaces when the air gap between the waste package and concrete liner was filled with convection/diffusion elements. The second ~~of~~ analyses used a similar model with the air gap meshed with elements of the convection/diffusion type (DCCAX4D). Both initial models assumed the axial tunnel length to be 20 m.

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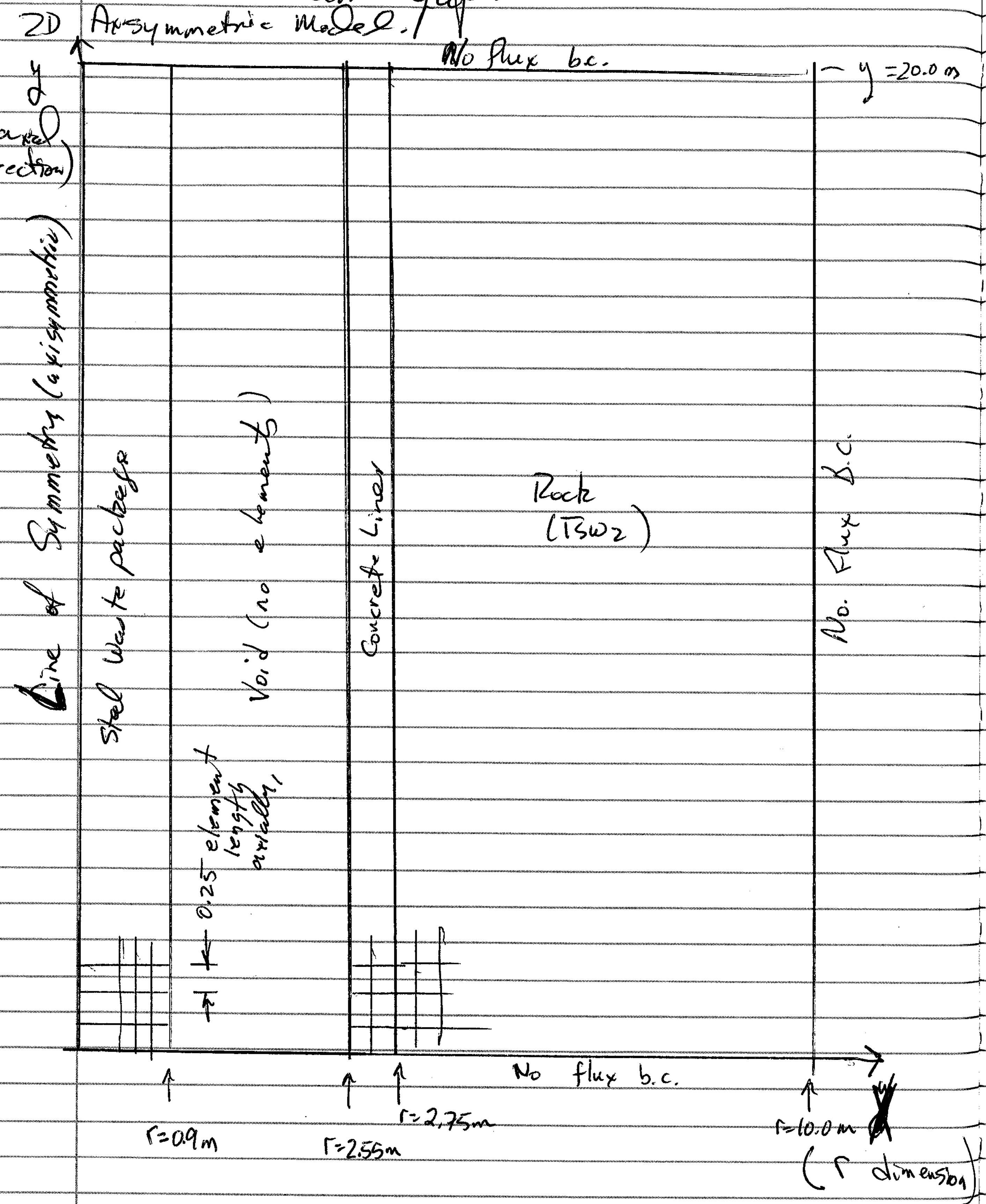
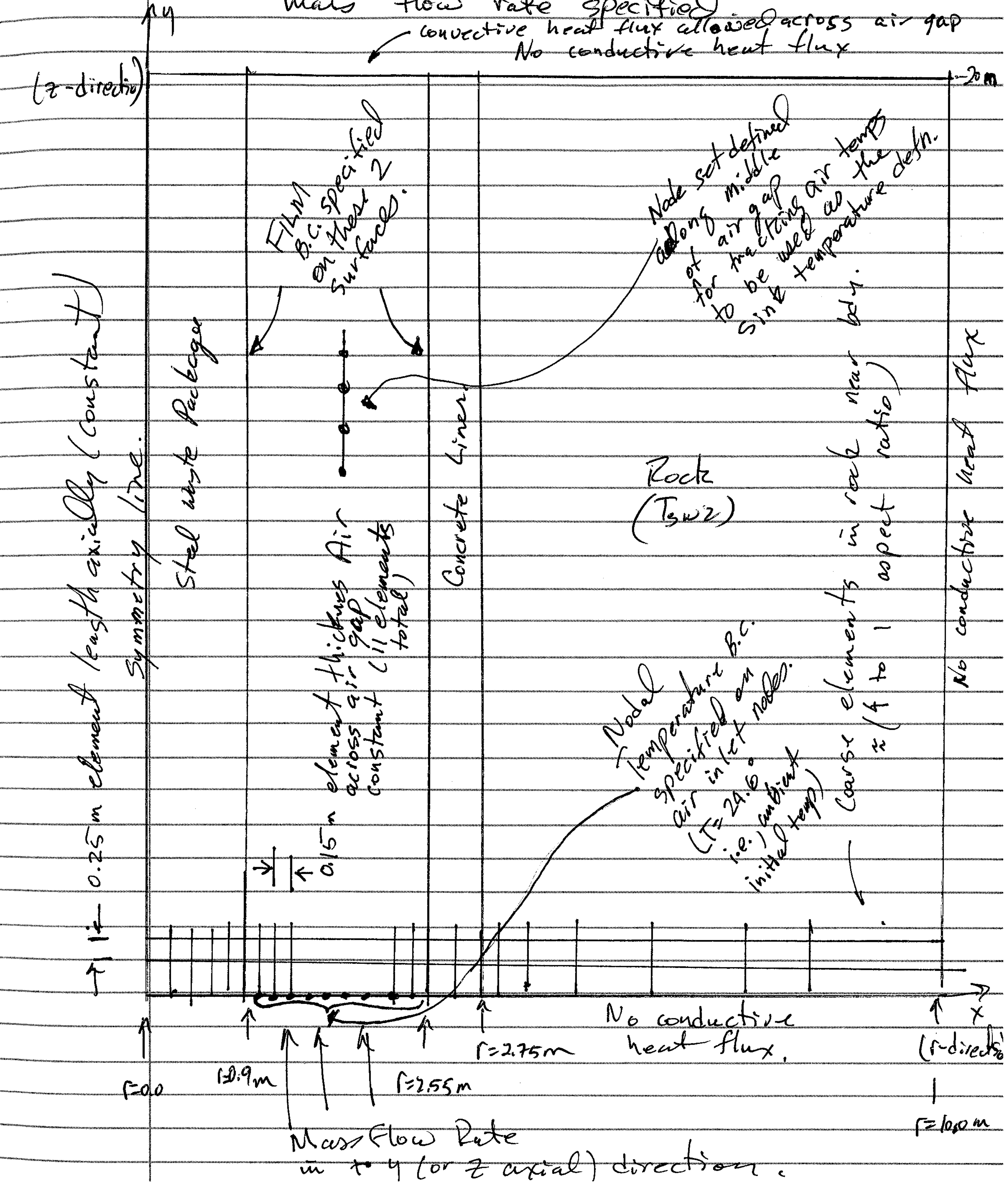
The radial extent of both models was 10 m from tunnel centerline.

Model #1 - Radiation heat transfer / no convection/diffusion elements in air gap.



Model #2 - Radiation heat transfer w/ convection/diffusion elements filling air void and mass flow rate specified



After several initial runs with Model #2 it was revealed that the mass flow rates needed to be specified for all Nodes within the air gap making up ~~the conve~~ or connected to the forced convection elements.

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Also, the ~~Nodal~~ air temperature at the inlet air nodes was required to be fixed at whatever the ventilation air temperature was to be. (in this model it was assumed fixed at initial temp of 24.6 °C).

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Again, for initial analyses, a constant mass flow rate was assumed. Basic ABAQUS commands for including mass flow rate as derived on page 7 are:

Model Definition Part of input deck

* Initial Mass Flow Rate
AIR_GAP, Value
Node ~~set~~ set containing all air gap nodes

CW 4/20/01

*STEP

Step Definition Section

* Mass Flow Rate
AIR_GAP, Value

ABAQUS commands in input decks of Both Models 1 and 2 for including the cavity radiation heat transfer from waste package to concrete liner.

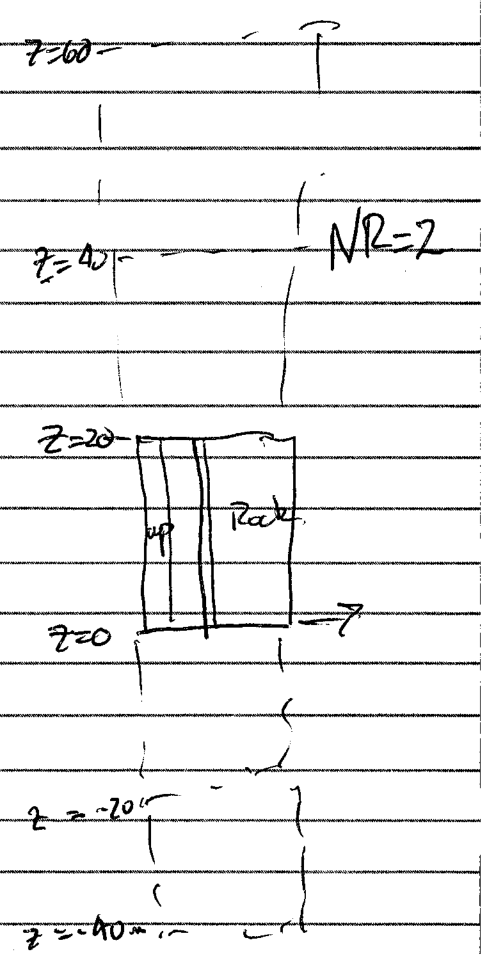
Model definition Part of input deck.

* Surface definition ← define waste pack and Conc. liner Surfaces.
* Emissivity
* Surface Property
* Physical Constants
* Cavity Definition.

*STEP

Step definition section

* Radiation Symmetry
* Radiation Viewfactor.



Note: Radiation Z-symmetry assume with # reflections i.e. -NR=2.

Requirement ⇒ NR > 0

As discussed earlier on pg 21, some approximation for the air "sink" temperature needed to be defined for the convective heat transfer off waste package and drift wall surfaces. In reality the air would begin to heat up down the axial length of the drift so that setting the sink temperature to a constant value would be inaccurate.

In order to specify a non-uniform sink temperature, the USER subroutine FILM within ABAQUS needed to be used with appropriate modifications. It was decided as an initial approach to track the temperature ~~of nodes~~ along a line of nodes centered between the waste package and concrete liner. The sink temperature to use for both waste package and conc. liner surface elements would be that midnodal air temperature at the same (or near) z-elevation. In order to track a list of nodal temperatures, the ABAQUS user subroutine UFIELD was required in addition to the FILM user subroutine.

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9/5/00

The following two pages contain the FORTRAN coding within these two user subroutines for linking/compiling with main ABAQUS input deck.

Note: NLIST = list of nodes along axial direction midway between wp an cl
ZLIST = z-elevations of such nodes.


```
      SUBROUTINE UFIELD(FIELD,KFIELD,MSECPT,KSTEP,KINC,TIME,NODE,
     1           COORDS,TEMP,DTEMP,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION FIELD(MSECPT,NFIELD),TIME(2),COORDS(3),
     1          TEMP(MSECPT),DTEMP(MSECPT)
C
C     This subroutine updates the values of temperature at nodal points
C     along a line using temperature calculated by ABAQUS. The line is
C     defined by nodes NLST, each of which lies at a distance ZLST from
C     the line's origin. The arrays NLST, ZLST, and TLST are consistent
C     and in order of increasing ZLST. All three arrays are initialized
C     in the BLOCK DATA named KDAXIS, but only TLST is updated inside
C     this subroutine
C
C     Author:                     G. I. Ofoegbu
C     Date:                       August 2 2000
C     System:                     ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KNLIST/ NLST(81)
      COMMON /KZLIST/ ZLST(81)
      COMMON /KTLIST/ TLST(81)
C
      I = 0
  100 I = I + 1
        IF (I .GT. 81) THEN
C
C         Error message for debugging if necessary
C
          RETURN
        ENDIF
        IF (NLST(I) .NE. NODE) GO TO 100
        TLST(I) = TEMP(1)
        FIELD(1,1) = TEMP(1)
        RETURN
      END
      BLOCK DATA KDAXIS
      INCLUDE 'ABA_PARAM.INC'
      COMMON /KNLIST/ NLST(81)
      COMMON /KZLIST/ ZLST(81)
      COMMON /KTLIST/ TLST(81)
      DATA NLST/
        2597,  2607,  2617,  2627,  2637,  2647,  2657,  2667,
     1  2677,  2687,  2697,  2707,  2717,  2727,  2737,  2747,
     2  2757,  2767,  2777,  2787,  2797,  2807,  2817,  2827,
     3  2837,  2847,  2857,  2867,  2877,  2887,  2897,  2907,
     4  2917,  2927,  2937,  2947,  2957,  2967,  2977,  2987,
     5  2997,  3007,  3017,  3027,  3037,  3047,  3057,  3067,
     6  3077,  3087,  3097,  3107,  3117,  3127,  3137,  3147,
     7  3157,  3167,  3177,  3187,  3197,  3207,  3217,  3227,
     8  3237,  3247,  3257,  3267,  3277,  3287,  3297,  3307,
     9  3317,  3327,  3337,  3347,  3357,  3367,  3377,  3387,
     A  3397/
      DATA ZLST/
        0.00,  0.25,  0.50,  0.75,  1.00,  1.25,  1.50,  1.75,
     1  2.00,  2.25,  2.50,  2.75,  3.00,  3.25,  3.50,  3.75,
     2  4.00,  4.25,  4.50,  4.75,  5.00,  5.25,  5.50,  5.75,
     3  6.00,  6.25,  6.50,  6.75,  7.00,  7.25,  7.50,  7.75,
     4  8.00,  8.25,  8.50,  8.75,  9.00,  9.25,  9.50,  9.75,
     5 10.00, 10.25, 10.50, 10.75, 11.00, 11.25, 11.50, 11.75,
     6 12.00, 12.25, 12.50, 12.75, 13.00, 13.25, 13.50, 13.75,
     7 14.00, 14.25, 14.50, 14.75, 15.00, 15.25, 15.50, 15.75,
     8 16.00, 16.25, 16.50, 16.75, 17.00, 17.25, 17.50, 17.75,
     9 18.00, 18.25, 18.50, 18.75, 19.00, 19.25, 19.50, 19.75,
     A 20.00/
      DATA TLST/81*24.6/
      END
      SUBROUTINE FILM(H,SINK,TEMP,KSTEP,KINC,TIME,NOEL,NPT,
     1    COORDS,JLTYP,FIELD,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION H(2),TIME(2),COORDS(3),FIELD(NFIELD)
C
C----67--1---------2---------3---------4---------5---------6---------7--
C     This subroutine evaluates the ambient temperature SINK required
C     to implement a convection boundary condition at the boundary point
C     defined by coordinates COORD (at integration point NPT of element
C     NOEL). The ambient temperature is solution-dependent and is set
C     equal to the temperature along the KDAXIS line at the axial
C     coordinate of NPT. The KDAXIS-line temperature is initialized in
C     the BLOCK DATA named KDAXIS and is updated in subroutine UFIELD.
C
```

File Name = airTemp01.f

mpa
9/5/00

```
C     This version of the subroutine is for an axisymmetric model (axial
C     coordinate equals COORD(2)) and the convection coefficient is
C     assumed to be constant (2.65 W/m/m/K)
C
C     Author:                  G. I. Ofoegbu
C     Date:                    August 2 2000
C     System:                  ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KZLIST/ ZLST(81)
      COMMON /KTLIST/ TLST(81)
C
      H(1) = 2.65
      H(2) = 0.0
      ZC = COORDS(2)
      IF (ZC .LT. ZLST(1)) THEN
C
C        Error message for debugging if necessary
C
        RETURN
      ENDIF
      I = 1
  100 I= I + 1
        IF (I .GT. 81) THEN
C
C        Error message for debugging if necessary
C
          RETURN
        ENDIF
        IF (ZC .GT. ZLST(I)) GO TO 100
        Z0 = ZLST(I-1)
        Z1 = ZLST(I)
        T0 = TLST(I-1)
        T1 = TLST(I)
        SINK = T0 + (T1 - T0)*(ZC - Z0)/(Z1 - Z0)
        RETURN
      END
```

Additional ABAQUS commands to include within input deck to incorporate above 2 user subroutines.

model defn. section

*Initial Conditions, TYPE=FIELD, VAR=1
AIR_SINK, 24.6 ← initial temp.
↑ line of nodes.

*USER SUBROUTINES, INPUT = airTemp01.f

Step defn section.

*STEP

*FIELD, VAR=1, USER
AIR_SINK.

*FILM
$\underbrace{\quad\quad}_{\text{Surface}}$, FNU,
↑ face #

MA/8/14/00

Initial ABAQUS analyses results.

Model #1 - Radiation heat transfer only.

Transient Thermal Analyses.

Time Period = 1.0 month (2.592×10^{6} Sec)

Wast Package Surface Temp (Nodal)
- Entrance = 60.71 °C
- Exit = 60.71 °C

Concrete Liner Surface Temp (Nodal)
- Entrance = 44.73 °C
- Exit = 44.73 °C

Heat Flux (Element) in Radial Direction (HFL1)

Waste Package = 89.25 W/m^2
Concrete Liner = 33.01 W/m^2.

Note: Temperatures and heat fluxes constant in axial z-direction because of Symmetry.

Model #2. Radiation heat transfer analyses with convection / diffusion elements included. Conduction allowed across convection / diffusion elements, but mass flow rate set to 0.0 $kg/m^2 \cdot s$.

Thus, model still symmetric in z-axial direction.

Transient Thermal Analyses.

Time Period = 1 month.

Waste package Surface Temp. (Nodal)
- Entrance = 61.61 °C
- Exit = 61.61 °C

Concrete Liner Surface Temp (Nodal)
- Entrance = 45.56 °C
- Exit = 45.56 °C

Mid-Air Nodal Temp = 52.3 °C

Heat Flux in Radial Direction (HFL1)

Waste Package = 90.83 W/m^2
Concrete Liner = 33.66 W/m^2.

Discussion

As can be seen in the results of the two transient analyses the radiation heat transfer (i.e. cavity radiation) is effectively being modeled even with the presence of the convection / diffusion elements filling the air gap as can be seen by comparison of temperatures and element heat fluxes on WP an CL surface. The temperature and heat flux on concrete liner surface is slightly higher in Model 2 results because of the additional conductive heat transfer component across the air gap. The conduction through air is very small as expected, leading only to a slight increase after 1 month of heating.

MA 8/15/00

ABAQUS analyses was next conducted for Model #2 with the air mass flow rate turned on.

Transient Thermal analyses

- Radiation / Conduction heat transfer of to a time period of t = 1.0 yr, with mass flow rate set to 0.0 kg/m²s.
- At t = 1.0 yr, mass flow rate (constant) turned on for a period of 1/2 hr based on volumetric flow rate = 10.0 m³/s.

ABAQUS Results. –

Waste Package Surface.

Z coord (m)	t = 1 year: Temperature Radiation/Conduction only (°C)	t = 1 year + 1/2 hr ventilation: Temperature Radiation/Conduction Convection (°C)
0.0	80.20	80.13
5.0	87.36	86.61
10.0	89.04	88.40
15.0	88.61	88.06
20.0	86.58	86.04

Leftmost Air Node (immediately adjacent to Waste Package.

0.0	24.6	24.6
5.0	85.9	25.10
10.0	87.57	25.63
15.0	87.15	26.16
20.0	85.15	26.65

Mid Air Gap Nodes:

Z coord (m)	Temp Radiation/ Conduction only (°C)	Temp Radiation/ Conduction/ Convection °C
0.0	24.6	24.6
5.0	81.60	24.6
10.0	83.24	24.6
15.0	82.81	24.6
20.0	80.82	24.6

Rightmost air Node (immediately adjacent to concrete liner)

0.0	24.6	24.6
5.0	78.06	25.04
10.0	79.62	25.52
15.0	79.20	25.59
20.0	76.88	26.44

Concrete Liner Surface

0.0	65.27	65.32
5.0	77.49	75.20
10.0	79.03	76.99
15.0	78.61	76.82
20.0	76.17	74.64

Element Heat Flux (Radial Direction – HFL1)

Waste Package

Approx Element Location Int. Pt #4 Z (m)	Heat Flux Rad./Cond only (W/m²)	Heat Flux Rad/cond/conv. W/m²
0.0	155.2	201.4
5.0	92.12	230.3
10.0	93.96	213.3
15.0	93.79	197.4
20.0	106.2	207.2

Concrete Liner

0.0	30.07	-22.59
5.0	30.77	-15.99
10.0	30.40	-10.75
15.0	26.41	-10.58
20.0	26.28	-8.07

Discussion of Results:

This ABAQUS analysis was a transient heat transfer analyses to test out use of the forced convection/diffusion analyses. The drift was first heated with mass flow rate set to 0.0 kg/m²·s. Analyses run out to thermal time of 1 year. Because mass flow rate was 0.0 large thermal time steps could be allowed, such that 1st part of analyses was completed in say

r 15 minutes. Once the ventilation was turned on with use of the (DCCAX4D) convection/diff.-elements w/ dispersion control, time step was automatically reduce to roughly 0.3 s based on Courant stability condition (see pgs. 17-19). Even a 1/2 hour transient ventilation analyses was an over night job on an SGI R10,000 workstation.

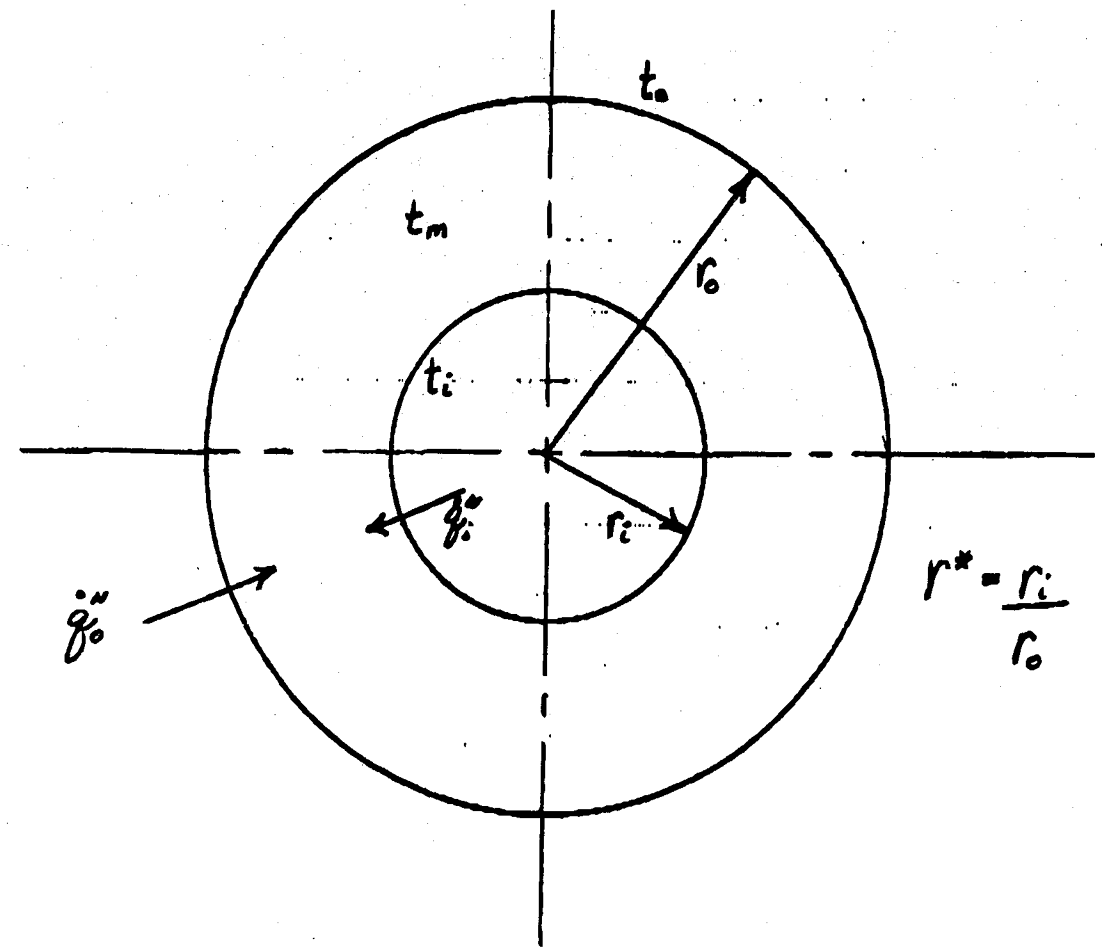
However, transient results with ventilation for this 1/2 hour period shows that the cool ventilation air is convected down the axial length of drift. Central portion of air remains at 24.6°C and only a small thermal boundary layer develops in the air where (or within which) all the convection heat transfer takes place (i.e., 1-2 elements into the air stream based on this 20 m length of model in axial direction.

The temperature of the concrete liner surface can be seen to begin cooling down with the ventilation (albeit only a few degrees after 1/2 hour of cooling). The flux of heat of the concrete liner also turns negative as more heat is being convected into air stream than is being radiated across air gap.

Finally, the heat flux of the waste package is greatly increased with the added component of the convective heat flux into the air stream in addition to the radiation and conductive heat flux components.

MA
8/16/00

Discussions were held with G. Ofoegbu and D. Gute (CNWRA) on use of a constant mass flow rate across the air gap for the ventilation analyses. In reality, assuming a fully developed flow regime, a parabolic velocity profile develops across the airgap, with the velocity (axial) = 0.0 at both surfaces and reaching a maximum value at the center of the air gap. As the mass flow rate/unit area is simply the velocity of the fluid multiplied by the air density (assume constant) the mass flow rate for a fully developed flow regime should also have a parabolic type profile. It was not clear whether using a constant mass flow rate was strongly influencing the convective and conductive heat transfer off the waste package and concrete liner surfaces. It was decided to improve on the mass flow rate input to the air gap (i.e. cross-sectional flow area) based on a solution for fully developed laminar flow between two concentric cylinders. The solution was developed by Doug Gute based on concentric - circular tube annulus w/ fully developed vel. and temp profiles, "Convective Heat and Mass Transfer", Kays/Crawford, 2nd Ed. McGraw Hill. Solution provided on following 2 pages.



The Concentric Circular-Tube Annulus With Fully Developed Velocity and Temperature Profiles, Asymmetric Heating, from "Convective Heat and Mass Transfer," Kays/Crawford, 2'nd Edition, McGraw-Hill, ISBN 0-07-033457-9.

$$u(r) = 2\frac{V}{M}\left[1 - \left(\frac{r}{r_o}\right)^2 + B \ln\frac{r}{r_o}\right]$$; fluid velocity in the axial direction

where

$$B = \frac{r^{*2} - 1}{\ln(r^*)}$$

$$M = 1 + r^{*2} - B$$

$$V = \frac{\dot{m}}{A_c \rho}$$; mean fluid velocity in the axial direction

$$\dot{m} = \int_{A_c} u \rho \, dA_c \quad ; \text{ total mass flow rate}$$

$A_c \equiv$ flow cross-sectional area

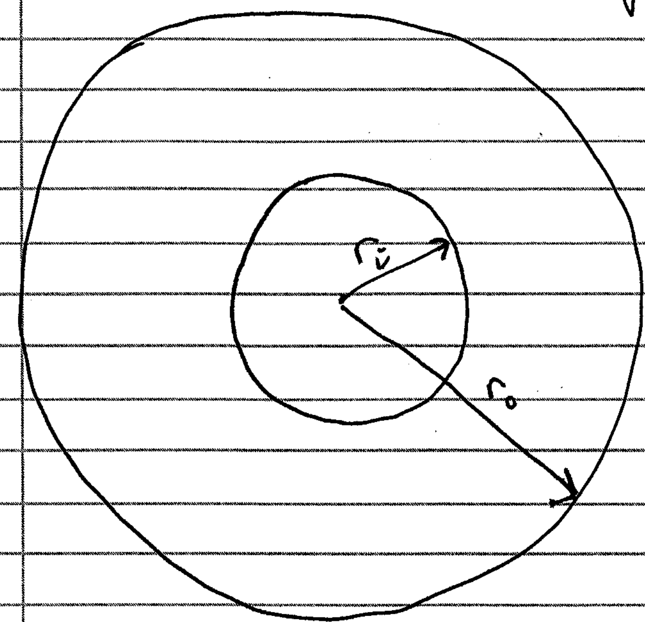
$$t_m = \frac{1}{A_c V} \int_{A_c} u t \, dA_c \quad ; \text{ mixed mean fluid temperature}$$

$$\dot{q}_o'' = h\,(t_o - t_m)$$

$$\dot{q}_i'' = h\,(t_i - t_m)$$

MA
8/16/00

Velocities u(r) were developed for Model #2 for each radial node location within the air gap.



$r_i = 0.90$ m

$r_o = 2.55$ m,

$$r^* = \frac{r_i}{r_o} = \frac{0.9\text{m}}{2.55\text{m}} = 0.35294$$

$$u(r) = \frac{2V}{M}\left[1 - \left(\frac{r}{r_o}\right)^2 + B \ln \frac{r}{r_o}\right]$$

where u(r) = air velocity in axial direction

and

$$B = \frac{r_*^2 - 1}{\ln(r^*)} = \frac{(0.35294)^2 - 1}{\ln(0.35294)} = \frac{-0.87543}{-1.04146}$$

$\underline{B = 0.84058}$

$$M = 1 + r^{*2} - B = 1 + (0.35294)^2 - 0.84058$$

$\underline{\underline{M = 0.28399}}$

$$V = \frac{\dot{m}}{A_c \rho}$$

where V = mean fluid velocity in axial direction.

A_c = flow cross-sectional area.

$$A_c = \pi(r_o^2 - r_i^2) = \pi\left[(2.55\ m)^2 - (0.9\ m)^2\right]$$

$$A_c = 17.88\ m^2$$

$\rho_{air} = 1.205\ Kg/m^3$ @ $20^\circ C$

$$\dot{m} = \text{mass flow rate} = \int_{A_c} u \rho \, dA_c$$

$$= (\text{Volumetric flow rate}) * (\text{Density})$$

$$\dot{m} = \left(10\ \frac{m^3}{s}\right)\left(1.205\ \frac{Kg}{m^3}\right) = 12.05\ Kg/s$$

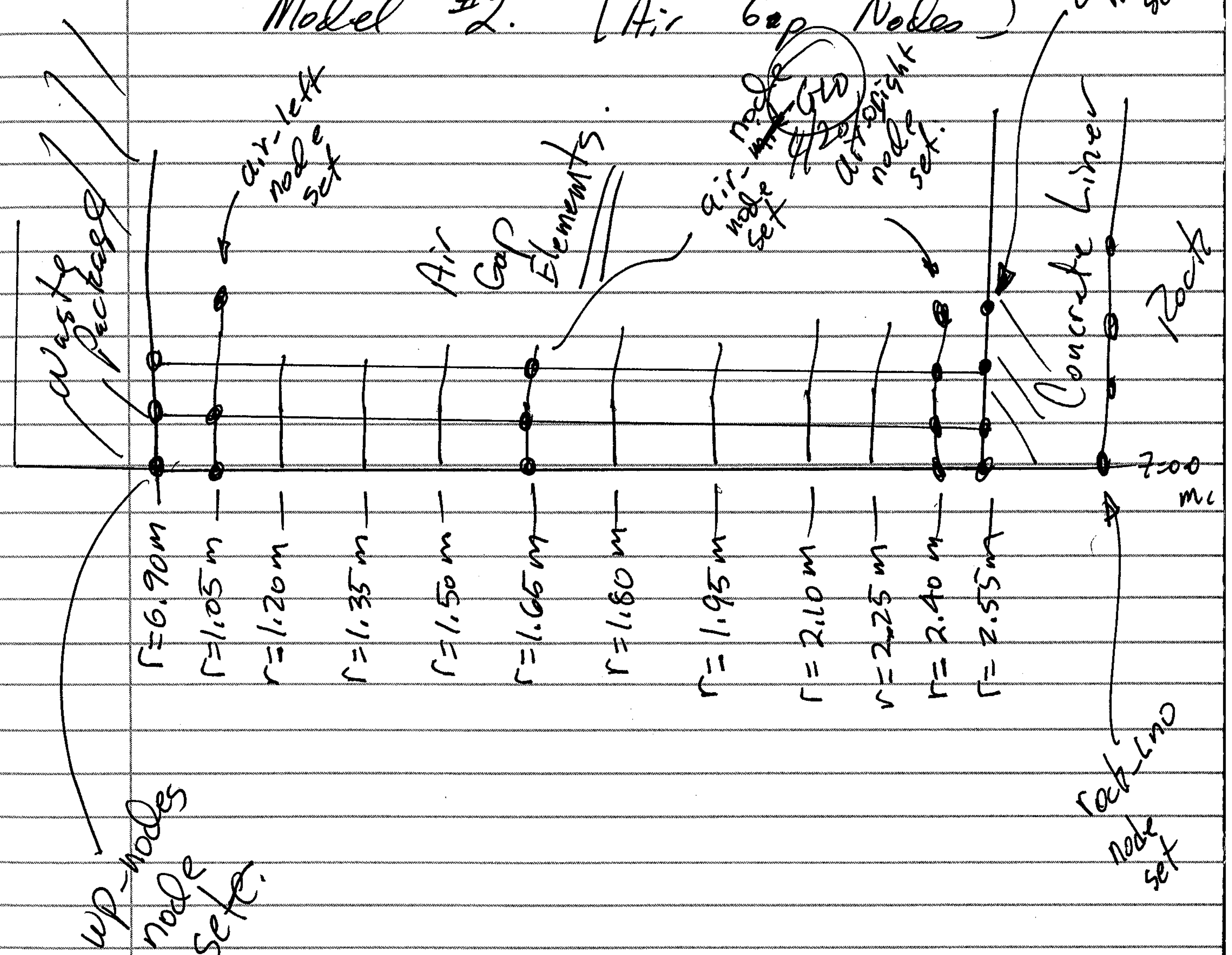
$$\therefore V = \frac{\dot{m}}{A_c \rho} = \frac{12.05\ Kg/s}{(17.88\ m^2)(1.205\ Kg/m^3)}$$

$$\underline{\underline{V = 0.559\ m/s.}}$$

$$\therefore u(r) = \frac{2(0.559)}{0.28399}\left[1 - \left(\frac{r}{2.55}\right)^2 + 0.84058 \ln\left(\frac{r}{2.55}\right)\right]$$

$$\underline{\underline{u(r) = 3.9368\left[1 - \left(\frac{r}{2.55}\right)^2 + 0.84058 \ln\left(\frac{r}{2.55}\right)\right]}}$$

Note. Model #2. [Air Gap Nodes]



Axial Air Velocity		Mass Flow Rate/unit Area ($kg/m^2 s$)
$u(r=0.90) = 0.0$		$M(r=0.90) = 0.0$
$u(r=1.05) = 0.33306$	m/s.	$M(r=1.05) = 0.40134$
$u(r=1.20) = 0.5706$	m/s.	$M(r=1.20) = 0.68757$
$u(r=1.35) = 0.72880$	m/s.	$M(r=1.35) = 0.87820$
$u(r=1.50) = 0.81863$	m/s.	$M(r=1.50) = 0.98645$
$u(r=1.65) = 0.84797$	m/s	$M(r=1.65) = 1.0218$
$u(r=1.80) = 0.8226$	m/s.	$M(r=1.80) = 0.99123$
$u(r=1.95) = 0.74692$	m/s.	$M(r=1.95) = 0.90004$
$u(r=2.10) = 0.62436$	m/s	$M(r=2.10) = 0.75235$
$u(r=2.25) = 0.45763$	m/s	$M(r=2.25) = 0.55144$
$u(r=2.40) = 0.24891$	m/s.	$M(r=2.40) = 0.29994$
$u(r=2.55) = 0.0$		$M(r=2.55) = 0.0$

mass flow rate/unit area $= u(r) * \rho = \frac{m}{s} \cdot \frac{kg}{m^3} = \frac{kg}{m^2 \cdot s}$

Assume $\rho = 1.205\ kg/m^3$ @ 20°C

Note:
For the revised future ABAQUS analyses, a variable mass flow rate with radial distance within air gap as defined on page 48. Within the ABAQUS input deck, separate node sets had to be generated for each column of air nodes at a given radial distance and assigned a distinct mass flow rate.

MA
8/17/00

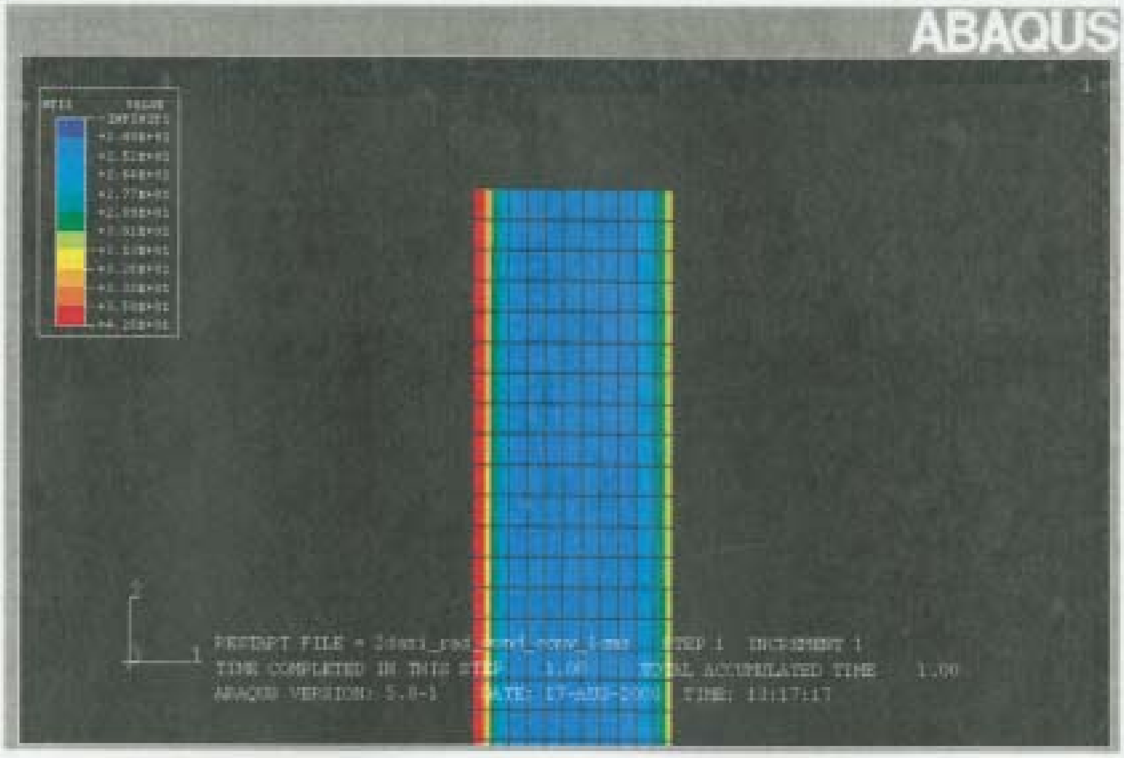
It was decided that steady-state solutions be attempted with ABAQUS for both the 1.0 m^3/s and 10.0 m^3/s. For the steady state solution, a constant heat flux (ie volumetric) value must be assumed and not the AMPLITUDE decay curve as was used for the transient analyses. An initial value of 237.6 W/m^3 at $t=0$ as shown on page 9 was assumed.

It is thought that because of the small time step limitations in the transient analyses, that an alternative approach would be to develop several steady state solutions at different vol. heat flux values along the decay curve. defined on page 9.

Figure 1 on the following page shows a steady state solution for temperature contours within the air gap elements alone (ie. waste package, concrete liner, and rock not shown) at both the inlet and exit region of the 20 m long model (#2) based on a 1.0 m^3/s volumetric flow rate and constant heat generation rate = 237.6 W/m^3.

Note: ABAQUS assumes laminar air flow with no mixing of the air.

Variable NT11 = Temperature (°C)



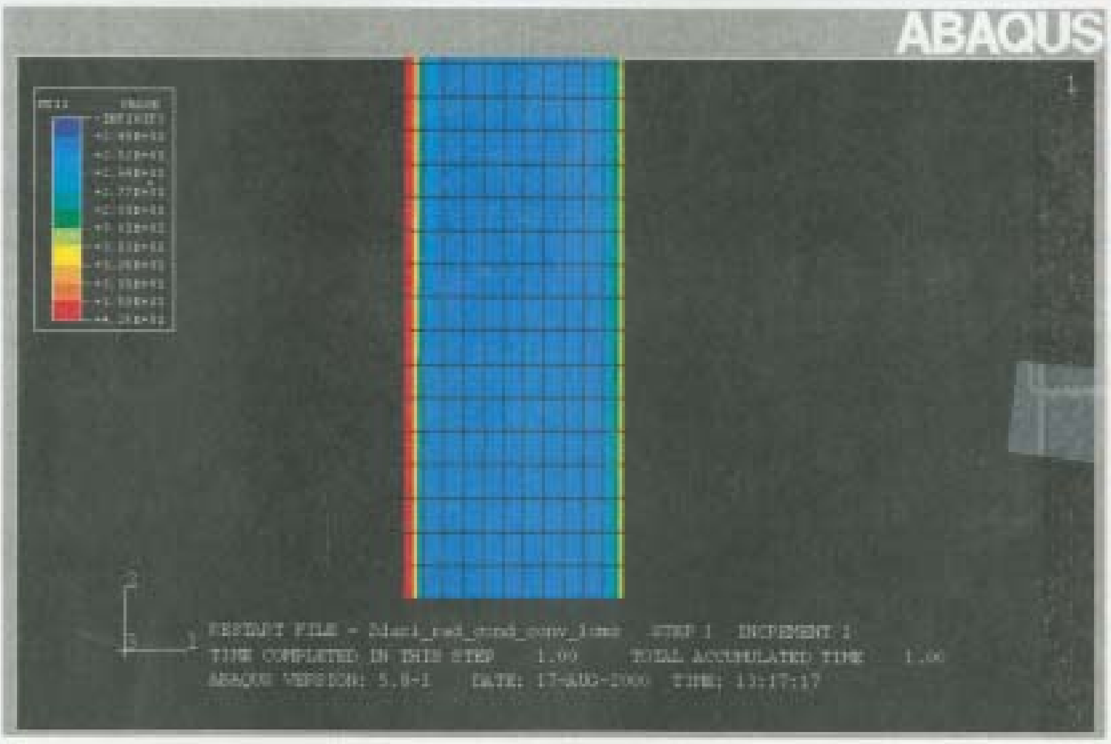


Figure 1. Temperature within air gap based on a steady-state solution assuming 1.0 m^3/s volumetric flow rate for inlet region (bottom figure) [inlet air temperature = 24.6 deg], and the exit region (top figure). [Note: Total axial length of model = 20.0 m, Constant waste package volumetric heat flux = 237 W/m^3, Outer waste package surface on left side and concrete liner on right side of air gap, Air flow in positive y-direction (i.e., upwards)]

Again, over this 20 m axial length, only a small thermal boundary layer develops where all the convective heat transfer occurs, even for a rather small vol. flow rate of 1.0 m^3/s. Air adjacent to waste package and concrete liner is heated up within only 1 element at inlet region, and slightly over 2 elements at exit region. This steady state solution was achieved in a matter of only a few minutes for this 20 m drift model (axisymmetric).

However, as can be seen from Figure 1, it will take a considerably longer drift length to be included in the model to show significant heating of the air and noticeable changes in temperature and heat fluxes in the axial direction along the drift. These results include a variable mass flow rate and sink temperature defined by mid-air gap node temperature.

The following pages show printouts of nodal temps and heat fluxes based on steady-state solutions for the 1.0 m^3/s and 10.0 m^3/s volumetric flow rates. [Same constant heat flux = 237.6 W/m^2] for waste package.

34 2000 res_1cms Page 1

ABAQUS Results

S T E P 1 S T E A D Y S T A T E H E A T T R A N S F E R

Volumetric Flow Rate ⇒ 1.0 m^3/s.

Steady-State Heat Transfer Analysis

MPA 8/18/00

AUTOMATIC TIME CONTROL WITH -
A SUGGESTED INITIAL TIME INCREMENT OF 1.00
AND A TOTAL TIME PERIOD OF 1.00
THE MINIMUM TIME INCREMENT ALLOWED IS 1.000E-05
THE MAXIMUM TIME INCREMENT ALLOWED IS 1.00

UNSYMMETRIC MATRIX STORAGE AND SOLUTION WILL BE USED

INCREMENT 1 SUMMARY

TIME INCREMENT COMPLETED 1.00 , FRACTION OF STEP COMPLETED 1.00
STEP TIME COMPLETED 1.00 , TOTAL TIME COMPLETED 1.00

E L E M E N T O U T P U T

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET WP_ELEMS waste package

ELEMENT	PT	FOOT-NOTE	HFL1 (radial heat flux W/m^2)	
6	1		98.30	~ z=0 m
6	2		98.30	
6	3		98.31	
6	4		98.31	
126	1		98.29	z= 5 m
126	2		98.29	
126	3		98.29	
126	4		98.29	
246	1		98.27	z= 10 m
246	2		98.27	
246	3		98.27	
246	4		98.27	
366	1		98.26	z= 15 m
366	2		98.26	
366	3		98.26	
366	4		98.26	
480	1		98.32	z=20 m
480	2		98.32	
480	3		98.32	
480	4		98.32	

MPA 8/18/00

MAXIMUM 98.32
ELEMENT 480

MINIMUM 98.26
ELEMENT 366

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET WP_ELEMS waste package

(axial heat flux w/m^2)

MPA 8/18/00

ELEMENT	PT	FOOT-NOTE	HFL2
6	1		-5.2412E-03
6	2		-3.7638E-03
6	3		-5.2412E-03
6	4		-3.7638E-03
126	1		-0.4395
126	2		-0.4402
126	3		-0.4395
126	4		-0.4402
246	1		-0.4334
246	2		-0.4336
246	3		-0.4334
246	4		-0.4336
366	1		-0.2536
366	2		-0.2541
366	3		-0.2536
366	4		-0.2541
480	1		1.7562E-02
480	2		2.1818E-02
480	3		1.7562E-02
480	4		2.1818E-02

Same approx. Z-coords as previous page.

MAXIMUM 2.1818E-02
ELEMENT 480

MINIMUM -0.4402
ELEMENT 126

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET CL_ELEMS concrete liner

(radial) MPA 8/18/00

ELEMENT	PT	FOOT-NOTE	HFL1
481	1		-3.8670E-03
481	2		-3.8670E-03
481	3		-5.7317E-03
481	4		-5.7317E-03
519	1		-1.9566E-02
519	2		-1.9566E-02
519	3		-1.8818E-02
519	4		-1.8818E-02
559	1		3.8786E-03
559	2		3.8786E-03
559	3		4.4485E-03
559	4		4.4485E-03
599	1		2.0277E-02
599	2		2.0277E-02
599	3		2.0628E-02
599	4		2.0628E-02

639	1		-1.5563E-02
639	2		-1.5563E-02
639	3		-2.0256E-02
639	4		-2.0256E-02

MAXIMUM 2.0628E-02
ELEMENT 599

MINIMUM -2.0256E-02
ELEMENT 639

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET CL_ELEMS concrete liner

(axial) MPA 8/18/00

ELEMENT	PT	FOOT-NOTE	HFL2
481	1		4.9107E-03
481	2		4.1648E-03
481	3		4.9107E-03
481	4		4.1648E-03
519	1		-1.7229E-02
519	2		-1.6929E-02
519	3		-1.7229E-02
519	4		-1.6929E-02
559	1		-1.8928E-02
559	2		-1.8700E-02
559	3		-1.8928E-02
559	4		-1.8700E-02
599	1		-9.8315E-03
599	2		-9.6910E-03
599	3		-9.8315E-03
599	4		-9.6910E-03
639	1		9.9228E-03
639	2		8.0456E-03
639	3		9.9228E-03
639	4		8.0456E-03

MAXIMUM 9.9228E-03
ELEMENT 639

MINIMUM -1.8928E-02
ELEMENT 559

MPA 8/18/00

N O D E O U T P U T

(See Page 47 for radial location of Node sets)

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET WP_NODES

NODE	FOOT-NOTE	NT11

— Temperature (°C)

147	42.53
287	42.58
427	42.62
567	42.63

MAXIMUM 42.63
AT NODE 567

MINIMUM 42.50
AT NODE 7

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_LEFT

MPA 8/18/00

NODE	FOOT-NOTE	NT11	
2593		24.60	z=0
2793		26.79	z=5 m
2993		28.44	z=10 m
3193		29.71	z=15 m
3393		30.67	z=20 m

MAXIMUM 30.67
AT NODE 3393

MINIMUM 24.60
AT NODE 2593

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_NODE (middle)

MPA 8/18/00

NODE	FOOT-NOTE	NT11
2597		24.60
2797		24.60
2997		24.60
3197		24.60
3397		24.60

MAXIMUM 24.60
AT NODE 3397

MINIMUM 24.60
AT NODE 2597

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_RGHT

NODE	FOOT-NOTE	NT11
2602		24.60
2802		25.82
3002		26.66
3202		27.26

3402	27.69

MAXIMUM 27.69
AT NODE 3402

MINIMUM 24.60
AT NODE 2602

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET CL_NODES (r=2.55m)

MPA 8/18/00

NODE	FOOT-NOTE	NT11
568		31.75
628		31.76
688		31.80
748		31.83
808		31.82

MAXIMUM 31.83
AT NODE 748

MINIMUM 31.75
AT NODE 568

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET ROCK_LNO (r=2.75m)

MPA 8/18/00

NODE	FOOT-NOTE	NT11	
570		31.75	z=0.0
630		31.76	z=5.0
690		31.80	z=10.0 m
750		31.83	z=15.0
810		31.82	z=20.0 m

same z-coord for all ~~temp~~ node output at all node sets.

MAXIMUM 31.83
AT NODE 750

MINIMUM 31.75
AT NODE 570

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET ROCK_RNO (r=10.0m)

NODE	FOOT-NOTE	NT11
1632		31.77
1872		31.78
2112		31.80
2352		31.81
2592		31.81

MAXIMUM 31.81

ABAQUS Results

STEP 1 STEADY STATE HEAT TRANSFER

Steady-State Heat Transfer Analysis

Volumetric Air Flow = 10.0 m^3/s.

AUTOMATIC TIME CONTROL WITH -
A SUGGESTED INITIAL TIME INCREMENT OF 1.00
AND A TOTAL TIME PERIOD OF 1.00
THE MINIMUM TIME INCREMENT ALLOWED IS 1.000E-05
THE MAXIMUM TIME INCREMENT ALLOWED IS 1.00

MPA 8/18/00

UNSYMMETRIC MATRIX STORAGE AND SOLUTION WILL BE USED

INCREMENT 4 SUMMARY

TIME INCREMENT COMPLETED 0.203 , FRACTION OF STEP COMPLETED 1.00
STEP TIME COMPLETED 1.00 , TOTAL TIME COMPLETED 1.00

ELEMENT OUTPUT

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET WP_ELEMS

waste package (radial heat flux, w/m^2)

ELEMENT	PT	FOOT-NOTE	HFL1	
6	1		98.28	z=0.0 m
6	2		98.28	
6	3		98.28	
6	4		98.28	
126	1		98.28	z=5.0 m
126	2		98.28	
126	3		98.28	
126	4		98.28	
246	1		98.28	z=10.0 m
246	2		98.28	
246	3		98.28	
246	4		98.28	
366	1		98.28	z=15.0 m
366	2		98.28	
366	3		98.28	
366	4		98.28	
480	1		98.27	z=20.0 m
480	2		98.27	
480	3		98.27	
480	4		98.27	

Note: 4 integration points/element

MPA 8/18/00

MAXIMUM 98.28
ELEMENT 126

MINIMUM 98.27
ELEMENT 480

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET WP_ELEMS

waste package (Axial heat flux, w/m^2)

MPA 8/18/00

ELEMENT	PT	FOOT-NOTE	HFL2
6	1		1.2893E-03
6	2		1.5088E-03
6	3		1.2893E-03
6	4		1.5088E-03
126	1		-3.3661E-02
126	2		-3.3703E-02
126	3		-3.3661E-02
126	4		-3.3703E-02
246	1		-6.1674E-02
246	2		-6.1705E-02
246	3		-6.1674E-02
246	4		-6.1705E-02
366	1		-6.5261E-02
366	2		-6.5343E-02
366	3		-6.5261E-02
366	4		-6.5343E-02
480	1		-2.1159E-03
480	2		-1.8759E-03
480	3		-2.1159E-03
480	4		-1.8759E-03

MAXIMUM 1.5088E-03
ELEMENT 6

MINIMUM -6.5343E-02
ELEMENT 366

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET CL_ELEMS

concrete liner (radial heat flux, w/m^2)

ELEMENT	PT	FOOT-NOTE	HFL1
481	1		3.4255E-04
481	2		3.4255E-04
481	3		2.8777E-04
481	4		2.8777E-04
519	1		-3.2300E-03
519	2		-3.2300E-03
519	3		-3.2035E-03
519	4		-3.2035E-03
559	1		-1.0968E-03
559	2		-1.0968E-03
559	3		-1.0135E-03
559	4		-1.0135E-03
599	1		2.2424E-03
599	2		2.2424E-03
599	3		2.3527E-03
599	4		2.3527E-03

MPA 8/18/00

Same approx. z-coords as on adjacent page.

639	1	2.9167E-03
639	2	2.9167E-03
639	3	2.5125E-03
639	4	2.5125E-03

MAXIMUM 2.9167E-03
ELEMENT 639

MINIMUM -3.2300E-03
ELEMENT 519

THE FOLLOWING TABLE IS PRINTED AT THE INTEGRATION POINTS FOR ELEMENT TYPE DCAX4 AND ELEMENT SET CL_ELEMS Concrete liner.

(axial heat flux, W/m^2)

MPA 8/18/00

ELEMENT	PT	FOOT-NOTE	HFL2
481	1		2.9840E-04
481	2		2.7649E-04
481	3		2.9840E-04
481	4		2.7649E-04
519	1		-9.5026E-04
519	2		-9.3963E-04
519	3		-9.5026E-04
519	4		-9.3963E-04
559	1		-2.7532E-03
559	2		-2.7199E-03
559	3		-2.7532E-03
559	4		-2.7199E-03
599	1		-2.8508E-03
599	2		-2.8067E-03
599	3		-2.8508E-03
599	4		-2.8067E-03
639	1		6.7616E-04
639	2		5.1446E-04
639	3		6.7616E-04
639	4		5.1446E-04

MAXIMUM 6.7616E-04
ELEMENT 639

MINIMUM -2.8508E-03
ELEMENT 599

MPA 8/18/00

N O D E O U T P U T

(See page 47 for radial location of following node sets).

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET WP_NODES r=0.9 m

NODE FOOT-NOTE NT11 — Temper~~ature~~ature (°C)

147	42.43
287	42.43
427	42.44
567	42.44

MAXIMUM 42.44
AT NODE 567

MINIMUM 42.42
AT NODE 7

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_LEFT

MPA 8/18/00

NODE	FOOT-NOTE	NT11	
2593		24.60	— z=0.0
2793		24.85	— z=5.0
2993		25.09	— z=10.0
3193		25.33	— z=15.0
3393		25.55	— z=20.0 m

Note: Same z-coord for all node set temperature results.

MAXIMUM 25.55
AT NODE 3393

MINIMUM 24.60
AT NODE 2593

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_NODE

NODE	FOOT-NOTE	NT11
2597		24.60
2797		24.60
2997		24.60
3197		24.60
3397		24.60

MAXIMUM 24.60
AT NODE 3397

MINIMUM 24.60
AT NODE 2597

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET AIR_RGHT

NODE	FOOT-NOTE	NT11
[illegible]602		24.60
[illegible]02		24.74
[illegible]002		24.88
[illegible]202		25.01

3402	25.14

MAXIMUM 25.14
AT NODE 3402

MINIMUM 24.60
AT NODE 2602

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET CL_NODES

r=2.55 m

MPA
8/18/00

NODE	FOOT-NOTE	NT11
568		31.67
628		31.67
688		31.68
748		31.68
808		31.69

MAXIMUM 31.69
AT NODE 808

MINIMUM 31.67
AT NODE 628

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET ROCK_LNO

r=2.75 m

MPA
8/18/00

NODE	FOOT-NOTE	NT11
570		31.67
630		31.67
690		31.68
750		31.68
810		31.68

MAXIMUM 31.68
AT NODE 810

MINIMUM 31.67
AT NODE 630

THE FOLLOWING TABLE IS PRINTED FOR NODES BELONGING TO NODE SET ROCK_RNO

MPA
8/18/00

r= 10.0 m.

NODE	FOOT-NOTE	NT11
1632		31.67
1872		31.68
2112		31.68
2352		31.68
2592		31.68

MAXIMUM 31.68

Note:
No flux
Boundary.
[will need to be modified]

Note: Steady state results on previous pages assume a no-flux boundary at r=10.0 m. There is no way to simulate the vertical symmetry plane midway between the drifts with an axisymmetric model. The outer radial boundary should actually be at r=14.0 m to represent a 28 m drift spacing for final calculations. However, in addition, this outer boundary is not entirely correct assuming it [no flux.].

~~Note. Because of the incorrect outer thermal boundary condition, final analysis should be full 3D Analyses.~~

MA
8/18/00

Further discussions w/ Goodluck Ofoegbu indicated the need [based on previous results] to extend the model in the axial direction. This was felt necessary in order to simulate the heating of the air and axial direction changes in temperatures and heat fluxes.

It was suggested by G. Ofoegbu to extend the 2D axisymmetric model to the full 600 m drift length [as is actually planned in the repository].

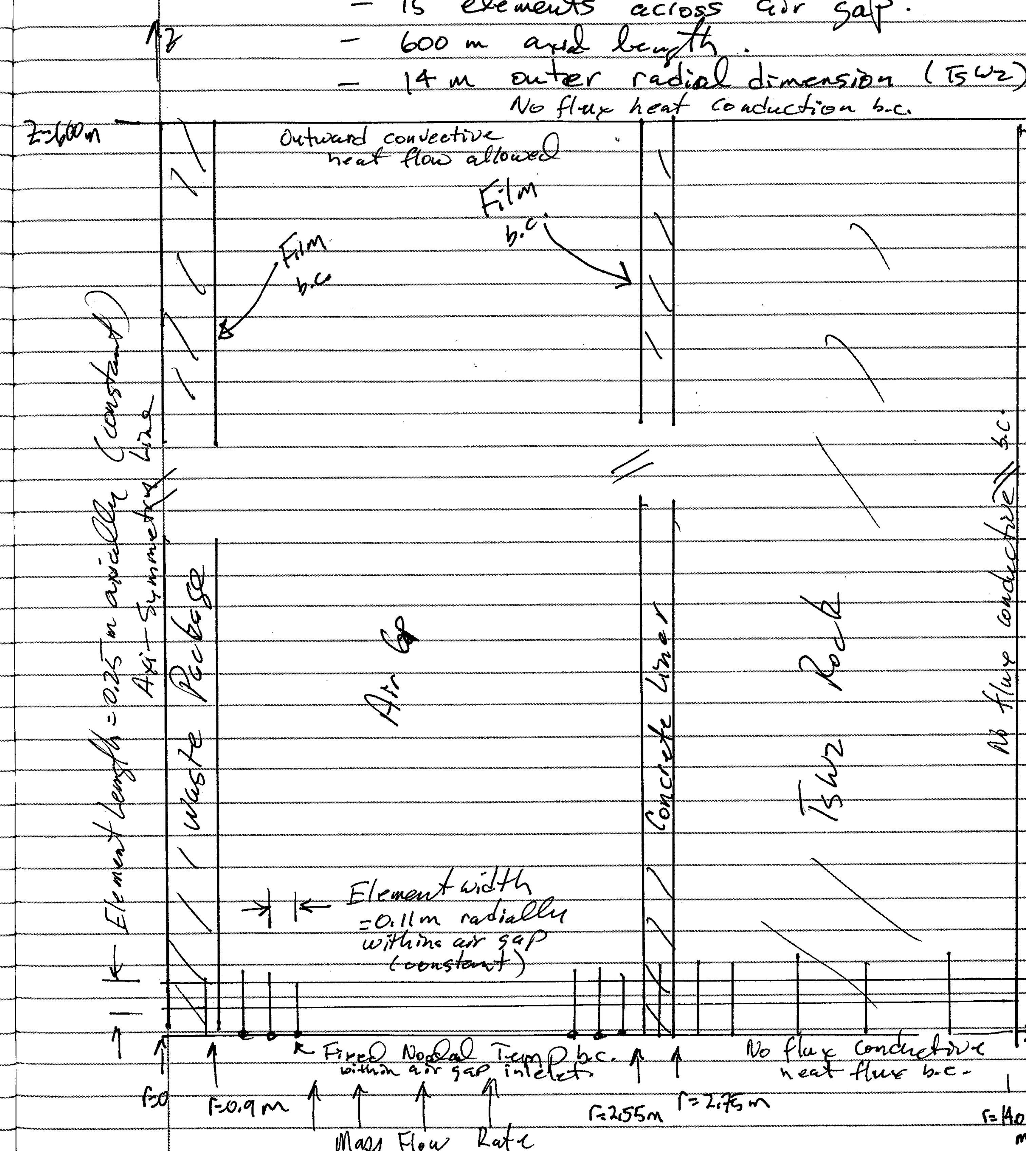
In addition to extending the model in the axial direction to 600 m assuming a constant element length in axial direction of 0.25 m, the element width of the air gap elements was reduced from 0.15 m to 0.11 m to model more accurately the temperature profile across the air gap. The outer radial dimension of the model was also extended

from r=10.0 m to r=14.0 m to better represent the 28 m drift spacing. [See Note on page 63 regarding assumed b.c. at r=14.0m].

MA 8/18/00

Revised Model #2 (600 m drift)

- 15 elements across air gap.
- 600 m axial length.
- 14 m outer radial dimension (TSw2)



Note:

Because of the modified radial mesh through the air gap (i.e., reduced element width from 0.15 m to 0.11 m), the mass flow rates to each column of nodes within air gap at a fixed radius was required to be recalculated [see page 47 for u(r) equation].

The following page shows the modified mass flow rates assuming a volumetric flow rate of 10.0 m3/s.

MA
8/18/00

Revised Model #2.

Volumetric Flow Rate = 10 m3/s.	Mass Flow Rate / unit Area
u(r=0.90 m) = 0.0 m/s	m(r=0.90m) = 0.0 kg/m2 sec
u(r=1.01 m) = 0.25441 m/s.	m(r=1.01 m) = 0.30656 "
u(r=1.12 m) = 0.45466 m/s.	m(r=1.12 m) = 0.54787
u(r=1.23 m) = 0.60818 m/s.	m(r=1.23 m) = 0.73286
u(r=1.34 m) = 0.72048 m/s.	m(r=1.34 m) = 0.86818
u(r=1.45 m) = 0.79575 m/s.	m(r=1.45 m) = 0.95888
u(r=1.56 m) = 0.83727 m/s.	m(r=1.56 m) = 1.00891
u(r=1.67 m) = 0.84764 m/s.	m(r=1.67 m) = 1.02141
u(r=1.78 m) = 0.82897 m/s.	m(r=1.78 m) = 0.99891
u(r=1.89 m) = 0.78299 m/s.	m(r=1.89 m) = 0.94350
u(r=2.00 m) = 0.71113 m/s.	m(r=2.00 m) = 0.85691
u(r=2.11 m) = 0.61459 m/s.	m(r=2.11 m) = 0.74058
u(r=2.22 m) = 0.49440 m/s.	m(r=2.22 m) = 0.59575
u(r=2.33 m) = 0.35142 m/s.	m(r=2.33 m) = 0.42346
u(r=2.44 m) = 0.18640 m/s.	m(r=2.44 m) = 0.22461
u(r=2.55 m) = 0.0	m(r=2.55 m) = 0.0

It was also decided for this Revised model that a better representation of the air sink temperature used in the convective heat transfer calculations be revised and improved.

Page 44 shows the derivation of the mixed fluid air temperature (t_m) which is what actually should be used in the convective heat transfer calculations along the waste package an concrete liner surfaces.

The following 3 pages show the revised ABAQUS user subroutine FORTRAN coding to calculate a mixed fluid air temperature at each Z-elevation for calculating the updated sink temperature (t_m) at each time step. Again, the ABAQUS user subroutine UFIELD is needed to keep an updated list of air node temperatures [in this case all the nodes in the air gap are included].

The following printouts are based on a volumetric flow rate $= 1.0\ m^3/sec$.

MA
8/19/00


```
      SUBROUTINE UFIELD(FIELD,KFIELD,MSECPT,KSTEP,KINC,TIME,NODE,
     1            COORDS,TEMP,DTEMP,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION FIELD(MSECPT,NFIELD),TIME(2),COORDS(3),
     1           TEMP(MSECPT),DTEMP(MSECPT)
C
C     This subroutine updates values of mean air temperature as a function
C     of z-axis coordinate for an axisymmetric model.
C
C     Author:                G. I. Ofoegbu
C     Date:                  August 21 2000
C     System:                ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KRDATA/ RAD(16),AREA(16),VEL(16)
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
C
      pi = 3.141592654
      tTol = 1.0d-8
      r0 = rad(1)
      rMax = rad(16)
      rInc = 0.11
      vRate = 1.0
      tArea = pi*(rMax*rMax - r0*r0)
      uAvg = vRate/tArea

      temN = temp(1)
      tCur = time(2)
C
C     Determine address of current node in vector F using its z coordinate
C
      z = coords(2)
      z0 = 0.0
      zMax = 600.0
      zInc = 0.25
      if (z .lt. z0) z = z0
      else if (z .gt. zMax) z = zMax
      j = 1 + (z - z0)/zInc
C
C     Determine address of current node in vector RAD using its r coordinate;
C     Correct address for possible truncation error
C
      r = coords(1)
      if (r .lt. r0) r = r0
      else if (r .gt. rMax) r = rMax
      i = 1 + (r - r0)/rInc
      if (r .gt. rad(i)) i = i+1
C
      aN = area(i)
      uN = vel(i)
      dTMean = aN*uN*temN/(tArea*vAvg)
C
C     Initialize accumulated term if there is a change in total time;
C     Otherwise continue the accumulation
C
      If (dabs(tCur - tLast(j)) .gt. tTol) then
        tMean(j) = dTMean
        tLast(j) = tCur
      Else
        tMean(j) = tMean(j) + dTMean
      EndIf
```

```
      Return
      END
      BLOCK DATA KDAXIS
      INCLUDE 'ABA_PARAM.INC'
      COMMON /KRDATA/ RAD(16),AREA(16),VEL(16)
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
      DATA RAD/
     1 0.900000000000, 1.010000000000, 1.120000000000, 1.230000000000,
     2 1.340000000000, 1.450000000000, 1.560000000000, 1.670000000000,
     3 1.780000000000, 1.890000000000, 2.000000000000, 2.110000000000,
     4 2.220000000000, 2.330000000000, 2.440000000000, 2.550000000000/
      DATA AREA/
     1 0.330024308260, 0.698061887628, 0.774088429845, 0.850114972061,
     2 0.926141514278, 1.002168056495, 1.078194598712, 1.154221140929,
     3 1.230247683146, 1.306274225363, 1.382300767580, 1.458327309796,
     4 1.534353852013, 1.610380394230, 1.686406936447, 0.862210103778/
      DATA VEL/
     1 0.000000000000, 0.025447374307, 0.045479074034, 0.060836487627,
     2 0.072070066802, 0.079599739164, 0.083753169170, 0.084790951866,
     3 0.082923754059, 0.078324306790, 0.071136000208, 0.061479174278,
     4 0.049455808989, 0.035153079149, 0.018646088420, 0.000000000000/
      DATA TLAST/2401*0.0/
      END
      SUBROUTINE FILM(H,SINK,TEMP,KSTEP,KINC,TIME,NOEL,NPT,
     1     COORDS,JLTYP,FIELD,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION H(2),TIME(2),COORDS(3),FIELD(NFIELD)
C
C----67--1---------2---------3---------4---------5---------6---------7--
C     This subroutine evaluates the ambient temperature SINK required
C     to implement a convection boundary condition at the boundary point
C     defined by coordinates COORDS (at integration point NPT of element
C     NOEL). The ambient temperature is solution-dependent and is set
C     equal to the mean air temperature at the z coordinate of NPT
C     which is determined by linear interpolation in vector TMEAN
C
C     This version of the subroutine is for an axisymmetric model (axial
C     coordinate equals COORDS(2)) and the convection coefficient is
C     assumed to be constant (2.65 W/m/m/K)
C
C     Author:                 G. I. Ofoegbu
C     Date:                   August 21 2000
C     System:                 ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
C
      H(1) = 2.65
      H(2) = 0.0

      zC = COORDS(2)
      z0 = 0.0
      zMax = 600.0
      zInc = 0.25
      j1 = 1 + (zC - z0)/zInc
      j2 = j0 + 1
      jMax = 1 + (zMax - z0)/zInc
      if (j2 .gt. jMax) j2 = jMax
C
      tm1 = tMean(j1)
      tm2 = tMean(j2)
```



```
      z1 = z0 + (j1 - 1)*zInc
      z2 = z0 + (j2 - 1)*zInc
      SINK = Tm1 + (tm2 - tm1)*(zC - z1)/(z2 - z1)
      Return
      END
```

MA
8/20/00

Note: with a 600 m axial dimension and constant 0.25 m axial element length, the total # of elements in axial direction was 2400. Even though the elements were graded fairly coarsely in the radial direction within the rock mass, a total of slightly over 90,000 elements was necessary to maintain the 0.25 m axial element length and 0.11 m element widths through the air gap.

Based on discussions with other ITT personnel who had run 90,000 + element models for structural analyses on the same machines, this problem was felt doable in terms of size especially since in the diffusive elements the only degree of freedom was temperature! Also, only a steady-state heat transfer analyses was to be run. Additional degrees of freedom were required in the convection / diffusion elements (i.e, velocity components).

M.A.
8/23/00

Attempts to run this analyses (i.e, Revised Model #2) failed after ABAQUS pre had finished its processing and model was passed on to ABAQUS Standard. The error was in allocation of sufficient memory for ABAQUS standard. After numerous attempts to adjust memory limits within the ABAQUS.env file and discussions with HKS technical support it was discovered that the cavity radiation algorithm was requiring excessive memory in the viewfactor and other radiation calculation memory requirements. For the problem as developed (i.e, 2400 elements defining the surfaces of each the waste package and concrete liner for the radiation cavity, the SGI's with 256 Mb RAM plus 1 Gb swap memory were not able to provide enough memory to run calculation.

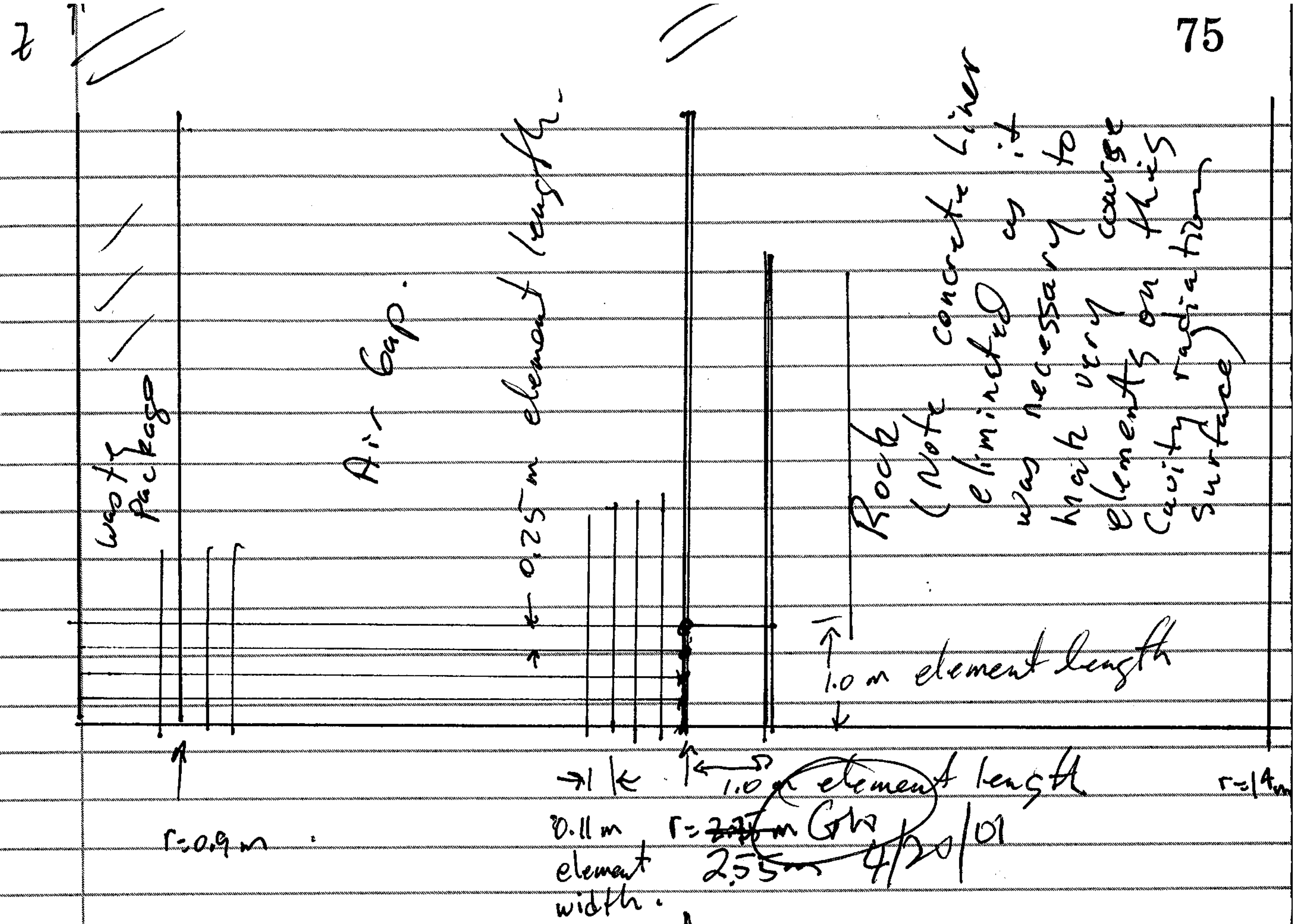
MA
8/23/00

A first attempt was to reduce the number of elements on the Concrete liner surface in the axial direction so as to reduce the # of elements for the cavity radiation surface making up the concrete liner.

A separate mesh was then developed for the rock mass / concrete liner with an axial element length ≐ 1.0 m (i.e., 4 times the axial element length of the air gap element)

This Rock / concrete liner mess was then tied to the air gap mesh using the ABAQUS Contact Pair commands and specifying the two surfaces to be tied together. Note: that the nodes along these two surfaces were not equivalenced together as it was thought that this might create problems.
A gap conductance across this interface was also specified to allow conduction heat transfer between the air and concrete liner.

Model is revised as shown on attached page.

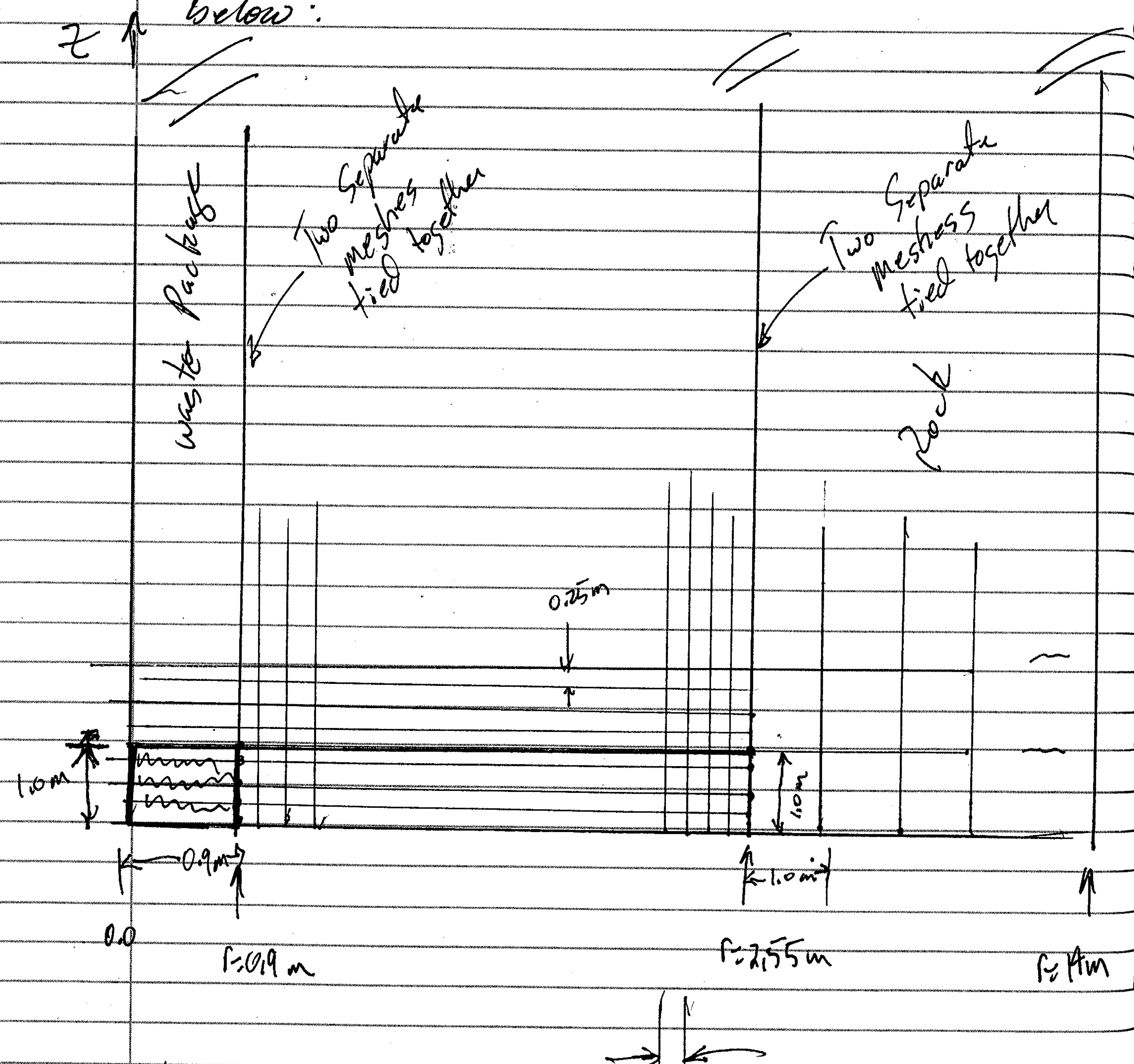


Two Separat meshes along this interface. (Tied together)

Note: Cavity radiation surface of drift wall uses coarser mesh.

This model also failed upon submission from ABAQUS Pre to ABAQUS Standard as again memory allocation was not sufficient.

Model 2 was again revised to this time also include a coarse mesh of the waste package side (i.e., separate mesh) and again tied to the air gap mesh using a tied contact pair. The second revised mesh is shown below:



Note:
Concrete liner element length = 1.0 m axially. (can't use whiteout)
Cavity Radiation uses coarse surface of waste package side.

This mesh was within memory limitations of the SGI R10000 machines. Steady State ~~wng~~ run was not completed at this time. mpa 9/5/00

M.A.
8/25/00

The steady state solution to this revised model was able to be achieved without the inclusion of the 2 USER subrouties (i.e., assuming a constant SINK temperature on the FILM statement lines of 24.6 °C within the ABAQUS input deck.) This steady state solution was achieved in about 3 hrs of CPU time on the SGI R10000 workstations. After reviewing the 2 ABAQUS USER subroutine FORTRAN coding, a number of errors were found and corrected. Also, explicit type conversion functions IDINT and DFLOAT were inserted everywhere within the USER subroutines where a type conversion was requested. Other check statements were inserted to identify any potential situations which would lead to a divide by zero error during the run. This was apparently the primary source of error within the initial versions of the USER subroutines as listed on pages 69-71. The following pages contain a new listing of the UFIELD and FILM user subroutines with the above revisions for the 1.0 m^3/s volumetric air flow rate.

One additional change was made to the waste package volumetric heat source strength for these steady stat runs. Based on phone discussions w/ G. Ofoegbu 9/11/00 it was indicated that the waste heat source strength currently adopted by DOE was in the range of an initial value at time = 0.0 (i.e., emplacement) of


```
      SUBROUTINE UFIELD(FIELD,KFIELD,MSECPT,KSTEP,KINC,TIME,NODE,
     1            COORDS,TEMP,DTEMP,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION FIELD(MSECPT,NFIELD),TIME(2),COORDS(3),
     1          TEMP(MSECPT),DTEMP(MSECPT)
C
C     This subroutine updates values of mean air temperature as a function
C     of z-axis coordinate for an axisymmetric model.
C
C     Author:               G. I. Ofoegbu
C     Date:                 August 21 2000
C     System:               ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KRDATA/ RAD(16),AREA(16),VEL(16)
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
C
      pi = 3.141592654
      tTol = 1.0d-8
      r0 = rad(1)
      rMax = rad(16)
      rInc = 0.11
      vRate = 1.0
      tArea = pi*(rMax*rMax - r0*r0)
      uAvg = vRate/tArea
C
      temN = temp(1)
      tCur = time(2)
C
C     Determine address of current node in vector TMEAN using its z coordinate
C
      z = coords(2)
      z0 = 0.0
      zMax = 600.0
      zInc = 0.25
      if (z .lt. z0) z = z0
      if (z .gt. zMax) z = zMax
      dj = (z - z0)/zInc
      j = 1 + IDINT(dj)
C
C     Determine address of current node in vector RAD using its r coordinate;
C     Correct address for possible truncation error
C
      r = coords(1)
      if (r .lt. r0) r = r0
      if (r .gt. rMax) r = rMax
      di = (r - r0)/rInc
      i = 1 + IDINT(di)
      if (r .gt. rad(i)) i = i+1
C
      aN = area(i)
      uN = vel(i)
      dTMean = aN*uN*temN/(tArea*uAvg)
C
C     Initialize accumulated term if there is a change in total time;
C     Otherwise continue the accumulation
C
      If (dabs(tCur - tLast(j)) .gt. tTol) then
        tMean(j) = dTMean
        tLast(j) = tCur
      Else
```

```
        tMean(j) = tMean(j) + dTMean
      EndIf
      Return
      END
      BLOCK DATA KDAXIS
      INCLUDE 'ABA_PARAM.INC'
      COMMON /KRDATA/ RAD(16),AREA(16),VEL(16)
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
      DATA RAD/
     1 0.900000000000, 1.010000000000, 1.120000000000, 1.230000000000,
     2 1.340000000000, 1.450000000000, 1.560000000000, 1.670000000000,
     3 1.780000000000, 1.890000000000, 2.000000000000, 2.110000000000,
     4 2.220000000000, 2.330000000000, 2.440000000000, 2.550000000000/
      DATA AREA/
     1 0.330024308260, 0.698061887628, 0.774088429845, 0.850114972061,
     2 0.926141514278, 1.002168056495, 1.078194598712, 1.154221140929,
     3 1.230247683146, 1.306274225363, 1.382300767580, 1.458327309796,
     4 1.534353852013, 1.610380394230, 1.686406936447, 0.862210103778/
      DATA VEL/
     1 0.000000000000, 0.025447374307, 0.045479074034, 0.060836487627,
     2 0.072070066802, 0.079599739164, 0.083753169170, 0.084790951866,
     3 0.082923754059, 0.078324306790, 0.071136000208, 0.061479174278,
     4 0.049455808989, 0.035153079149, 0.018646088420, 0.000000000000/
      DATA TLAST/2401*0.0/
      END
      SUBROUTINE FILM(H,SINK,TEMP,KSTEP,KINC,TIME,NOEL,NPT,
     1    COORDS,JLTYP,FIELD,NFIELD)
      INCLUDE 'ABA_PARAM.INC'
      DIMENSION H(2),TIME(2),COORDS(3),FIELD(NFIELD)
C
C----67--1---------2---------3---------4---------5---------6---------7--
C     This subroutine evaluates the ambient temperature SINK required
C     to implement a convection boundary condition at the boundary point
C     defined by coordinates COORDS (at integration point NPT of element
C     NOEL). The ambient temperature is solution-dependent and is set
C     equal to the mean air temperature at the z coordinate of NPT
C     which is determined by linear interpolation in vector TMEAN
C
C     This version of the subroutine is for an axisymmetric model (axial
C     coordinate equals COORDS(2)) and the convection coefficient is
C     assumed to be constant (2.65 W/m/m/K)
C
C     Author:                 G. I. Ofoegbu
C     Date:                   August 21 2000
C     System:                 ABAQUS 5.8 (UserSubroutine)
C
      COMMON /KZDATA/ TMEAN(2401),TLAST(2401)
C
      H(1) = 2.65
      H(2) = 0.0
C
      zC = COORDS(2)
      z0 = 0.0
      zMax = 600.0
      zInc = 0.25
      dj = (zC - z0)/zInc
      j1 = 1 + IDINT(dj)
      if (j1 .lt. 1) j1 = 1
      j2 = j1 + 1
      dj = (zMax - z0)/zInc
```



```
      jMax = 1 + IDINT(dj)
      if (j2 .gt. jMax) j2 = jMax
C
      tm1 = tMean(j1)
      tm2 = tMean(j2)
C
      If (j1 .eq. j2) then
        SINK = tm1
      ELSE
        z1 = z0 + DFLOAT(j1 - 1)*zInc
        z2 = z0 + DFLOAT(j2 - 1)*zInc
        SINK = tm1 + (tm2 - tm1)*(zC - z1)/(z2 - z1)
      Endif
C
      Return
      END
```

1.2 to 1.5 KW/m along the length of the waste emplacement drift. We opted for a value of 1.25 KW/m (1250 W/m). Based on a waste package radius r = 0.9 m assumed in the model, the 1.25 KW/m strength was converted to a volumetric heat source strength of 491 W/m^3 (i.e., $\{1250\ W/m / [\pi (0.9 m)^2]\}$.)

For modeling purposes, we assumed an initial rate of 500 W/m^3. For the steady state runs, this value was chosen to be constant. Earlier runs had used a smaller initial constant volumetric heat generation at t=0.0 of 237.6 W/m^3 [see pg. 9 for rationale at that time and associated reference.]

It should be noted that the majority of the steady state solution time

(roughly 2/3 of total) is spent in the ABAQUS viewfactor calculations as part of the cavity radiation option. The long 600 m length of the drift appears to lead to a large portion of the CPU time spent in the cavity radiation portion of the calculation. The revised ABAQUS 2D axisymmetric model for the 600 m drift now consists of slightly over 40,000 elements including the convection/diffusion elements within the annular air space between the waste package and drift wall.

Based on the new revised model geometry for the 600 m drift, the modified user subroutines (i.e., pgs 79-81), and the increased initial volumetric heat flux of 500 W/m³ steady state runs were performed with ABAQUS for the 1.0 m³/s and 10.0 m³/s air flow rates. The results are tabulated on the following pages with regard to heat flux values and temperatures. Again each of the steady state runs took approximately 3.6 hours for the total CPU time on an SGI R10000 work station.

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Run # 1 – Steady-State Solution
- Volumetric Air Flow Rate = 10.0 m³/s
- Q = 500 W/m³ = Constant WP vol. flux
- 600 m drift

Element Output

Heat Flux (W/m²) – Radial Direction
Integration Pt #3 (HFL1)

Z-Coordinate (m)	Waste Package Surface Flux (W/m²)	Drift Wall Surface Flux (W/m²)
0.0	149.2	0.521
100.0	150.0	3.7581×10^{-3}
200.0	150.0	1.0892×10^{-3}
300.0	150.0	4.864×10^{-4}
400.0	150.0	2.8592×10^{-4}
500.0	150.0	2.2094×10^{-4}
600.0	151.4	-0.5614

Nodal Output

Nodal Temperatures (°C) Across Air Gap.

	Radial Coord (m)	Z=0 m	Z=100 m	Z=200 m	Z=300 m	Z=400 m	Z=500 m	Z=600
WP Surface →	0.90	61.00	61.40	62.09	62.58	62.99	63.36	63.20
Air Gap Nodes	1.02	24.60	38.80	43.69	46.17	47.80	49.02	49.99
	1.12	24.60	27.10	30.50	33.23	35.33	37.00	38.36
	1.23	24.60	24.83	25.68	26.85	28.10	29.30	30.41
	1.34	24.60	24.61	24.73	25.00	25.41	25.92	26.47
	1.45	24.60	24.60	24.61	24.65	24.74	24.88	25.07
	1.56	24.60	24.60	24.60	24.61	24.62	24.65	24.70
	1.67	24.60	24.60	24.60	24.60	24.60	24.61	24.62
	1.78	24.60	24.60	24.60	24.60	24.60	24.61	24.62
	1.89	24.60	24.60	24.60	24.61	24.63	24.66	24.71
	2.00	24.60	24.60	24.61	24.66	24.76	24.89	25.07
	2.11	24.60	24.62	24.74	24.99	25.33	25.73	26.15
	2.22	24.60	24.82	25.49	26.32	27.15	27.91	28.60
	2.33	24.60	26.34	28.36	29.86	31.00	31.91	32.68
	2.44	24.60	32.06	34.35	35.61	36.51	37.23	37.82
Rock Wall →	2.55	40.64	40.75	41.47	42.00	42.45	42.86	42.48

Inlet Nodes Fixed @ Z=0m

$\boxed{\text{Run \#2}}$ - Steady-State Solution

Volumetric Air Flow Rate = 1.0 m^3/s
Q = 500 W/m^3 (constant) - 600 m Drift.

Element Output

Heat Flux (W/m^2) - Radial Direction.

Z-Coordinate (m)	AH 4-16-01 Waste Package Surface Heat Flux (W/m^2)	Drift Wall Surface Flux (W/m^2)
0.0	150.0	-3.911×10^{-2}
100.0	150.0	1.713×10^{-3}
200.0	150.0	2.981×10^{-4}
300.0	150.0	9.856×10^{-5}
400.0	150.0	4.203×10^{-5}
500.0	150.0	3.49×10^{-5}
600.0	150.5	-0.2374

Nodal Output

Nodal Temperatures Across Air Gap (°C)

	Radial Coord (m)	z (0m)	z (100m)	z (200m)	z (300m)	z (400m)	z (500m)	z (600m)
WP Surface →	0.90	60.58	61.50	61.63	61.69	61.73	61.77	61.58
Air Gap	1.01	24.60	50.65	52.82	53.90	54.64	55.22	55.65
	1.12	24.60	41.04	44.88	46.87	48.22	49.29	50.18
	1.23	24.60	33.50	38.11	40.72	42.56	44.05	45.30
	1.34	24.60	28.63	32.84	35.66	37.82	39.60	41.14
	1.45	24.60	26.12	29.20	31.86	34.12	36.08	37.80
	1.56	24.60	25.10	27.05	29.35	31.55	33.55	35.35
	1.67	24.60	24.78	26.06	28.03	30.09	32.03	33.81
	1.78	24.60	24.78	25.96	27.75	29.64	31.46	33.13
	1.89	24.60	25.07	26.59	28.34	30.07	31.70	33.21
	2.00	24.60	25.86	27.91	29.65	31.19	32.60	33.89
	2.11	24.60	27.45	29.89	31.50	32.80	33.96	35.01
	2.22	24.60	30.01	32.38	33.72	34.73	35.61	36.40
	2.33	24.60	33.36	35.16	36.11	36.80	37.39	37.91
	2.44	24.60	37.05	38.02	38.52	38.88	39.18	39.37
Drift Wall →	2.55	40.03	40.68	40.78	40.84	40.88	40.91	40.61

Discussion of Results for Steady-State Runs #1 and #2.

One can see from the results on pages 83 and 84 that the steady state solutions for the waste package and drift wall surface temperatures (and AH 4-16-01 as well as radial heat fluxes off these two surfaces, varies little between the 1.0 m^3/s and 10.0 m^3/s air flow rates. In both the solutions, the heat flux radially of the waste package is 150 W/m^2 and constant in the axial direction over the 600 m drift length. Oddly enough, the radial heat flux into the drift wall is essentially zero for both air flow rates in the long term steady-state solution. Both solutions give roughly a waste package temperature in the low 60°C and drift wall temperature near 40°C. Although it is very odd that the higher air flow rate (i.e, 10.0 m^3/s) gives slightly higher waste package and drift wall surface temperatures than the lower air flow rate (1.0 m^3/s). For instance, the waste package surface temperature varies from 61.0 °C to 63.20 °C from z=0 to z=600 m, respectively, ~~On the other hand, the was~~ for the 10.0 m^3/s air flow. On the other hand, the waste package surface temperature varies from a slightly lower 60.55 °C to 61.58 °C from z=0 to z=600m, respectively for the 1.0 m^3/s air flow rate. The same pattern exists for the drift

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wall temperature from inlet to exit. One would expect the opposite, with the higher air flow rate giving lower waste package surface and drift wall surface temperatures. The air temperatures themselves look reasonable, with the lower air flow rate resulting in a higher mean air temperature across the air gap than for the higher air flow rate. ~~One can see~~ ~~a~~ for any given Z-coordinate location. One can see a dominant increase in air temperatures in the axial Z-direction for any given radial coordinate. However, on the waste package surface (r=0.9m) and drift wall (r=2.55m) there is very little change in temperature in the Z-direction.

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It is difficult to say without an analytic solution or long term experimental data whether these steady state solutions are giving the correct solution even though convergence has been achieved. One possible explanation for the similarities mentioned above is that both air flow rates are sufficiently high enough that in the very long term they eventually both cool the waste package and drift wall to the same degree. Although at this time we the steady-state results appear somewhat suspect without further investigation.

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ACH 4-16-01

It was decided that an attempt would be made to conduct a transient analyses of the revised 600 m drift model. Before this was done some simple transient runs were conducted on both the 20 m and 600 m drift models without the air flow turned on to verify that heat fluxes were being computed properly across the air gap with and without the air gap meshed with forced convection elements. Some concern was raised by G. Ofoegbu (CNWRA) as to why the heat flux of the waste package surface was not the same as that into the concrete liner surface on the drift wall.

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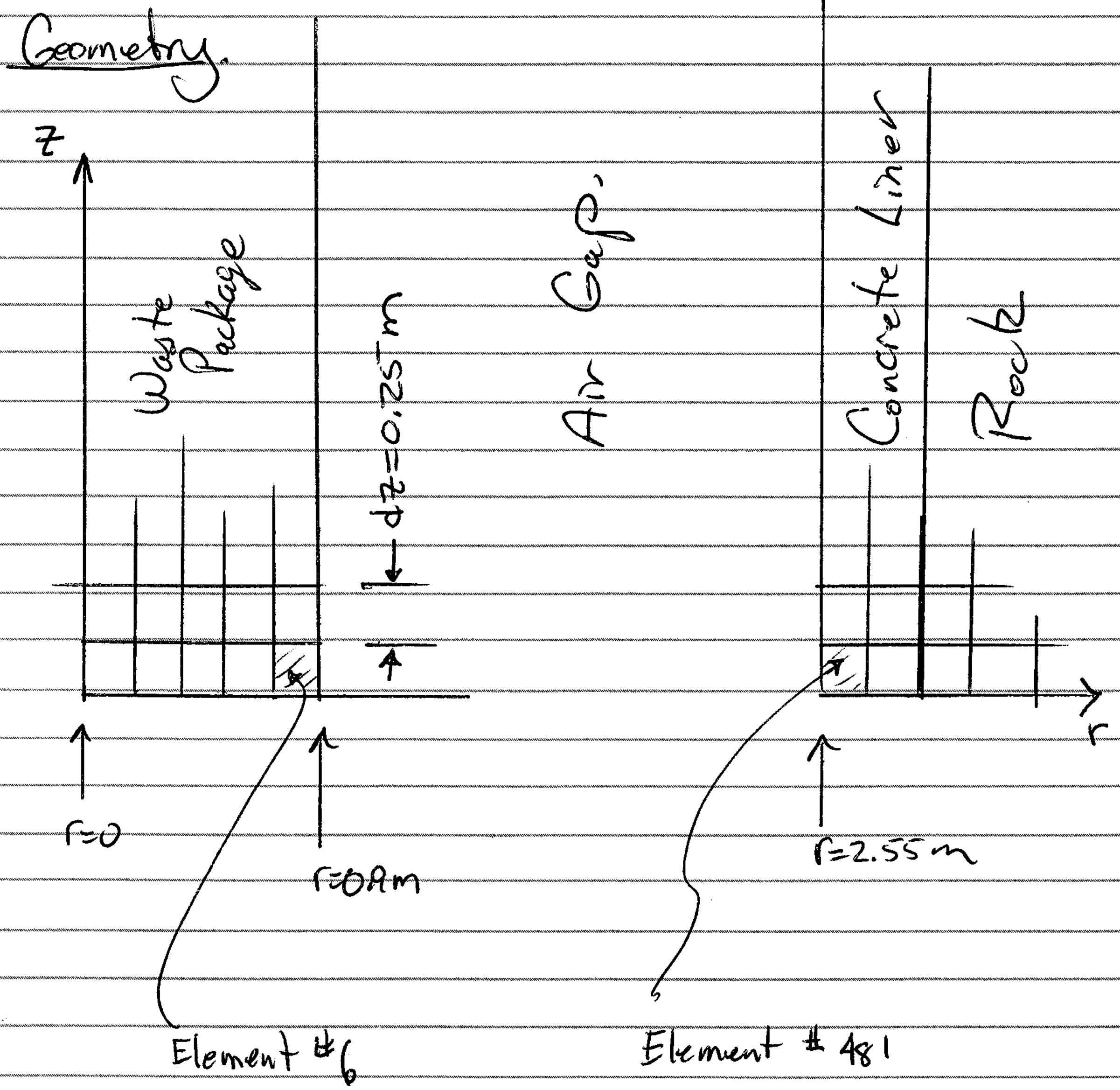
The following is a run conducted with the 20 m drift model without convection/diffusion elements filling the air gap. designated as Run #3. It consisted of a transient analysis to a time of 1.0 year (radiation only). The next run (designated Run #4) was the same as run #3, only with the air gap filled with convection/diffusion elements. Both these two runs required only a few minutes of CPU time to complete. The final run designated as Run #5 was also a transient run to 1.0 years (with no air flow) for the revised 600 m drift model with convection/diff. elem. All 3 runs are discussed on the following pages.

$\boxed{\text{Run \#3}}$

- 20 m Drift Model.
- Transient Analyses to t = 1.0 year
- Radiation Heat transfer across gap
- No Convection/Diffusion Elements within air gap.
- $Q_0 = 237.6\ W/m^3$ @ $t = 0.0$
- 2D Axisymmetric Model

Geometry.



Transient Results @ t = 1.0 year $\boxed{\text{Run \#3}}$

Thermal Parameter	Value
HFL1 (W/m²) Heat Flux Off Waste Package	95.12 W/m²
HFL1 (W/m²) Heat Flux into Concrete Liner	35.71 W/m²
NT11 - Waste Package Surface Temperature	99.55 °C
NT11 - Concrete Liner Surface Temperature	87.60 °C
RADFL Waste Package	−103.5
RADFLA Waste Package	−146.3
RADFL Concrete Liner	36.52
RADFLA Concrete Liner	146.3

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Note: ~~RDFL~~ RADFL = Radiation Flux per Unit Area
RADFLA = Radiation Flux over the Facet.

$$RADFLA_{\text{waste package}} = RADFLA_{\text{concrete liner}}$$

(i.e., elements #6 and Element #481)
Positive flux into element (concrete liner)
Negative flux out of element (waste package)

Waste Package Surface (wp) → r = 0.9 m.

$$RADFL_{wp} = \frac{RADFLA_{wp}}{2\pi(0.9m)(0.25m)} = -103.5\ W/m^2$$

<u>Concrete Liner Surface</u> (CL) $\Rightarrow r = 2.55\text{ m}$

$$RADFL_{CL} = \frac{RADFLA_{CL}}{2\pi(2.55\text{ m})(0.25)} = 36.52\ \text{W/m}^2$$

<u>Total Radiation Heat Output off Waste Package</u>

$$A_{wp} = 2\pi(0.9\text{ m})(20\text{ m}) = 113.097\ \text{m}^2$$

$$RADFL_{wp} = -103.5\ \text{W/m}^2$$

$$Q_{wp}(\text{radiation}) = A_{wp}\,RADFL_{wp} = $$

$$= (113.097\ \text{m}^2)(-103.5\ \text{W/m}^2)$$

$$= \underline{\underline{11{,}705.5\ \text{W}}}.$$

<u>Total Radiation Heat Input into Concrete Liner</u>

$$A_{CL} = 2\pi(2.55\text{ m})(20\text{ m}) = 320.44\ \text{m}^2$$

$$RADFL_{CL} = 36.52\ \text{W/m}^2$$

$$Q_{CL}(\text{radiation}) = A_{CL}\,RADFL_{CL}$$

$$= (320.44\ \text{m}^2)(36.52\ \text{W/m}^2)$$

$$= \underline{\underline{11{,}702.5\ \text{W}}}$$

$$\therefore\ Q_{wp}(\text{radiation}) = Q_{CL}(\text{radiation})\ \checkmark$$

It is not quite clear why $HFLI_{wp}$ is slightly different from $RADFL_{wp}$ (i.e., 95.12 W/m² GW 11/20/01 versus 103.5 W/m²). Also, $HFLI_{CL}$ ~~[illegible]~~ mpah (35.71 W/m²) is slightly different from $RADFL_{CL}$ (36.52 W/m²).

One explanation might be that HFLI is calculated at the element integration points and not on the element surface. Rerunning analyses with waste package surface and concret liner surface emissivities set equal to 1.0 did little to changed the heatflux values, only changeng temperatures slightly. All in all, the heat flux appears to be conserved across the air gap.

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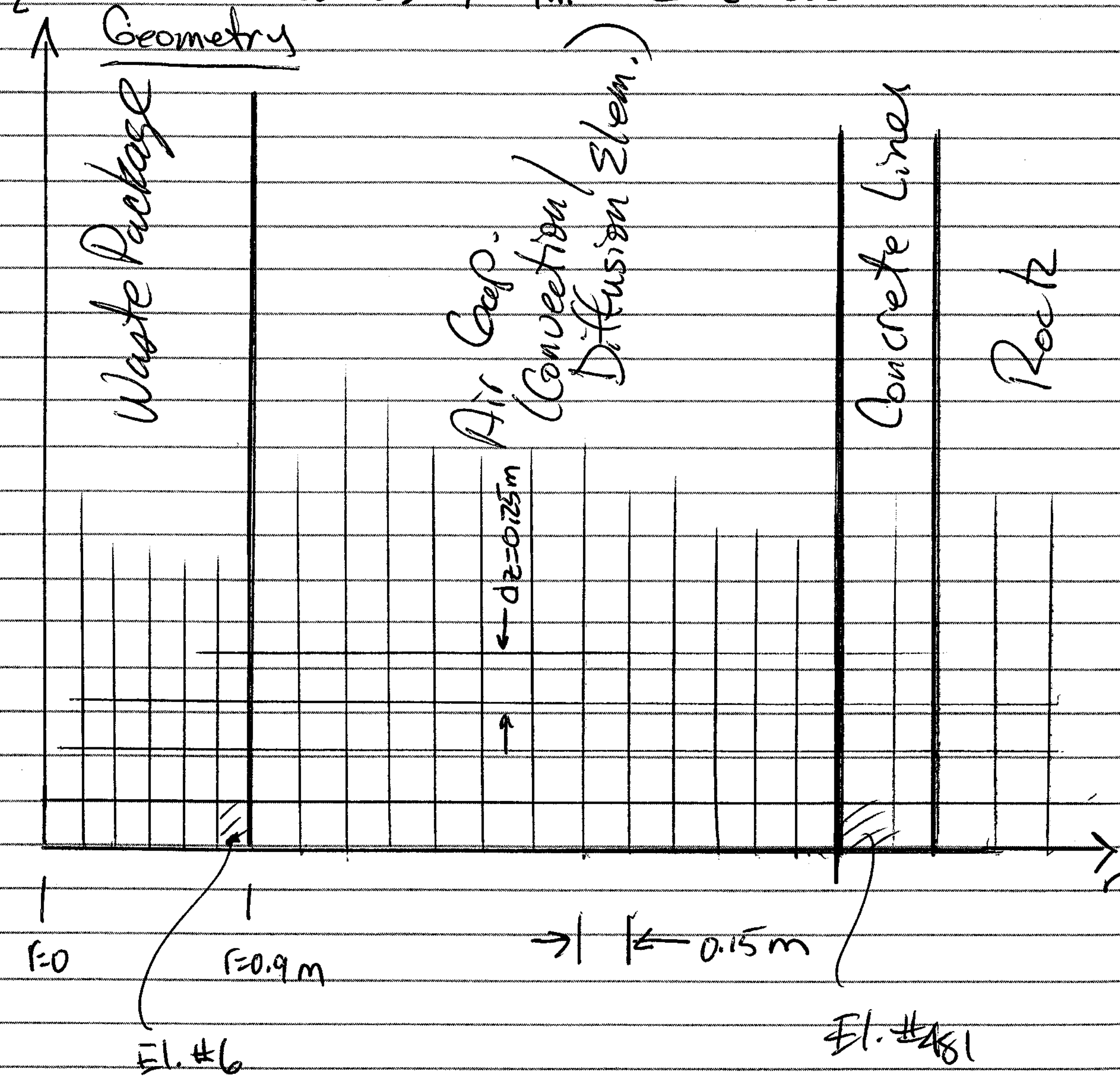
Run #4

- 20 m Drift Model
- Transient Analyses to t = 1.0 year
- 2D Axisymmetric Model
- Convection / Diffusion Elements included within air gap.
- Mass Flowrate = 0.0 m³/s.
- No FILM boundary conditions on waste package or concrete surface
- Conduction allowed across air gap elements (although k_{air} very low)
- Radiation allowed across air gap.
- $Q_0 = 236.7\ W/m^3$ @ t = 0.0

Geometry



Transient Results - t = 1 year Run #4

Thermal Parameter	Value
HFL1 - Heat Flux off Waste Package	95.12 W/m²
HFL1 - Heat Flux into Concrete Liner	35.71 W/m²
NT11 - Temperature Waste Package Surface	99.54 °C
NT11 - Temperature Concrete Liner Surface	87.63 °C
RADFL - Waste Package	-103.1 W/m²
RADFLA - Waste Package Facet	-145.7 W/m²
RADFL - Concrete Liner	36.38 W/m²
RADFLA - Concrete Liner Facet	145.7 W/m²

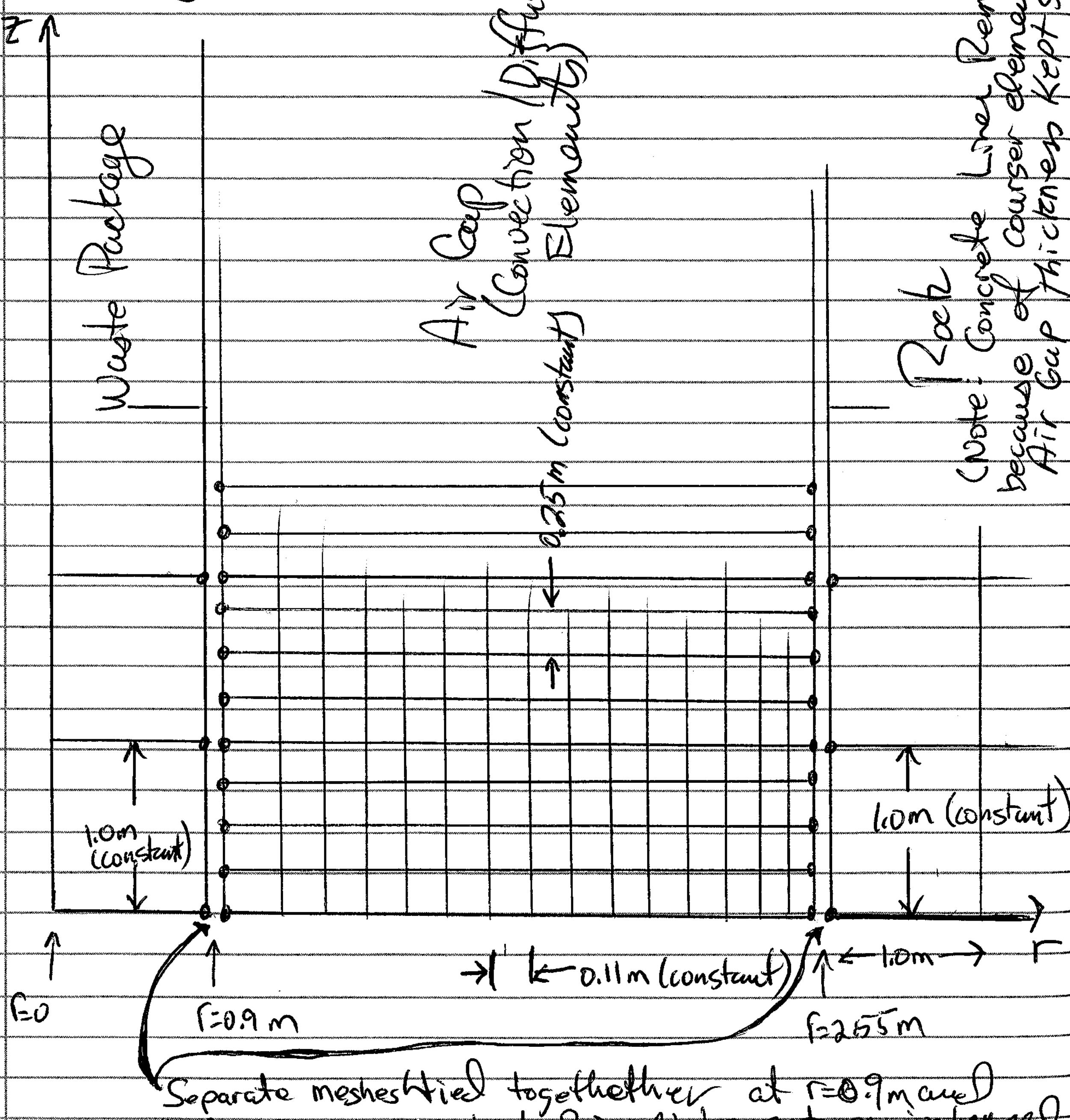
Comparing results of Run #4 (this page) to Results of Run #3 (page 89), one can see nearly identical values for heat fluxes and temperatures on the waste package and concrete liner surfaces. Thus, the radiation heat transfer is accurately modeled across air gap filled w/ convection elements. Conductive Heat transfer across air is negligible.

Run #5

- 600 m Drift Model.
- 2D Axisymmetric
- Transient Analysis to t = 1.0 year.
- $Q_0 = 236.7\ W/m^3$ @ t=0.0.
- Convection / diffusion elements in air gap
- Mass flow rate = 0.0 m3/s.
- No FILM boundary conditions.

Note: Radiation Cavity Surfaces Defined on the Coarser Mesh Sides w/ fewer Elements.

Geometry



Transient Results - t=1.0 year - Run #5

Thermal Parameter	Value
HFL1 - Heat Flux Off Waste Package	69.25 W/m^2
HFL1 - Heat Flux Into ~~Concrete~~ Rock Wall mpa 9/27/00	31.03 W/m^2
NT11 - Temperature Waste Package Surface	94.96 °C
NT11 - Temperature Rock Wall	82.44°C

Note: Radiation Flux output not printed for this Run.

In comparing results from Run #5 (600 m drift) with those from Run #4 (20 m drift), one can see that the waste package and ~~or~~ mpa 9/27/00 rock wall surface temperatures are close, but for the Run #5 (600 m drift) they are approximately 5°C cooler. One reason for the difference might be that the 600 m drift model is much coarser on the waste package side and rock wall side (i.e., 1.0 m versus 0.25 m elements). Also, the meshes are tied in the 600 m model. Finally, due to the mesh coarsness, the concrete liner was removed and replaced with rock properties potentially causing some thermal discrepancy in temperatures of the wall.

Differences in the heat flux values (HFL1) between Run #5 and #4, are likely due to the fact that Run #5 uses coarser elements and thus the radial location of the element integration points is different between the two models.

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Transient analysis for the 600m drift model was carried forward with the mass air flow turned on simulating the ventilation of the drift. Essentially Run #5 was extended to include ventilation effects. Note that for these ventilation runs for the 600m drift model the element type used for the convection/diffusion elements within the air gap was the DCCAX4 type ABAQUS elements. Use of these type of elements allowed ABAQUS to gradually increase the thermal time step during ventilation eventually to reasonable values, at least for the lower air flow rates. The DCCAX4D element types with added dispersion control result in very stringent time step requirements for stability and not practical in this type of analyses.

This first Run (designated Run #6) utilized an air flow rate down the axis of the drift of 1.0 m³/s.

The inlet air nodes at z=0.0 m were fixed at the assumed inlet air ventilation temperature of 24.6°C. Transient analyses was first carried out to a time of t=1.0 year with mass air flow =0.0. At t=1.0 year, the mass air flow was turned on for a period of 10 days. Plots/Results are discussed on the following pages.

Figures 1 and 2 show the input conditions for the waste package volumetric heat flux and the mass flow rate of air as a function of radial coordinate across the air gap. This mass flow rate of air simulates a total vol. air flow rate of 1.0 m³/s.

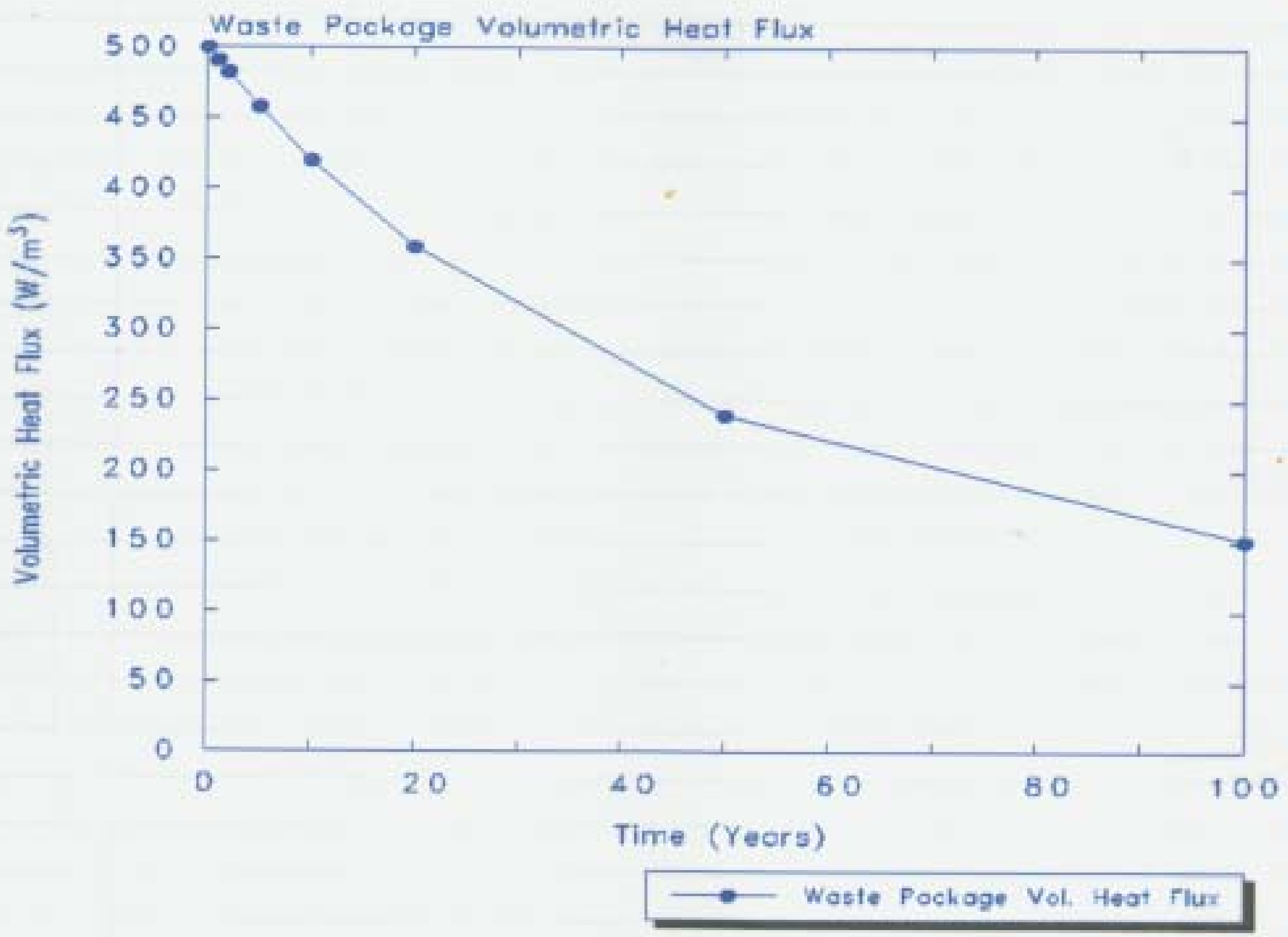

Figure 1. Input waste package volumetric heat flux as a function of time used in the ABAQUS transient thermal/forced convection analyses. Initial volumetric heat flux at time t = 0 years corresponds to a linear heat flux of 1.25 Kw/m.

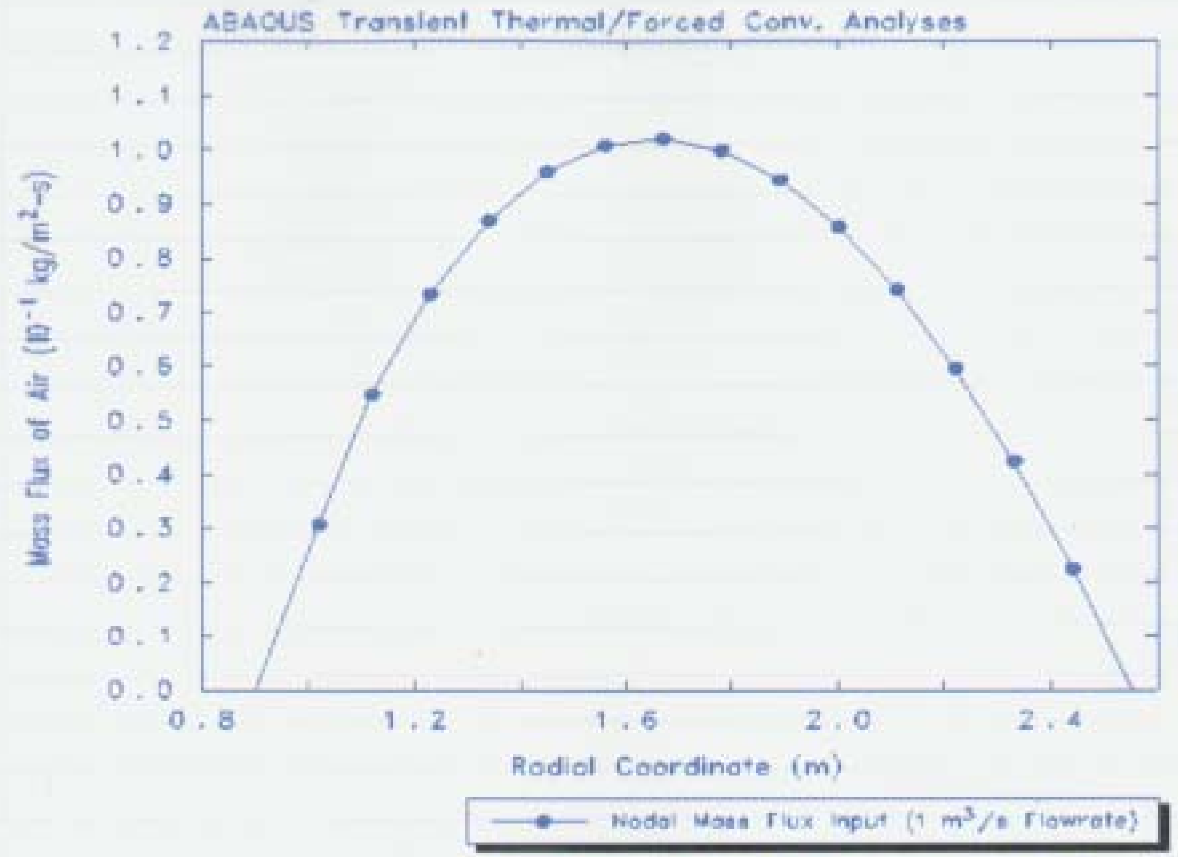

Figure 2. Input mass flux of air per unit area as a function of the radial coordinates of the air nodes across the air gap as used in the ABAQUS transient thermal/forced convection analyses. The mass flux is calculated from a volumetric flow rate of 1.0 m^3/s, the density of air at room temperature, and the available drift cross-sectional flow area.

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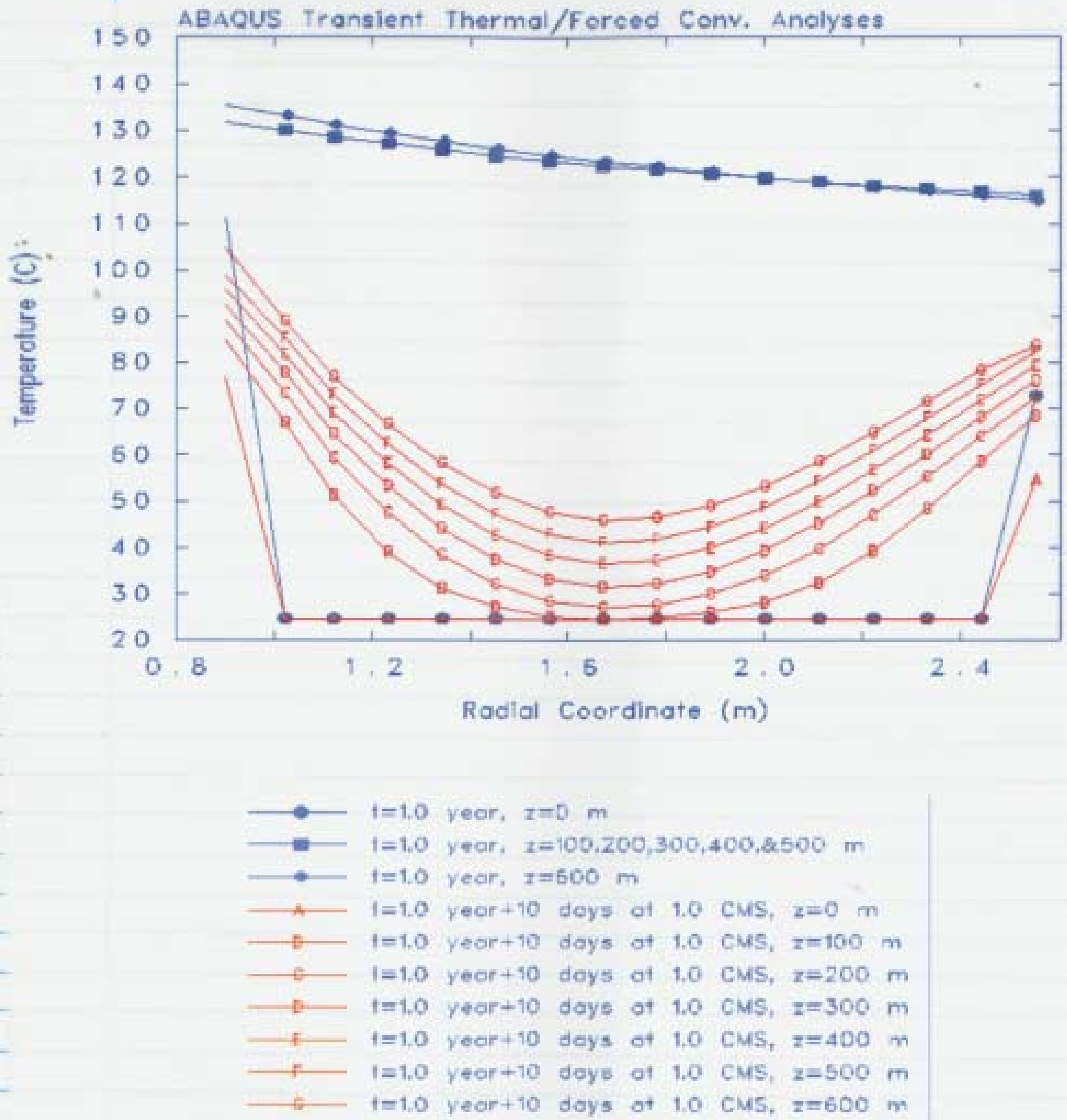

Figure 3. ABAQUS results demonstrating the effect of forced air convection on the waste package surface temperature, drift air temperatures, and drift wall surface temperature at various axial (z) locations along the 600 m drift. [Note: Blue curves represent 1 year of heating under radiation and conduction for initial waste package heat flux = 500 W/m^3, and the red curves represent the effect of 10 days of ventilation at a rate of 1.0 m^3/s with the radiation and conduction heat transfer still active].

Figure 3 shows the extent of cooling to the waste package surface (r=0.9m) and rock wall (r=2.55m)[i.e, two endpoints of the curves]. The temperature of the walls as well as the air heat up with axial distance down the drift as expected. Bottom blue curve at z=0 shows fixed inlet air node temps to 24.6°C. Mid airgap temperature increases from 24.6°C to roughly 45°C over the 600 m drift length.

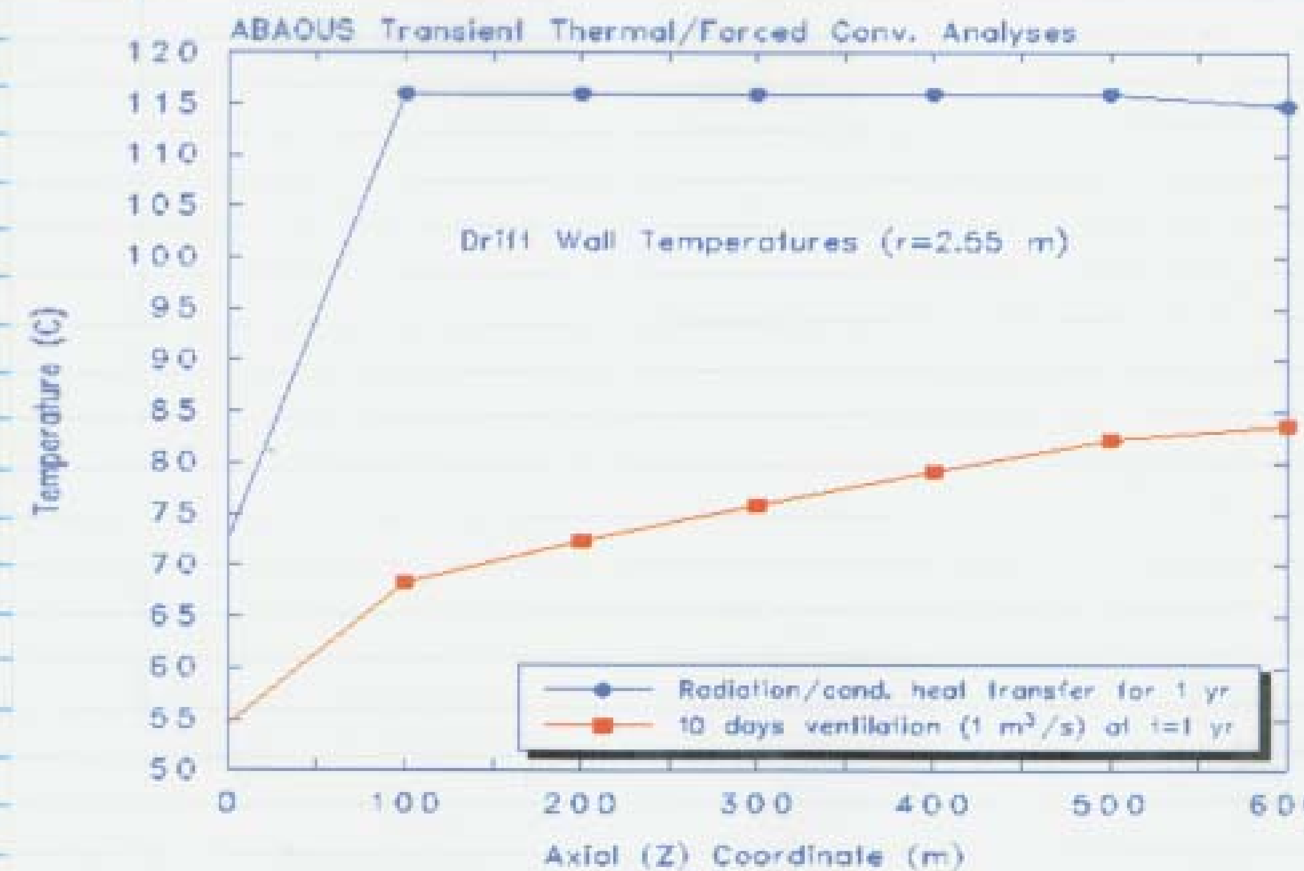

Figure 4. ABAQUS results demonstrating the effect of forced air convection on the drift wall surface temperature with axial (z) distance for the 600 m drift. [Note: Blue curves represent 1 year of heating under radiation and conduction for initial waste package heat flux = 500 W/m^3, and the red curves represent the effect of 10 days of ventilation at a rate of 1.0 m^3/s with the radiation and conduction heat transfer still active].

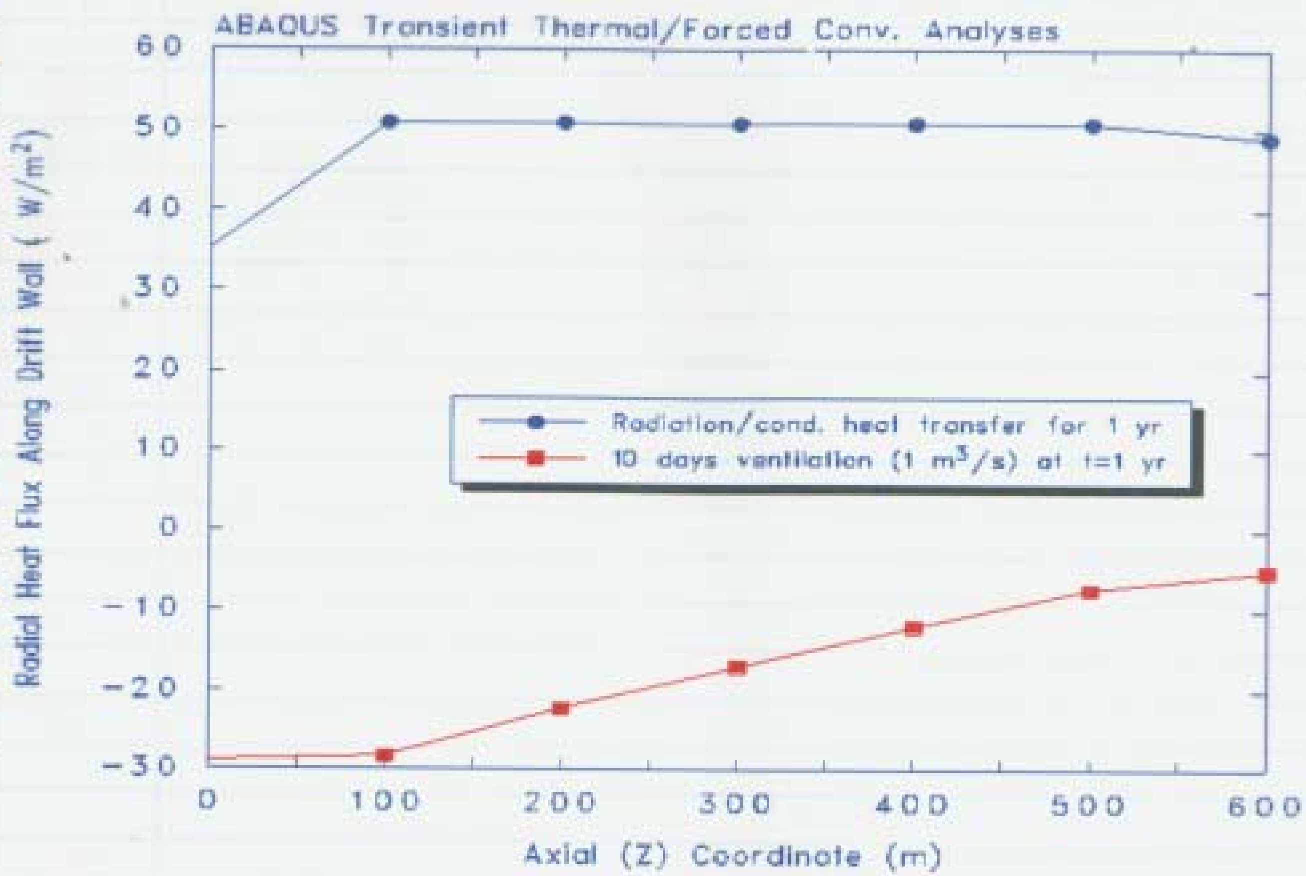

Figure 5. ABAQUS results demonstrating the effect of forced air convection on the drift wall radial heat flux with axial (z) distance for the 600 m drift. [Note: Blue curves represent 1 year of heating under radiation and conduction for initial waste package heat flux = 500 W/m^3, and the red curves represent the effect of 10 days of ventilation at a rate of 1.0 m^3/s with the radiation and conduction heat transfer still active].

Note: Negative heat flux (red curve) off drift wall indicates higher flux into the air stream (i.e., convection dominates radiation) and walls are cooling.

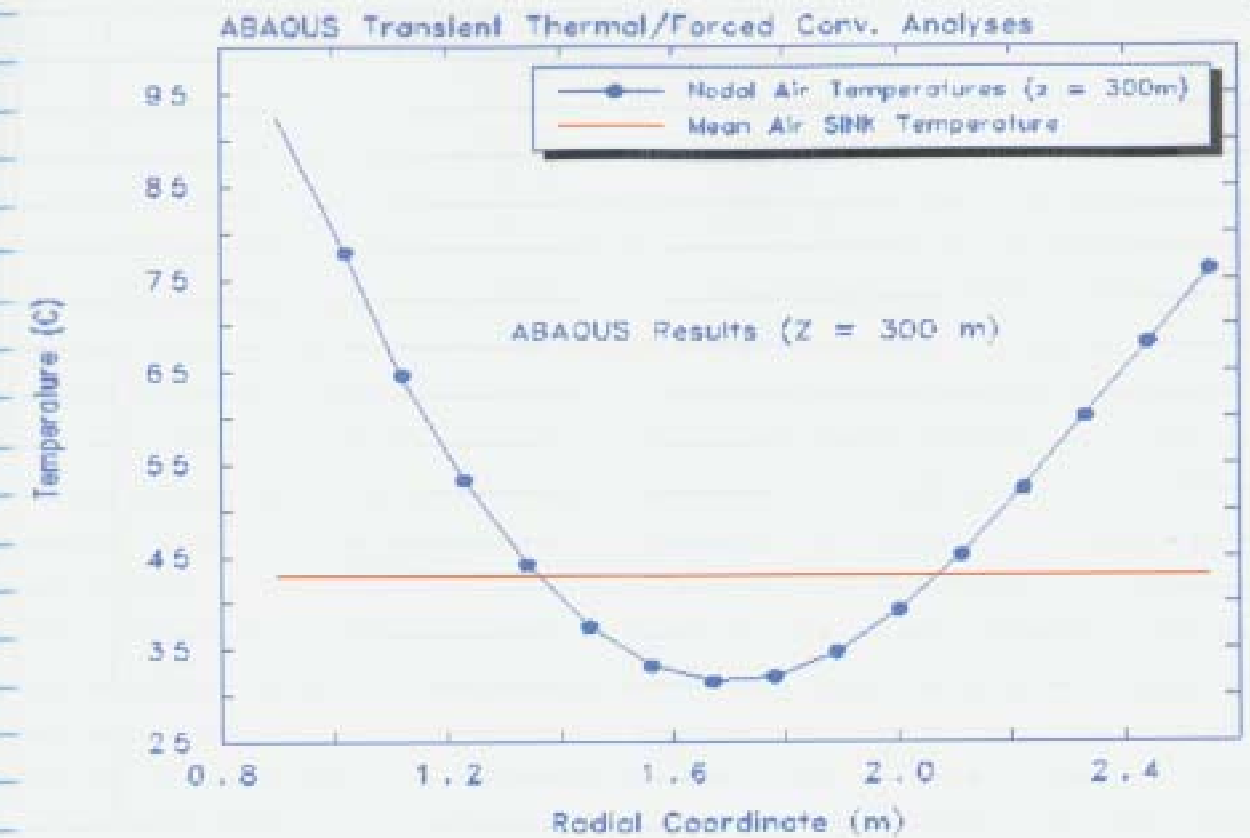

Figure 6. ABAQUS results for nodal air temperatures across the drift air gap at an axial distance of z = 300 m after 10 days of ventilation at a volumetric air flow rate of 1.0 m^3/s (blue curve). Also shown is the mean air temperature calculated by ABAQUS within the user subroutines UFIELD and FILM at this same axial coordinate for use as the air SINK temperature for the convective FILM boundary conditions on both the waste package and drift wall surfaces (red curve).

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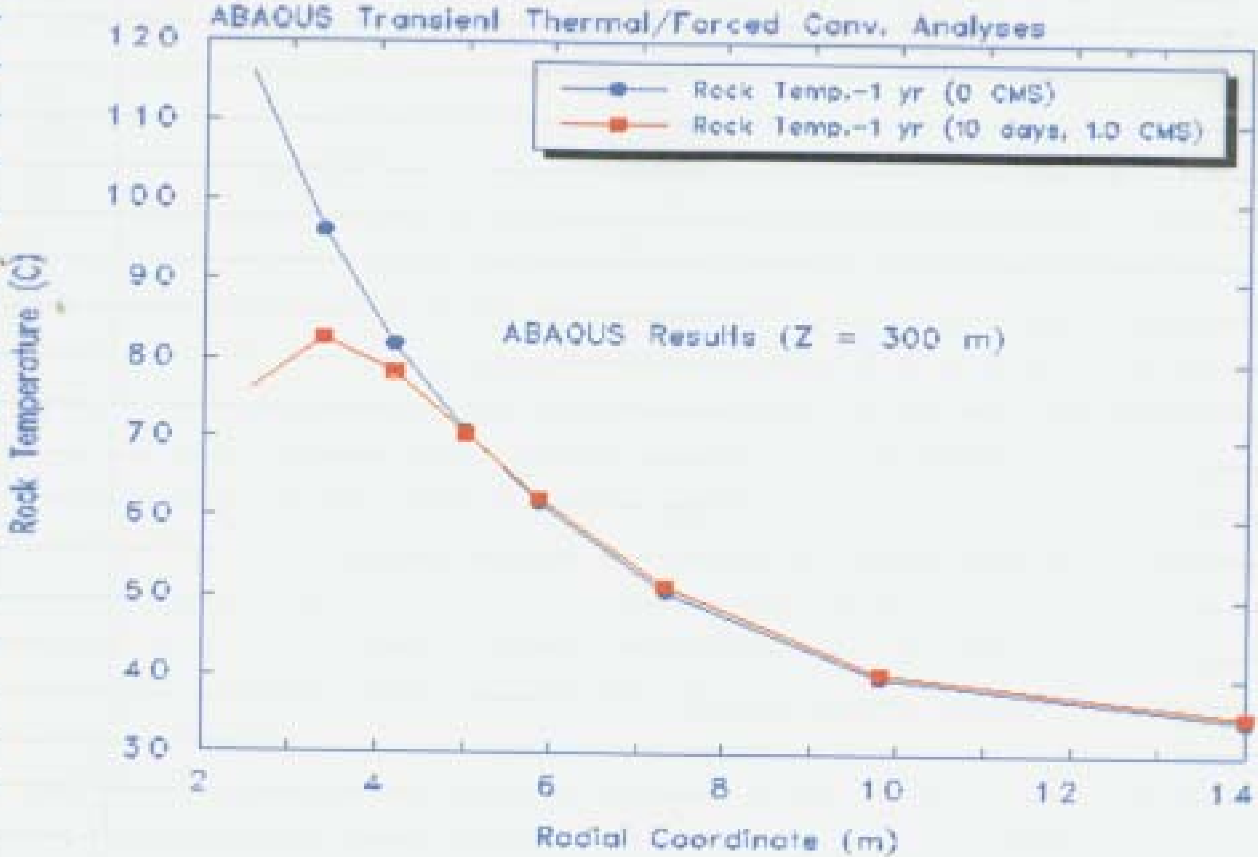

Figure 7. ABAQUS results for rock temperatures from the drift wall to the outer model radial boundary at an axial distance of z = 300 m before ventilation (blue curve), and after 10 days of ventilation at a volumetric air flow rate of 1.0 m^3/s (red curve). Note: The entire 600 m drift is heated up for a period of 1 year prior to turning on the ventilation.

Note: Effect of ventilation (i.e, 1.0 m^3/s air flow rate over a 10 day period) extends approximately 2.5 m into the rock wall as seen in above figure.

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ABAQUS Results for Mean Air SINK Temperatures for this last Run #6.

- 1.0 m^3/s air flow rate.
- Drift heated for 1 year under zero mass flow rate.
- At t=1.0 year, mass flow rate (ventilation) turned on for 10 days.

The following mean air SINK temperatures were calculated by User Subroutines UFIELD and FILM (see pgs 79-81) at the end of 10 days of ventilation.

	Axial z-Coordinate (m)	Air SINK temperature Calculated by ABAQUS (°C)	
	0.0	24.5 °C	
	100.0	32.5 °C	
	200.0	38.0 °C	
Red Curve Pg 103. ⇒	300.0	43.0 °C	⟸ Hand Calculation Verification = 42.6 °C (see pg 106).
	400.0	47.6 °C	
	500.0	52.4 °C	
	600.0	56.8 °C.	

Hand calculation to verify mean air SINK temperatures as calculated by ABAQUS user subroutines (UFIELD and FILM).

R-Coord (m)	Z=300m Nodal (t_i) Temperature (°C)	Nodal (u_i) Velocity (m/s)	Assoc. (dA_{c_i}) Nodal Area (m²)	$u_i t_i dA_{c_i}$
0.90	92.41	0.00	0.32052	0.00
1.01	77.85	0.025441	0.69806	1.38256
1.12	64.67	0.045466	0.77409	2.27605
1.23	53.32	0.060818	0.85011	2.75675
1.34	44.13	0.072048	0.92614	2.94464
1.45	37.37	0.079575	1.00217	2.98017
1.56	33.15	0.083727	1.07819	2.99257
1.67	31.42	0.084764	1.15422	3.07402
1.78	31.98	0.082897	1.23025	3.26145
1.89	34.63	0.078299	1.30627	3.54194
2.00	39.12	0.07113	1.38230	3.84640
2.11	45.12	0.061459	1.45833	4.04399
2.22	52.27	0.049440	1.53435	3.96511
2.33	60.10	0.035142	1.61038	3.40118
2.44	68.13	0.018640	1.68641	2.14164
2.55	75.97	0.00	0.87171	0.00

From pg 44:

$$t_m = \frac{1}{A_c V}\int_{A_c} u t \, dA_c = \frac{1}{A_c V}\left\{\sum_{i=1}^{16} u_i t_i dA_{c_i}\right\}$$

$$\sum_{i=1}^{16} u_i t_i dA_{c_i} = 42.6085$$

$A_c = 17.88 \text{ m}^2$, $V = 0.05593 \text{ m/s}$

$$t_m = \frac{1}{(17.88)(0.05593)}\left[42.6085\right] = 42.6\,^\circ\text{C}$$

ok ✓

ABAQUS Calculates 43.0 °C @ Z=300m (see pg 105)

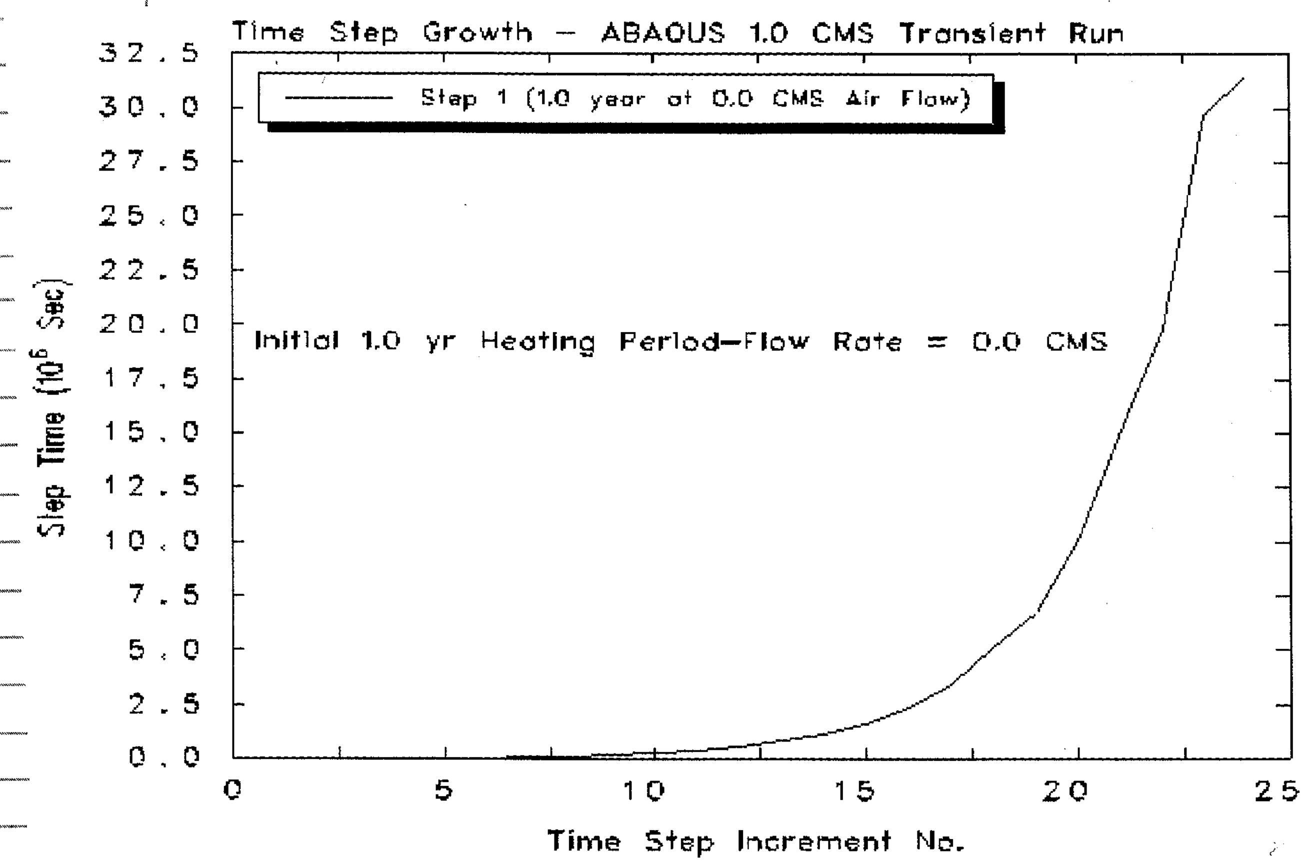

Figure 8. Plot of transient step time versus time step increment number for step number 1 of the ABAQUS analyses consisting of heating the drift under radiation and conduction heat transfer only for a period of 1.0 years (i.e., air mass flow rate set to zero during this 1st step). The initial transient time step was set to 1000 s.

Note: One can see that with the mass air flow rate set to zero for the initial heating to 1.0 years with only radiation heat transfer and conduction heat transfer, it takes only 10 to 15 time step increments before the transient thermal time step begins to grow exponentially. Entire 1.0 year analyses (transient) completed in 24 time increments.

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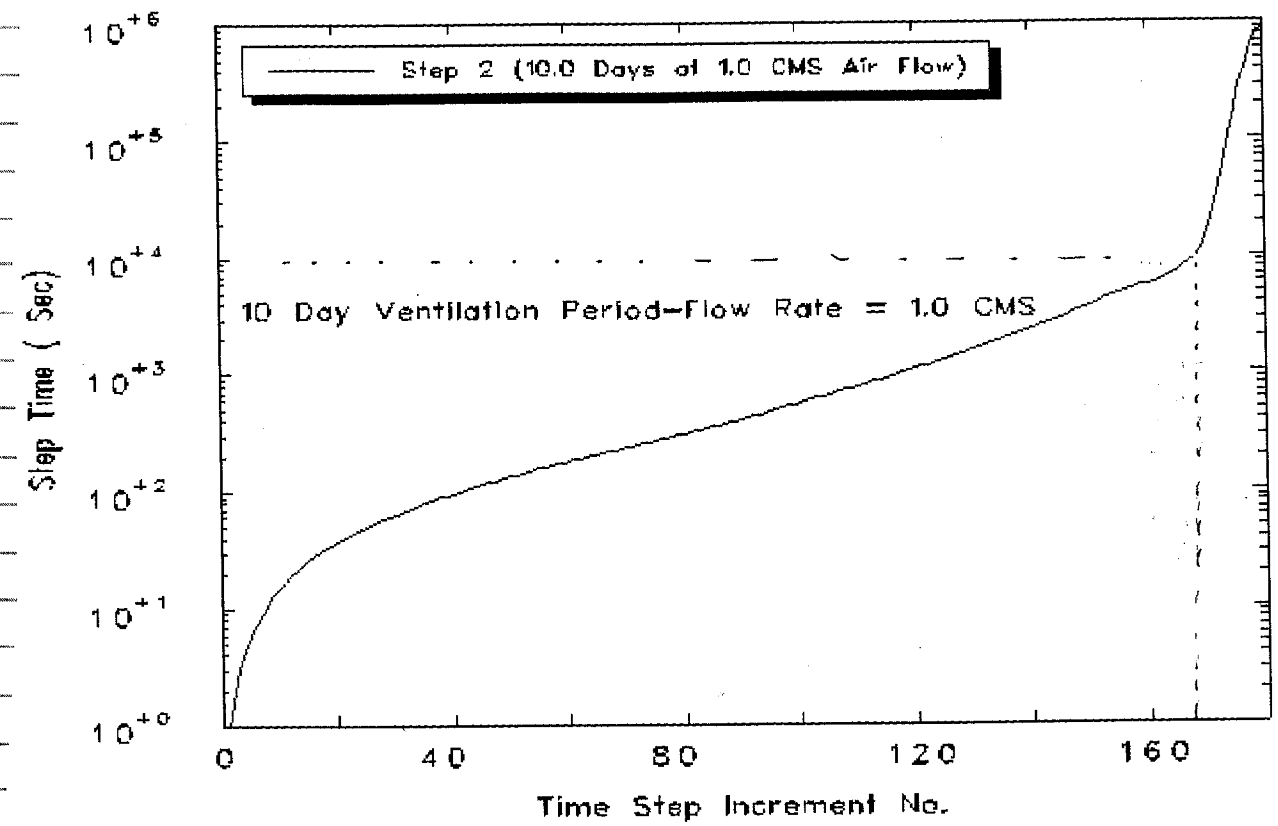

Figure 9. Plot of transient step time versus time step increment number for step number 2 of the ABAQUS analyses consisting of 10 days of ventilation at an air flow rate of 1.0 m^3/s beginning at a time of 1.0 years (i.e., end of step 1). The initial transient time step requirement for the ventilation portion of the analyses was on the order of 1.0 s. The total CPU time required to complete analyses (both steps 1 and 2) was approximately 1.67 days (40 hours) on a Silicon Graphics R10000 workstation.

Initiation of the ventilation @ an 1.0 m^3/s air flow rate required that the initial transient time step be reset to 1.0 sec. Total 10 day ventilation period required 180 time increments. However, it took roughly 160 increments to just get the time step up to 1.0 hours (3600 s). Note the sharp increase in step time @ approximately 1.0×10^4 s (~ 3 hours), on above plot (increment ~ 165). The reason that the time step is suddenly allowed

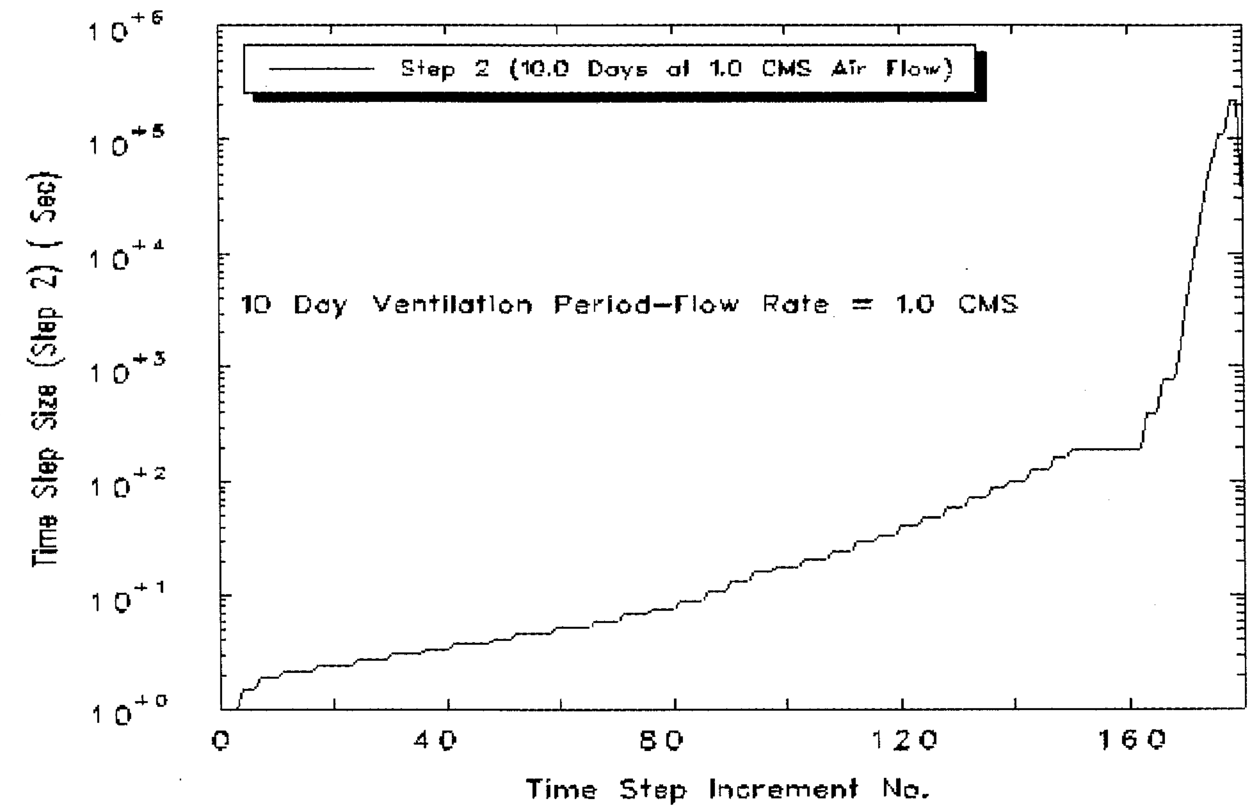

Figure 10. Plot of transient time step size versus time step increment number for step number 2 of the ABAQUS analyses consisting of 10 days of ventilation at an air flow rate of 1.0 m^3/s beginning at a time of 1.0 years (i.e., end of step 1). The initial transient time step requirement for the ventilation portion of the analyses was on the order of 1.0 s. The total CPU time required to complete analyses (both steps 1 and 2) was approximately 1.67 days (40 hours) on a Silicon Graphics R10000 workstation.

to grow large as shown (around increment 165) in Figures 9 & 10 is that at this time the cool air that initially entered the drift at z=0 m at the start of ventilation, has finally exited the 600 m end of the drift (i.e. all the hot drift air has been exhausted out the end of the drift). Until this time, there is a sharp temperature gradient or front between hot and the cooler ventilation air, which is

also moving slowly down the axial length of the drift. Until this sharp (high temperature gradient) front exits the drift at $z = 600$ m, the time step must remain low as seen in Figures 9 and 10.

For the 1.0 m^3/s air flow rate and available cross-sectional air flow area, the mean air velocity is calculated as follows:

$$\dot{V} = 1.0\ m^3/s$$

$$A_c = \pi\left[\underbrace{(2.5\ m)^2}_{\text{rock wall}} - \underbrace{(0.9\ m^2)}_{\text{waste package surface.}}\right] = 17.88\ m^2$$

$$v_{ave} = \frac{\dot{V}}{A_c} = \frac{1.0\ m^3/s}{17.88\ m^2} = 0.05592\ m/s$$

Time it takes for ventilation air entering drift @ $z = 0$ m to travel the full 600 m drift length is:

$$t_{travel} = \frac{600\ m}{0.05592\ m/s} = 10{,}730\ s\ [\approx 3\ hrs]$$

As seen from Figure 9, this is the step time at which the time step can increase greatly.

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~~The~~ following the previous analyses with the 1.0 m^3/s air flow rate, a similar analyses was attempted for a higher 10.0 m^3/s air flow rate. It was evident based on prior transient analyses with the 20 m drift model (pgs 37-39), that the initial time step at the start of the ventilation period (i.e. step 2) would have to be reduced further from the 1.0 s used for the prior 1.0 m^3/s air flow run. As such, this initial time step was set at 0.1 s. ABAQUS, however, reduced it further to 0.0681 s. Also, for the higher air flow rate, the time step growth was also much slower (i.e., many more increments were solved before the time step size increased.) At the end of approximately 54 hrs of CPU time, the time increment count was at 188 and the time step size had only reached 0.3358 s. It is believed that the time step growth would eventually accelerate, but it was estimated that > 1 week of CPU time would be required. This higher air flow rate ABAQUS run was stopped as computer CPU time cost would likely have been prohibitive.

For the 10.0 m^3/s air flow rate, the mean air velocity is

$$V_{ave} = \frac{10.0\ m^3/s}{17.88\ m^2} = 0.5592\ m/s.$$

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For the 600 m long drift, the travel time for air to travel the full 600 m drift length is

$$t_{travel} = \frac{600m}{0.5592 m/s} = 1073 s \ (\approx 0.3 \ hrs)$$

18 min.

Again, until the step time has reached roughly 18 minutes, the sharp thermal front between the moving cooler ventilation air and the stationary hot initial drift air would exist, and the time step size kept small. If sufficient computer resources were allowed, it is felt that this higher transient air flow rate ($10.0 m^3/s$) ~~pr~~ analyses could be completed.

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One alternative approach would be to turn on both the radiation heating and ventilation at time t=0.0. This way, a sharp temperature gradient within the air stream would not exist, and the time step would ~~possibly~~ grow much faster even for the higher air flow rates. Further investigation into this would be necessary.

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I have reviewed this scientific notebook and find it in compliance with QAP-001. There is sufficient information regarding procedures used for conducting tests, acquiring and analyzing data so that another qualified individual could repeat the activity.

4-16-01

Manager, MGFE