5/1/80 MR

.4, 1422

UCRL-52918

A method for calculating internal radiation and ventilation with the ADINAT heat-flow code

T. R. Butkovich
D. N. Montan

MASTER

April 1, 1980

Lawrence Livermore Laboratory

UCRL-52918
Distribution Category UC-70

A method for calculating internal radiation and ventilation with the ADINAT heat-flow code

T. R. Butkovich
D. N. Montan

Manuscript date: April 1, 1980

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • $5.00 per copy • (Microfiche $3.50)

A METHOD FOR CALCULATING INTERNAL RADIATION AND VENTILATION WITH THE ADINAT HEAT FLOW CODE

ABSTRACT

One objective of the spent fuel test in Climax Stock granite (SFTC) is to correctly model the thermal transport, and the changes in the stress field and accompanying displacements from the application of the thermal loads. We have chosen the ADINA and ADINAT finite element codes to do these calculations. ADINAT is a heat transfer code compatible to the ADINA displacement and stress analysis code. The heat flow problem encountered at SFTC requires a code with conduction, radiation, and ventilation capabilities, which the present version of ADINAT does not have. We have devised a method for calculating internal radiation and ventilation with the ADINAT code. This method effectively reproduces the results from the TRUMP multi-dimensional finite difference code, which correctly models radiative heat transport between drift surfaces, conductive and convective thermal transport to and through air in the drifts, and mass flow of air in the drifts. The temperature histories for each node in the finite element mesh calculated with ADINAT using this method can be used directly in the ADINA thermal-mechanical calculation.

INTRODUCTION

A test of retrievable dry geologic storage of spent fuel assemblies from an operating commercial nuclear reactor is underway at the Nevada Test Site (NTS) of the U.S. Department of Energy (DOE). This generic test is located 420 m below the surface in the Climax granitic stock. Eleven canisters of spent fuel approximately 2.3 years out of reactor core will be emplaced in the floor of a storage drift along with six electrical simulator canisters, and their effects will be compared. Two adjacent drifts will contain electrical heaters, which will be operated to simulate within the test array the thermal field of a large repository. This project, generally referred to as the Spent Fuel Test-Climax granite or SFTC, is part of the DOE Nevada Nuclear Waste Storage Investigations, which are managed by the Nevada Operations Office of the DOE. The Lawrence Livermore Laboratory (LLL) is responsible for the technical direction of the test.[1] During the test, thermomechanical data will be obtained which may ultimately be used in designing a spent fuel repository in granite. The SFTC will be instrumented with temperature, stress, and displacement gages. During the time of the test, the spent fuel drift and the two side drifts will be ventilated.

METHOD

One objective in the SFTC is to correctly model thermal transport, and displacements and changes in the stress field resulting from application of the thermal loads. Solving heat flow problems of this type requires a code with conduction, radiation, and ventilation capabilities. We have chosen two finite element codes: ADINA,[2] a displacement and stress analysis code, and ADINAT,[3] a compatible heat-transfer code. That is, ADINAT produces temperature histories for each node in a finite element mesh used with the ADINA calculation.

A problem, however, is that although radiative heat transfer occurs between floor, walls, and roof of the SFTC drifts, the present version of the ADINAT code allows transfer only external to the boundary of the calculation mesh. Heat loss to the ventilation air in the drift is also not directly available in the code.

We have modeled heat transfer processes for ADINAT from TRUMP,[4] a multi-dimensional, finite-difference computer code that correctly models radiative heat transport between the drift surfaces, conductive and convective thermal transport to and through the air in the drifts, and including the mass flow of the air. Unfortunately, a convenient mesh for a TRUMP calculation cannot be used directly in a thermal-mechanical ADINA calculation.

The method devised to enable ADINAT to model internal radiative heat transport and the effects of ventilation requires that, in each drift, all the side nodes be connected to a central node. Figure 1 shows the relative positions of the spent fuel drift and the heater drifts, and also the connections between the side nodes and a central node in each drift. Since $y = 0$ is a plane of symmetry, only half of the region is shown. Also shown are the positions of the spent fuel canisters and the electric heaters. Radiation is modeled by assigning to the materials within the drifts a high value of thermal conductivity (similar to that of a metal), and a low value

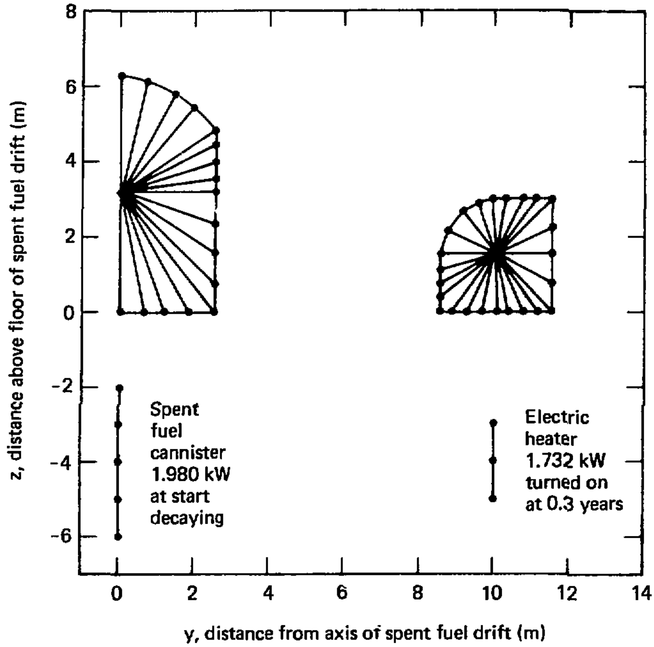

FIG. 1. Positions of excavations and heaters used in ADINAT calculations for ADINAT-TRUMP comparisons.

for mass density. Ventilation is modeled with a boundary convection element, using temperature-dependent convective heat transfer from the central nodes in both the drifts.

We made the input to the ADINAT and TRUMP calculations (Table 1) as similar as possible, so the results of the two calculations can be compared.

The decay of power level with time was identical in both calculations. It was assumed to be proportional to the decay for PWR fuel[5] with a burnup of 33,000 megawatt days per tonne of uranium (MW-d/MTU), at a specific power of 37.5 MW/MTU. Starting time is 2.3 years out of core.

To compare the ADINAT and TRUMP calculations, we estimated heat flow values in order to simulate in the ADINAT calculation the radiative transport between the drift surfaces, and ventilation. For the radiative transport--modeled by assigning a conductivity, density, and heat content to the material within the drift--we used the following procedure.

Radiative heat flow (q_r)

$$q_r = A\,\sigma \left(T_2^4 - T_1^4\right)$$

$$= A\,\sigma\,(T_2 + T_1)^2\,(T_2 + T_1)\,(T_2 - T_1), \tag{1}$$

TABLE 1. Input quantities to comparison calculations between ADINAT and TRUMP codes.

	ADINAT	TRUMP
Canister drift		
Cross section	5 × 6 m rounded corner	5 × 6 m rectangular
Floor position	2 m above canister top	2 m above canister top
Radiation	*	black body
Convection	*	$N = 0.13\ N_{Ra}$†,**
Ventilation	*	0.02 m^3/s
Heater drift		
Cross section	3 × 3 m rounded corner	3 × 3 m square
Floor position	3 m above canister top	3 m above canister top
Radiation	*	Black body
Convection	*	$N = 0.13\ N_{Ra}^{1/3}$†,**
Ventilation	*	0.01 m^3/s
Spent fuel canister		
Spacing	3 m on center	3 m on center
Length	4 m	4 m
Power	1.98 kW decaying	1.98 kW decaying
Start time	0 yr	0 yr
Guard heater		
Spacing	*6 m on center*	*6 m on center*
Length	2 m	2 m
Position	10 m from canister	10 m from canister
Power	1.732 kW constant	1.732 kW constant
Start time	0.3 yr	0.3 yr
Material properties		
Rock density	2650 kg/m^3	2650 kg/m^3
Rock heat capacity	930 J/kg	930 J/kg
Rock heat conductivity	3.11 W/m-K	3.11 W/m-K
Air density	1 kg/m^3†	1 kg/m^3
Air heat capacity	1000 J/kg-K†	1000 J/kg-K
Air heat conductivity	0.03 W/m-K†	0.03 W/m-K

*Simulated in ADINAT.

†Used to derive input values.

**Rayleigh number.

where A is the surface area, and σ is the Stefan-Boltzman constant. Conductive heat flow (q_c) can be written as

$$q_c = \frac{Ak}{L} (T_2 - T_1), \tag{2}$$

where k is the thermal conductivity coefficient and L the average path length. Equating $q_r = q_c$ and realizing that $T_2 \approx T_1 \approx T$,

$$k = 4 \sigma T^3 L. \tag{3}$$

Using $T = 300$ K, $\sigma = 5.672 \times 10^{-8}$ W/m^2-K^4, L = 6 m,

$$k = 36.75 \text{ W/m-K},$$

for a trial value.

For the convection coefficient needed to model heat transfer from the drift surfaces to the air in the drifts, we used an empirical correlation for natural convection in the turbulent range relating the Nusselt number (N_{Nu}) to the Rayleigh number[6]:

$$N_{Nu} = 0.13 \, N_{Ra}^{1/3},$$

where the Rayleigh number is the product of the Grashof number and the Prandtl number:

$$N_{Ra} = N_{Gr} \cdot N_{Pr}.$$

Forced convection due to the flow of ventilation air should be considered if the inertial forces due to the forced air flow are comparable to the buoyancy forces from heating. The ratio of these forces is given by

$$\frac{\text{buoyancy forces}}{\text{inertial forces}} = \frac{N_{Gr}}{\left(N_{Re}\right)^2},$$

where N_{Re} is the Reynolds number. For the case being considered here,

$N_{Gr} \approx 10^{10} - 10^{11}$ and $N_{Re} \approx 10^4$ (see Appendix A).

Thus natural convection clearly dominates.

The above correlation leads to a convective heat transfer (h) coefficient of the form

$$h = a(T_r - T_a)^{1/3} ,$$

where T_r and T_a are the rock surface and air temperature, respectively. The (dimensional) factor "a" is dependent on the physical properties of air, and at 300 K has a value of 1.5 $W/m^2K^{4/3}$ (see Appendix A). The heat flow (q) from the rock to the air is then given by

$$q = h\ A\ (T_r - T_a),$$

where A is the surface area of the rock being considered.

Since the time constants associated with heat removal through ventilation are orders of magnitude smaller than the time constants for temperature change in the rock mass around the drifts, the heat removed by ventilation is equal to heat flow from the rock surfaces. The heat removal by ventilation is given by

$$q = \rho\ c\ \dot{V}\ (T_a - T_o) ,$$

where ρ is the density, c the heat capacity, $\dot{V}$ the volumetric flow rate, and T_o the temperature of the inlet air.

For the TRUMP calculations, the above convection and mass flow are entered separately and calculated directly. ADINAT does not have the capability to handle these effects directly, but does allow a surface node to be connected to an external (fixed temperature) sink via an overall heat transfer coefficient (H) in which the heat flow is given by

$$q = H\ (T_r - T_o) ,$$

where H can be tabulated as a function of $(T_r - T_o)$. To obtain this function we equate the above three equations for heat flow:

$$H(T_r - T_o) = \rho\ c\ \dot{V}\ (T_a - T_o) = aA(T_r - T_a)^{4/3}$$

and solve parametrically to obtain

$$H = \rho \; c \; \dot{V} \; x$$

$$T_r - T_o = \left(\frac{\rho c \dot{V}}{aA}\right)^3 \frac{x^3}{(1 - x)^4}$$

where the parameter $x = \dfrac{T_a - T_o}{T_r - T_o}$ $(0 < x < 1)$

$$\rho c = (1) \; (1000) = 1000 \; J/m^3\text{-}K$$

$$a = 1.5 \; W/m^2\text{-}K^{4/3} \; .$$

For one-half of the spent fuel drift (5 m × 6 m, 1-m thick) modeled in the ADINAT calculation

$$A = (5 + 6)(1) = 11 \; m^2$$

and

$$\dot{V} = \frac{1}{2} \; (0.02)(1) = 0.01 \; m^3/s.$$

For the heater drift

$$A = 2(3 + 3)(1) = 12 \; m^2$$

and

$$\dot{V} = (0.01)(1) = 0.01 \; m^3/s \; .$$

RESULTS

We made an ADINAT calculation with the fore-mentioned values, using the first estimate of thermal conductivity of the tunnel material (36.75 W/m-K). Figure 2 shows temperature-time curves obtained at the center of the floors and roofs of both spent-fuel-canister and heater drifts. The comparisons of

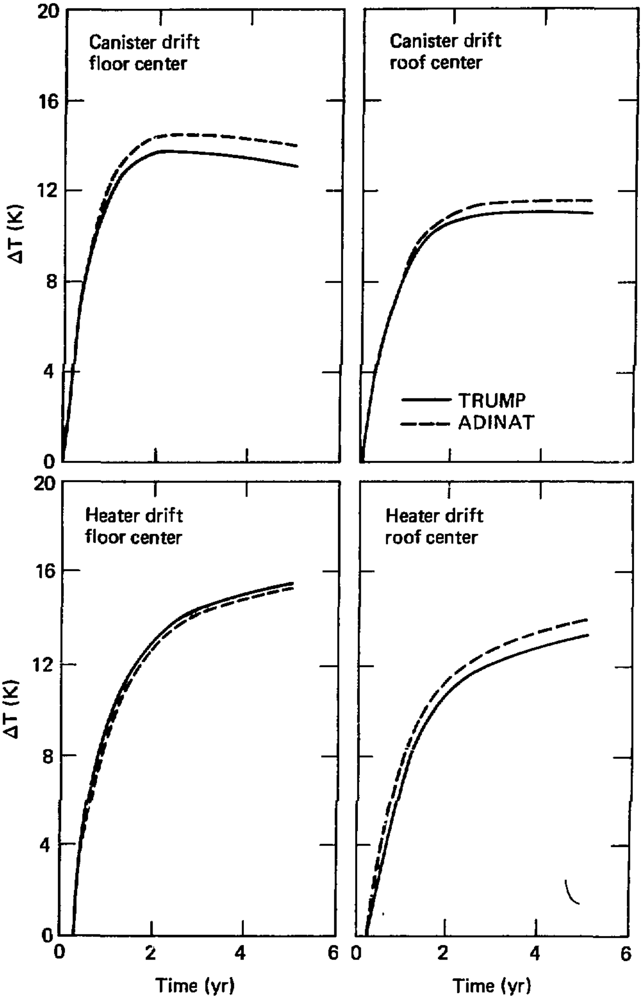

FIG. 2. Comparisons between ADINAT and TRUMP calculations at four points using k = 36.75 W/m-K for material in drifts in ADINAT calculations.

the ADINAT temperatures with the TRUMP calculation are quite good at the roof but deviate considerably at the floor of the canister drift. For the heater drift, the results are better. It appears that the values of k should be adjusted somewhat for better agreement, more for the canister drift than for the heater drifts, probably because of the greater average path length.

The thermal conductivity was changed to 50 W/m-K for the spent-fuel drift material, and 32 W/m-K for the heater drift material. These differences can be justified on the basis of the different average path lengths of conductivity in the two drifts. The ADINAT calculation was repeated, and the results for the same four points (Fig. 3) are in much better agreement with TRUMP calculations than those shown in Fig. 2. Changing the value of conductivity used for the drift materials influences the temperature at the floor of the drifts with very little effect on the roof temperatures. The temperature difference at the roof, while small, is probably caused by the way TRUMP and ADINAT remove heat by ventilation. However, there is no justification to change the values of convection coefficient used in ADINAT to affect better agreement.

The calculations shown in Fig. 3 include the effects of radiation and ventilation. As a comparison, ADINAT calculations were run assuming no radiation and assuming radiation without ventilation. For the no-radiation calculation, the material in the drifts was replaced with material with the conductivity, heat capacity, and density of air. For the radiation-without-ventilation calculation, no boundary convection was included. Figure 4 shows the temperatures at several nodes surrounding the spent fuel drift for these calculations at 1 year, indicating the importance of radiation and ventilation in SFTC calculations.

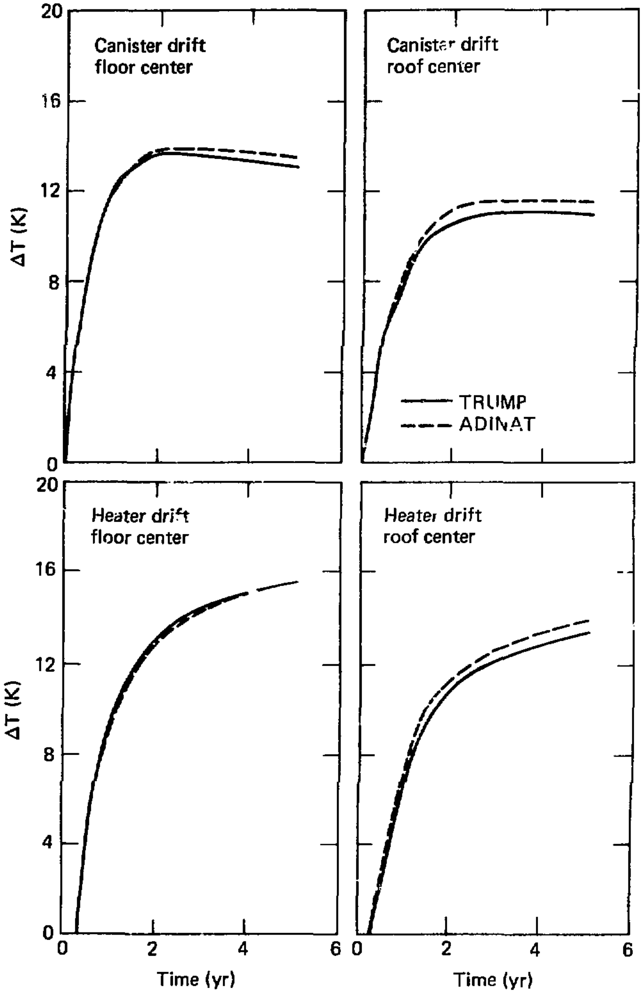

FIG. 3. Comparisons between ADINAT and TRUMP calculations at four points using k = 50 W/m-K for spent fuel drift material and 32 W/m-K for heater drift material in ADINAT calculation.

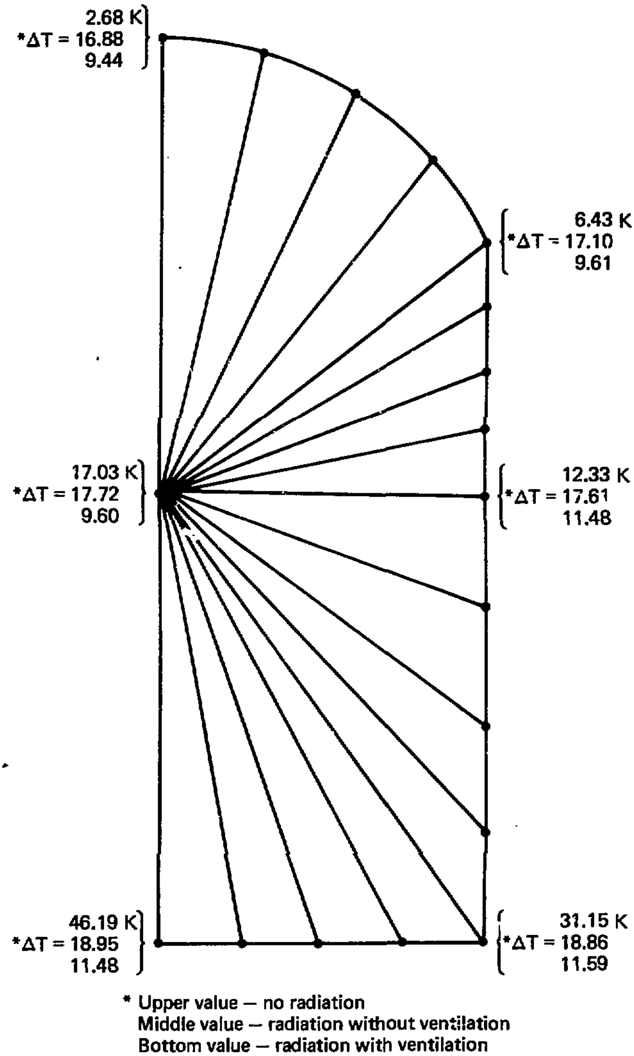

FIG. 4. Comparison between results obtained at 1 year from ADINAT calculations for conduction alone, conduction and radiation, and conduction radiation with ventilation.

APPENDIX A. DEFINITIONS AND VALUES USED TO DERIVE THE INPUT VALUES FOR CONVECTIVE HEAT TRANSFER THROUGH VENTILATION

The Nusselt number $= \frac{hL}{k}$

The Grashof number $= \frac{gL^3\beta\Delta T}{\nu^2}$

The Prandtl number $= \frac{\nu}{\kappa}$

The Reynolds number $= \frac{Lu}{\nu}$

The Rayleigh number $= N_{Gr}\ N_{Pr}$

The correlation $N_{Nu} = 0.13\ N_{Ra}^{1/3}$

is equivalent to Eq. (7-4a) on p. 172 of McAdams[6] using

h	heat transfer coefficient		W/m^2-K
L	typical dimension	5	m
k	thermal conductivity	0.03	W/m-K
g	acceleration of gravity	9.8	m/s^2
β	coefficient of thermal expansion	$-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_P = \frac{1}{300}$	(K^{-1})
ΔT	temperature difference		(K)
ν	kinematic viscosity	20×10^{-6}	(m^2/s)
κ	thermal diffusivity	30×10^{-6}	(m^2/s)
u	velocity ($1\ m^3/s$ thru a 5×5-m drift)	$\frac{1}{25}$	(m/s)

NOTE: The values of k, β, ν, κ (and ρ and c in the body of this report) are appropriate for air at 300 K at the SFTC elevation.

We find:

$$N_{Re} = \frac{(5)\left(\frac{1}{25}\right)}{20 \times 10^{-6}} = 10^4$$

$$N_{Pr} = \frac{20 \times 10^{-6}}{30 \times 10^{-6}} = 0.67$$

$$N_{Gr} = \frac{(9.8)\ (5^3)\ \left(\frac{1}{300}\right)\ \Delta T}{(20 \times 10^{-6})^2} = \Delta T \times 10^{10}$$

$$N_{Nu} = (0.13)\ (0.67 \times \Delta T \times 10^{10})^{1/3} = 250\Delta T^{1/3}$$

$$h = \frac{(0.03)\,(250)\Delta T^{1/3}}{5} = 1.5\Delta T^{1/3}\ W/m^2\text{-}k$$

NOTE: The dimension, L, cancels out in the calculation of h and is only needed to get estimates of N_{Gr} and N_{Re} to decide about forced convection.

REFERENCES

1. L. D. Ramspott, L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site,* Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52796 (1979).
2. K. J. Bathe, *ADINA, A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis,* Massachusetts Institute of Technology, Cambridge, Mass., Report 82448-1 rev. (1977).
3. K. J. Bathe, *ADINAT, A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis of Temperatures,* Massachusetts Institute of Technology, Cambridge, Mass., Report 82448-5 (1977).
4. A. L. Edwards, *TRUMP, A Computer Program for Transient and Steady State Temperature Distribution in Multidimensional Systems,* Lawrence Livermore Laboratory, Livermore, Calif., UCRL-14754, Rev. 3 (1972).
5. Rockwell International, *Spent Unreprocessed Fuel Facility Engineering Studies,* Rockwell International, Hanford, Wash., Informal Report RHO-LD-2 (1978).
6. W. H. McAdams, *Heat Transmission* (McGraw Hill Book Co., New York, 1954), 3rd ed.

SB/1f

LLL: 1980/6