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Analysis Report
AP-156 Revision 0

SDI Heater Testing Long-Term Thermal Effects Calculation

(AP-156: Analysis Plan for the Impact Determination of

SDI Heater Testing on Long-Term WIPP Performance)

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1.0 Introduction and Objectives

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste. Containment of TRU waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The DOE demonstrates compliance with the containment requirements according to the Certification Criteria in Title 40 CFR Part 194 by means of performance assessment (PA) calculations performed by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequence of potential radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years after facility closure. The models are maintained and updated with new information as part of a recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999.

With the recertification of the WIPP in November of 2010 (U.S. EPA 2010), a new PA baseline was established by the PABC-2009. Following this most recent recertification decision, the DOE plans to submit a planned change notice (PCN) to the EPA that justifies additional excavation in the WIPP experimental area. This excavation will be done in order to support salt disposal investigations (SDI) that include field-scale heater tests at WIPP.

The proposed expansion of the WIPP experimental area in order to facilitate SDI work requires an assessment of the impact of planned heater tests on the thermal state of the repository at the time of closure must be evaluated and quantified. The DOE has requested that SNL undertake calculations and analyses to determine the impacts of planned heater tests will be via an assessment of the evolution of heat dissipation from the beginning of SDI experimental work to the time of facility closure. Analysis plan AP-156 outlines the approach SNL will use to determine the impacts of the planned additional excavation and heater tests in the WIPP experimental area on long-term repository performance.

2.0 Thermal Impacts Summary

An analytic heat conduction solution is used to conservatively estimate the rise in temperature at the WIPP waste disposal panels due to the proposed SDI heater tests. The calculation uses a well-known two-dimensional analytic solution and the method of superposition. These solutions and methods are found in heat conduction textbooks: for example Ozisik (1993), and Carslaw and Jaeger (2003). The solution is analytic (there is no computational grid, time steps, or solver) and uses the simple mathematical concept of superposition to find the resulting expected rise in temperature. The advantages of an analytic solution include the lack of ancillary parameters related to numerical solution (e.g., grid spacing, time steps, and convergence criteria). In this case an analytic solution will capture the conservative bounding nature of the proposed calculation without the complications introduced by a potentially more realistic gridded numerical model.

Superposition is used to take a simple two-dimensional solution and build up a solution that considers both the timing and geometry of the proposed SDI heater tests. Superposition is possible due to the linearity of heat conduction in a solid (with constant thermal properties). The analytic solution will ignore the effects that the excavations or any small-scale heterogeneity would have on the solution. The drifts may be circulated with relatively cool air, and would therefore serve as a sink for heat during the operational life of WIPP. This potential cooling effect will not be taken into account in the proposed superposition of analytic solutions.

The calculation begins with a solution for a line source with cylindrical symmetry. We use superposition in time of a co-located source and sink to simulate a finite source (in this case 2 years). The effect of anhydrite Marker Beds 138 and 139 (above and below the repository, respectively) are what make the solution two-dimensional, treating them as if they are perfectly insulating boundaries. In a purely homogeneous and isotropic medium with spherical symmetry, heat flow would be three-dimensional (x, y and z). Accounting for the marker beds will be quite conservative, forcing the heat to flow in a two-dimensional manner (x and y only).

Superposition in time will produce a field of predicted temperature rise due to one heater. The effects of all five of the proposed heaters will be estimated by superimposing the required number of these line solutions at the proposed heater locations, (x and y); this final superposition will determine the expected total rise in temperature due to all proposed heaters at any location in space or time after the heaters are turned on.

This report documents the calculation, material properties, and temporal and geometrical arrangement used. Section 5 lists the Python script used to compute and plot the solution, allowing the calculations to be checked and verified. Any deviations from details in the analysis plan were related to corrections and comments received in the review process; the approach used in this report is conceptually simpler while effectively the same as that in AP-156.

2.1 Thermal Effects Screening Calculation

A bounding-type calculation has been performed to evaluate the effects proposed SDI heaters would have on the long-term compliance performance assessment of the WIPP. The discussion of the results, assumptions, and limitations for the analytic solution are given below. The listing of the calculation and plotting script are presented in the following sections.

The heat conduction solution used is for a specified flux at a line source, assuming angular symmetry for each heater. The solution for temperature rise, T, is well known and is presented in Carslaw and Jaeger (2003), section 10.4 (p. 261) as

$$T(r,t) = \frac{q}{4\pi\alpha}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = -\frac{q}{4\pi\alpha}Ei\left(-\frac{r^2}{4\alpha t}\right)$$

where Ei() is the exponential integral, $q = \varphi\rho C$ is the strength of the line source per unit length in the z-direction, φ is the heater power [8500 W], ρ is the density of salt [2190 kg/m^3], C is heat capacity of salt [931 J/(kg·K)], $\alpha = \frac{k}{\rho\, C_p}$is thermal diffusivity of salt [2.648E-6 m^2/s], and k is thermal conductivity of salt [5.4 W/(m·K)]. Material properties are taken from Table 1 of Stone et al. (2010). The two-dimensional line source strength, q, is related to the physical heater power, φ, with the assumption that the heaters are distributed across the entire thickness of the two-dimensional layer (16.67 m between Marker Beds 138 and 139; Beauheim & Roberts, 2002); this assumption is not unreasonable at a distance of more than 100 m from the proposed SDI heater experiment.

As an energy-balance check, the solution given in the next section are compared against

$$Qt_H = \rho VC\Delta T$$

where Q is the heater strength [8500 W = 8500 J/s], t_H is the length of time the heaters are on [2 yr = 6.312E+7 s], V is the volume of salt the energy is being distributed across [$\pi(700\text{ m})^2 \cdot 16.67$ m = 2.566E+7 m^3], and ΔT is the resulting average temperature rise across the volume V [K]. Using this relationship, the expected temperature rise due to five 8500 W heaters for two years over a cylindrical block 700 m × 16.67 m is 5.13E-2 K.

2.2 Heat conduction solution: results

The analytic solution allows the calculation of the predicted rise in temperature at any time after the heaters are turned on (the temperature rise is zero before they turn on). Figure 1 shows the predicted temperature rise due to the five 8,500 Watt heaters being on for two years at six different distances from the center of the constellation of five SDI experiment heaters. The distance to Panel 1 from the center of the SDI heater drift is approximately 700 meters (corresponding to the lowest curve in Figure 1).

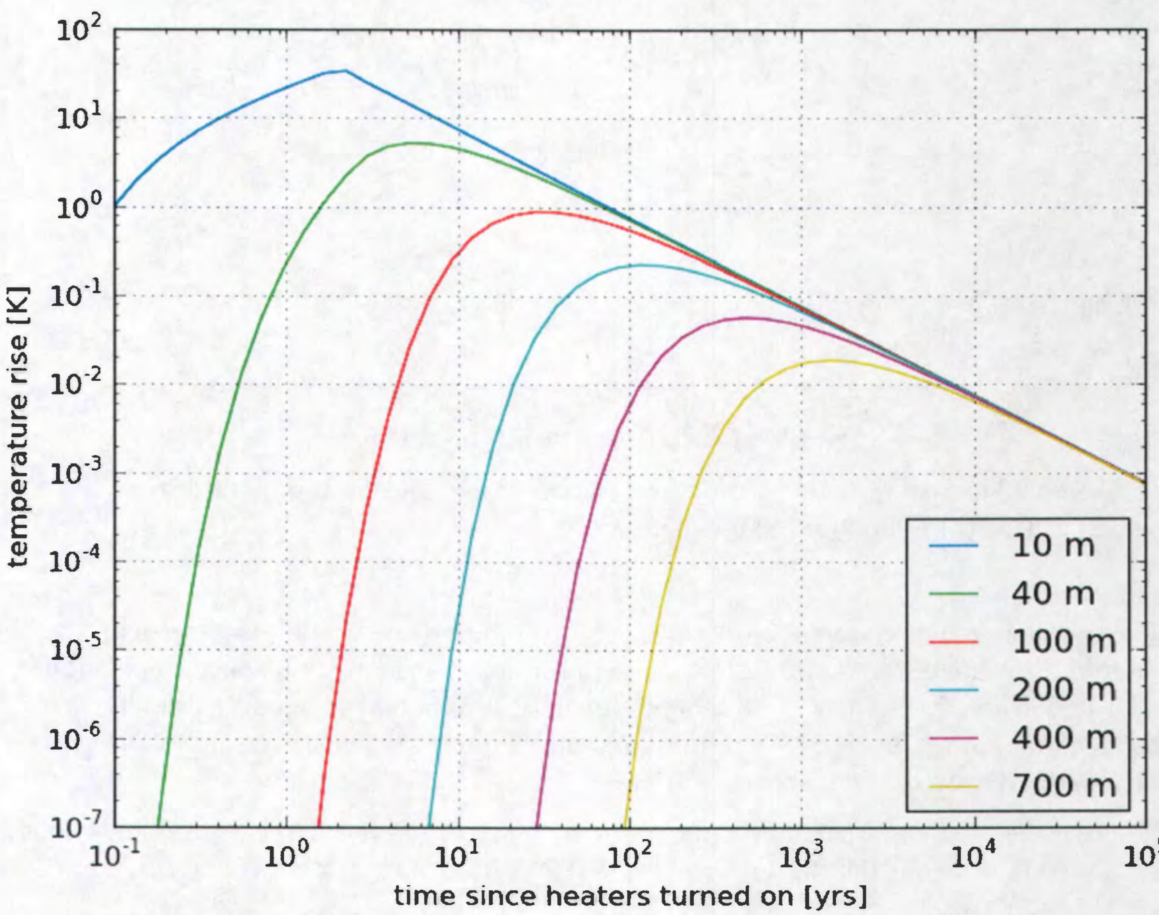

Figure 1. Predicted temperature rise through time (due to two years of heater tests) at six radial distances from proposed SDI experiment.

Figure 1 shows that the predicted peak temperature rise arrives at later times when observed from greater distance from the heaters. This is a simple well-known result from diffusion. At the distance

Panel 1 is from the SDI experiment, the peak temperature is very small (≈ 0.02 K) and arrives very late (>1,000 yrs). This prediction is a bounding conservative calculation (see following discussion of assumptions and limitations of this approach).

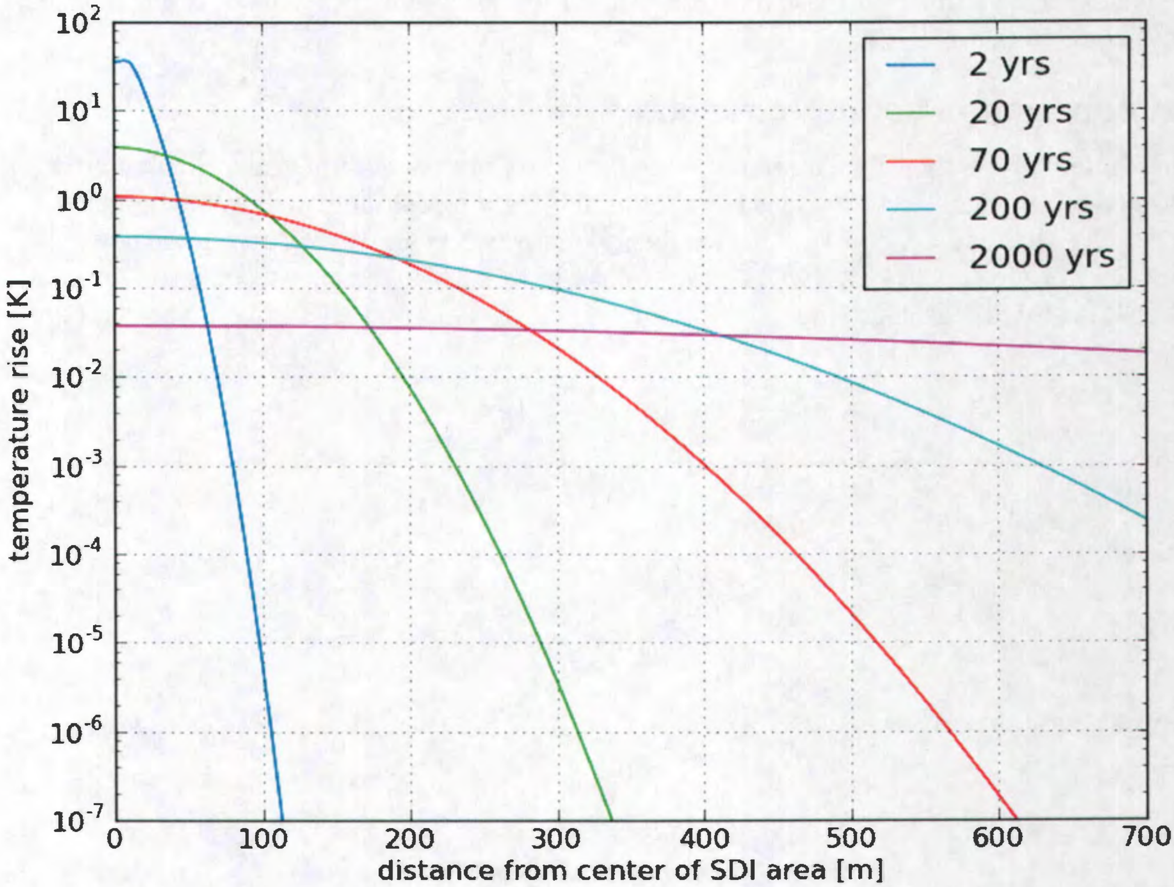

Figure 2. Predicted temperature rise profile (due to two years of heater tests) at five times after heaters are turned on (2013) from proposed SDI experiment.

Figure 2 shows the predicted spatial profile of the temperature rise At late time, the distribution of temperature rise becomes very uniform; the solution is close to the energy balance calculation in Section 2.1 (a uniform 0.05 K rise). After approximately 70 years the residual rise at almost all locations are at or below 1K. The assumptions and limitations of the analytic solution used to compute these results are given in the next section.

Figure 3 shows the predicted spatial distribution of the temperature rise 22 years after the beginning of heater tests (2035), which is the starting time for WIPP performance assessment calculations.

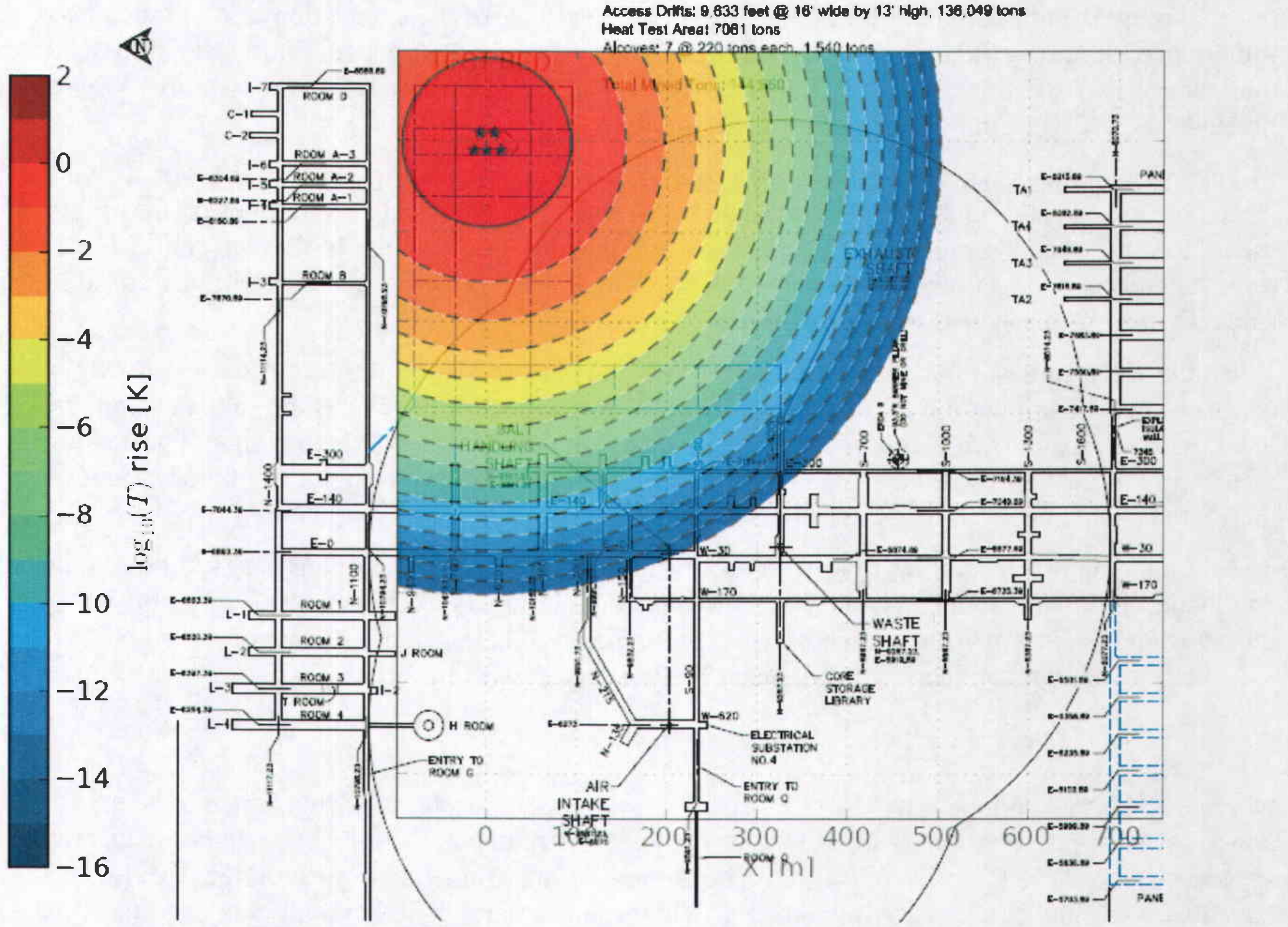

Figure 3. Predicted temperature rise distribution (due to two years of heater tests) at 2035, 22 years after heaters are turned on (2013) from proposed SDI experiment.

2.3 Analytic heat conduction solution: assumptions and limitations

The linear conduction of heat in a homogeneous isotropic solid is governed by the diffusion equation, and is covered in any textbook on heat transfer, diffusion, or conduction (e.g., Incropera & de Witt (1985), Carslaw & Jaeger (2003), Özişik (1993), or Crank (1985)). The salt in the underground facility at the WIPP deviates from the ideal circumstances in four main ways. These deviations are secondary effects or would lead to a less conservative result, and therefore the analytic solution is valid for a conservative screening calculation. The solution assumes homogeneous and linear properties, aside from the geometry handled through superposition. The most significant assumption is that heat conduction is the only mechanism to dissipate thermal energy introduced by heaters. Each of the deviations from the ideal conditions is discussed below, indicating how they were addressed, or explaining the ramifications of not addressing them.

1) The excavations within the salt do not contribute to the conduction of heat. Air-filled excavations have much lower thermal conductivity than intact salt and would essentially act as insulating boundaries for conduction (although radiation and convection would likely be significant heat transfer processes). By volume, the excavations are minor compared to the amount of salt available for conduction. Near the heaters, including the location and shapes of the excavations would be important

for predicting the temperature of the salt. At 700 m the effects of the excavations are of much less importance. Ignoring the thermal conductivity effects of the excavations does not necessarily lead to a more conservative estimate. Taking into account the heat transfer properties of excavations would preclude the use of a straightforward analytic solution.

2) The mine ventilation system will remove some thermal energy. During testing some drifts will be closed off to allow thermal energy to build up in the salt. The proposed design relies on the ability of the mine ventilation system to cool the drifts to a temperature low enough for human entry. The energy removed during convection of relatively cool air through the drifts is assumed to still be trapped in the salt, and must be dissipated by conduction.

When the test area is ventilated, thermal energy will be removed by convection and the salt will be cooled. This is the intention of ventilating the SDI experimental area. When the salt is cooled, the local thermal gradient will actually reverse, and heat will now flow towards the original heat source area, which is now a heat sink. This reversal is not accounted for in the analytic solution, and it is therefore considered a quite conservative estimate.

3) Thermal conductivity for WIPP salt is not constant. The straightforward analytic solution of the heat conduction problem is only possible when thermal conductivity is a constant. The variability of thermal conductivity over the range of expected temperature is less than an order of magnitude; specifically, thermal conductivity of halite at WIPP is given as (Stone et al., 2010)

$$k(T) = 5.4\left(\frac{300}{T}\right)^{1.14},$$

where k is thermal conductivity [W/(m*K)] and T is temperature [K]. It is considered to be a conservative approximation to use the highest value of thermal conductivity expected over that range, specifically $k(T{=}300\text{ K}) = 5.4$ W/(m*K). The volume of salt immediately surrounding the heater will have lower thermal conductivity than the far field, because of much higher temperatures; this will slow the flow of energy away from the heaters by conduction.

4) WIPP salt is not homogeneous and isotropic. The Salado formation consists of laterally extensive nearly horizontal layers of mostly halite, some anhydrite, minor clay, and minor other evaporites. The Salado formation has a much greater horizontal extent (tens to hundreds of kilometers) than vertical extent (few hundred meters). Any thermal pulse would encounter boundaries in the vertical direction much sooner, than in the horizontal directions. Halite has higher thermal conductivity than other materials found in the Salado (e.g., see point 5 on page 4 of DOE 2011b). A conservative prediction assumes these anhydrite marker beds just above and below the repository are perfectly insulating. In reality, the marker beds are only less conductive than halite, and there is a large thickness of halite both above and below these thin marker beds.

The analytic solution accounts for these maker beds by simulating the domain as being two dimensional. The vertical extent (approximately 16 meters) is much less than the horizontal extent (hundreds to thousands of meters) and therefore the two-dimensional approximation is conservative and accurate enough for the desired purpose. The analytic solution does not account for any other heterogeneity or anisotropy of thermal properties, aside from the insulating boundaries at the marker beds.

Although neglecting the excavation's effects on heat conduction is not handled in a conservative manner (point #1 above), it is believed that not taking credit for the heat lost to mine ventilation (#2) and conduction above and below the marker beds (#4) leads to a very conservative estimate of temperature rise at Panel 1. The overall result is conservative in its assumptions and shows that the

SDI heater experiments should create no discernable deviation from the current baseline condition at the WIPP.

3.0 Summary

The effects of two years of five 8500 Watt heaters in the SDI thermal tests will be insignificant at the location of the waste disposal panels(Panel 1 being the closest) for any time. The calculation in this report is very conservative and bounding; the results illustrate that even under such conservative estimates there is expected to be no change in repository conditions at the time the WIPP repository is planned for closure, based on the preliminary design presented in the letter and proposal from DOE (2011a; 2011b).

4.0 References

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J. Crank. The *Mathematics of Diffusion*. Oxford Science, second edition, 1985.

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U.S. Environmental Protection Agency (EPA). 2010. 40 CFR Part 194 Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance With the Disposal Regulations: Recertification Decision, Federal Register No. 222, Vol. 75, pp. 70584-70595, November 18, 2010.

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U.S. Department of Energy (DOE) 2011b. Inputs and Information for the SDI Thermal Test Planned Change Notice. U.S. Department of Energy Waste Isolation Pilot Plant, Carlsbad Area Office, Carlsbad, NM. ERMS 555495.

C. Stone, J. Holland, J. Bean, and J. Arguello 2010. Coupled thermal-mechanical analyses of a generic salt repository for high level waste. In 44th US Rock Mechanics Symposium and 5th US-Canadian Rock Mechanics Symposium, Salt Lake City, UT, June 2010. American Rock Mechanics Association.

5.0 Python Script Listing

The Python script used to compute the solution and plot the figures in this report is listed below for completeness.

```
# this script is part of the SNL SDI proposal scoping work
# by Kristopher L. Kuhlman, Repository Performance Dept. (6212)

import numpy as np                # array functionality
from scipy.special import exp1    # exponential integral
import matplotlib.pyplot as plt   # plotting functionality

def G(a1,f1,t1,r1):
    """2D solution for line source

    a1 = thermal diffusivity [W/(m*K)]
    t1 = 1D time vector    [s]
    r1 = radial distance (any shape >= 1D) [m]
    """

    oldshape = list(r1.shape)
    nt = t1.shape[0]
    r1.shape = (1,-1)  # reform into 1D vector with singleton second dim
    t1.shape = (-1,1)  # make t conformable with r

    Z1 = f1/(4.0*np.pi*a1)*exp1(r1**2/(4.0*a1*t1))

    # change inputs back to original shape
    r1.shape = oldshape
    t1.shape = (nt,)

    # reshape result so it has dimensions like r
    # with the t dimension added in front
    oldshape.insert(0,nt)

    Z1.shape = oldshape
    return Z1

def H(a2,f2,t2,tau2,r2):
    """use superposition in time to compute a
    source that is non-zero boundary flux from 0 <= t <= tau

    a2,k2,t2,r2 are same as in G()
    tau2 = time heaters are turned off [s]
    f2 = actual flux strength [W]

    NB: routine assumes times are listed in increasing order
    """

    # source on at t=0
    T0 = G(a2,f2,t2,r2)

    tt = t2-tau2 # shifted times

    # number of non-zero times at beginning of vector
    nnz = (tt[:] < 0).sum()

    # sink on at t=tau (only positive times are valid)
    T1 = G(a2,f2,tt[nnz:],r2)

    # combine source and sink
    T2 = np.empty_like(T0)
    T2[:nnz] = T0[:nnz]            # before heater turns off
    T2[nnz:] = T0[nnz:] - T1[:]    # after heater turns off
    return T2

def heaters(a3,f3,t3,tau3,xg,yg,htrs):
    """ use superposition to in horizontal (x,y) to sum up
    effects of multiple heaters installed at different x,y locations,
    assuming all heaters are at the same elevation.
```

```
    a4,k4,t4 are same as G()
    tau4,f4 are same as H()
    xg,yg are arrays of observation coordinates [m]
    source terms are located at complex coordinates passed
    in the list htrs (heaters) [m].
    """

    Wshape = list(xg.shape)
    Wshape.insert(0,t3.shape[0])
    W3 = np.zeros(Wshape,dtype=np.float64)

    Zg = xg + yg*1j

    for i,heat in enumerate(htrs):

        # compute relative horizontal (2D) distance from heater
        rg = np.abs(Zg - heat)
        W3 += H(a3,f3,t3,tau3,rg)

    return W3

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# setup material properties

k = 5.4        # thermal conductivity  [Watt/(meter*Kelvin)]
alfa = 2.648E-6  # thermal diffusivity   [meter^2/second]
density = 2190.0  # density of salt [kg/m^3]
Cp = 931.0  # heat capacity of salt [Joule/(kilogram*Kelvin)]
strength = 8500.0   # power of each heater [Watt]
f0 = strength/(Cp*density*16.67)  # line source strength

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# setup calculation grid and input parameters

secperyr = 365.2422*24.0*60.0*60.0  # seconds in a year

# time after t=0 heaters get turned off [2 years in seconds]
tau =   2.0 *secperyr  # end of heaters
maxt = 20.0 *secperyr  # "final" map calculation date (2035, assuming begins in 2015)

# Computational grid is with respect to SDI
# proposal figure (north is to left), so computational
# x+ is South (x- is North), y+ is East (y- is West)

# compute out to 750m since it is about 680 m
# from proposed heater locations (as per SDI proposal) to panel 1
nt,nx,ny  = (22,100,100)
minx,miny = (-100.0, -750.0)
maxx,maxy = (750.0,  100.0)

tg = np.linspace(1.0E-6,maxt,nt)  # time [seconds]

# compute on a grid, with center of heater array at origin.
xg,yg = np.meshgrid(np.linspace(miny,maxy,ny),np.linspace(minx,maxx,nx))

# 3D mesh for plotting
X,Y = np.mgrid[minx:maxx:nx*1j, miny:maxy:ny*1j]

# @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
# perform calculation

# distances related to proposed geometry of heaters
# estimated from figures in SDI proposal.
hdew = 15.5     # east-west distance between heaters
hdns = 20.0/2.0 # half north-south distance between heaters

htrs = [hdns - hdew/2.0*1j,
        hdns + hdew/2.0*1j,
        -hdns -hdew*1j,
        -hdns + 0j,
        -hdns + hdew*1j]
```

```
if __name__ == "__main__":

    # compute solution on a 3D grid from MB139 to MB138
    # T has dimensions : (nt,nx,ny,nz)
    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    # log plotting doesn't like zeros (underflow of calculation above)
    # but seems to be ok with NaNs
    T[T==0] = np.NaN

    ncnt = 19 # number of contours
    cntmin = -16.0  # min/max contour range
    cntmax = 2.0

    # @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
    # plot figures of results

    print 'X,Y,t,T',xg.shape,yg.shape,tg.shape,T.shape
    print 'min, max',np.nanmin(T),np.nanmax(T)

    # plot logT contours of heat at 2035
    fig = plt.figure(1)
    ax = fig.add_subplot(111)
    pp = ax.contourf(X[:,:],Y[:,:],np.log10(T[-1,:,:]),
                levels=np.linspace(cntmin,cntmax,ncnt))
    pc = ax.contour(X[:,:],Y[:,:],np.log10(T[-1,:,:]),
                levels=np.linspace(cntmin,cntmax,ncnt),colors='black',linewidth=0.5)
    cb = fig.colorbar(pp)
    cb.set_label('$\\log_{10}(T)$ rise [K]')
    ax.set_xlabel('X [m]')
    ax.set_ylabel('Y [m]')
    for h in htrs:
        ax.plot(h.imag,h.real,'k*')
    plt.axis('image')
    plt.grid()
    ax.set_title('temp rise contours at top of waste panel level')
    plt.savefig('end-logtemp-contours-at-panel-level.png',transparent=True)
    plt.close(1)

    # compute solution for radial profile at different times
    xg = np.linspace(0,700,500)
    yg = np.zeros_like(xg)
    mint = 0.1
    maxt = 100000.0
    tg = np.array([2,20,70,200,2000])*secperyr

    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    fig = plt.figure(1)
    ax = fig.add_subplot(111)
    for i,tval in enumerate(tg):
        ax.semilogy(xg,T[i,:],label='%.0f yrs' % (tval/secperyr,))
    ax.set_ylim([1.0E-7,100])
    ax.set_xlabel('distance from center of SDI area [m]')
    ax.set_ylabel('temperature rise [K]')
    plt.grid()
    ax.set_title('temp profile at different times')
    plt.legend(loc='upper right')
    plt.savefig('temp-profile.png')
    plt.close(1)


    # compute solution at log-spacing of time
    xg = np.array([10.0,40.0,100.0,200.0,400.0,700.0])
    yg = np.zeros_like(xg)
    mint = 0.1
    maxt = 100000.0
    tg = np.logspace(np.log10(mint*secperyr),np.log10(maxt*secperyr))

    T = heaters(alfa,f0,tg,tau,xg,yg,htrs)

    # plot temperature through time 50, 100, 200, 400, and 700 m east of heaters
```

```
fig = plt.figure(1)
ax = fig.add_subplot(111)
for i,xval in enumerate(xg):
    print i,xval
    ax.loglog(tg/secperyr,T[:,i],label='%.0f m' % xval)
ax.set_xlabel('time since heaters turned on [yrs]')
ax.set_ylabel('temperature rise [K]')
ax.set_ylim([1.0E-7,100.0])
ax.set_xlim([mint,maxt])
plt.grid()
plt.legend(loc='lower right')
plt.savefig('temperature-through-time.png')
plt.close(1)
```

Kuhlman, Kristopher L

From: Pasch, James Jay
Sent: Wednesday, May 25, 2011 2:12 PM
To: Kuhlman, Kristopher L
Cc: Lee, Moo
Subject: signature authority

I, James Pasch, give signature authority to Kris Kuhlman for the following document.

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