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Scientific Notebook No. 633: Calculations to Support Review of the U.S. Department of Energy Drift Degradation Analysis (01/27/2004 through 08/17/2004)

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

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Jan 27, 2004 GO 1/27/04

CALCULATIONS TO SUPPORT REVIEW OF U.S. DEPARTMENT OF ENERGY DRIFT DEGRADATION ANALYSIS

The U.S. Department of Energy (DOE) has recently released a report documenting aspects of its drift degradation analysis for the proposed Yucca Mountain repository (Drift Degradation Analysis. ANL-EBS-MD-000027, Revision 02, 2003). DOE intends to release other reports or amendments to the current report subsequently to complete the documentation of its drift degradation analysis.

The objective of drift degradation analysis is to characterize any potential instability of waste-emplacement drifts at the proposed Yucca Mountain repository for high-level nuclear waste during a regulatory period of 10,000 years after closure of the repository. Characterization of potential instability of the emplacement drifts is needed for several reasons. First, individual rock blocks large enough to cause mechanical damage may strike the drip shield one or more times during the regulatory period. The drip shield was introduced into the design of the engineered barrier system to protect the waste package from seepage water and from rockfall loads. Second, sustained mechanical loading from accumulated rockfall rubble may cause mechanical damage of the drip shield. Third, the insulating effects of accumulated rubble, if a sufficient amount of rubble accumulates in the openings early enough to affect heat flow, may cause an increase in temperature of the engineered barrier system components. Such increase in temperature may cause the load-bearing capacity of the drip shield to decrease and may affect other physical/chemical processes relevant to the long-term performance of the engineered barrier system. Fourth, the presence of rockfall rubble in the openings may affect the potential for seepage water contacting the engineered barrier system components.

The results of drift degradation analysis, therefore, are needed to evaluate the drip shield design and assess the values of environmental parameters such as temperature and relative humidity used in performance assessment calculations. The following information is needed from the analysis.

(1) Description of potential dynamic rock-block impacts on the drip shield. Such description should include the mass and impact energy associated with each event (of a rock block striking a drip shield) and the probability of occurrence of such event.

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(2) Weight of rubble supported by the drip shield and the rate of accumulation of such rubble.

(3) Change in configuration of the emplacement drifts owing to rockfall and accumulation of rockfall rubble.

The DOE report will be reviewed to determine if the information provided in the report will be adequate considering items (1)–(3). The review will be supported as necessary with a series of confirmatory calculations documented in this scientific notebook. Calculations may be provided by any one of the following participants

Goodluck I Ofoegbu GO

Biswajit Dasgupta BDG

AGhosh AG
Amitava Ghosh

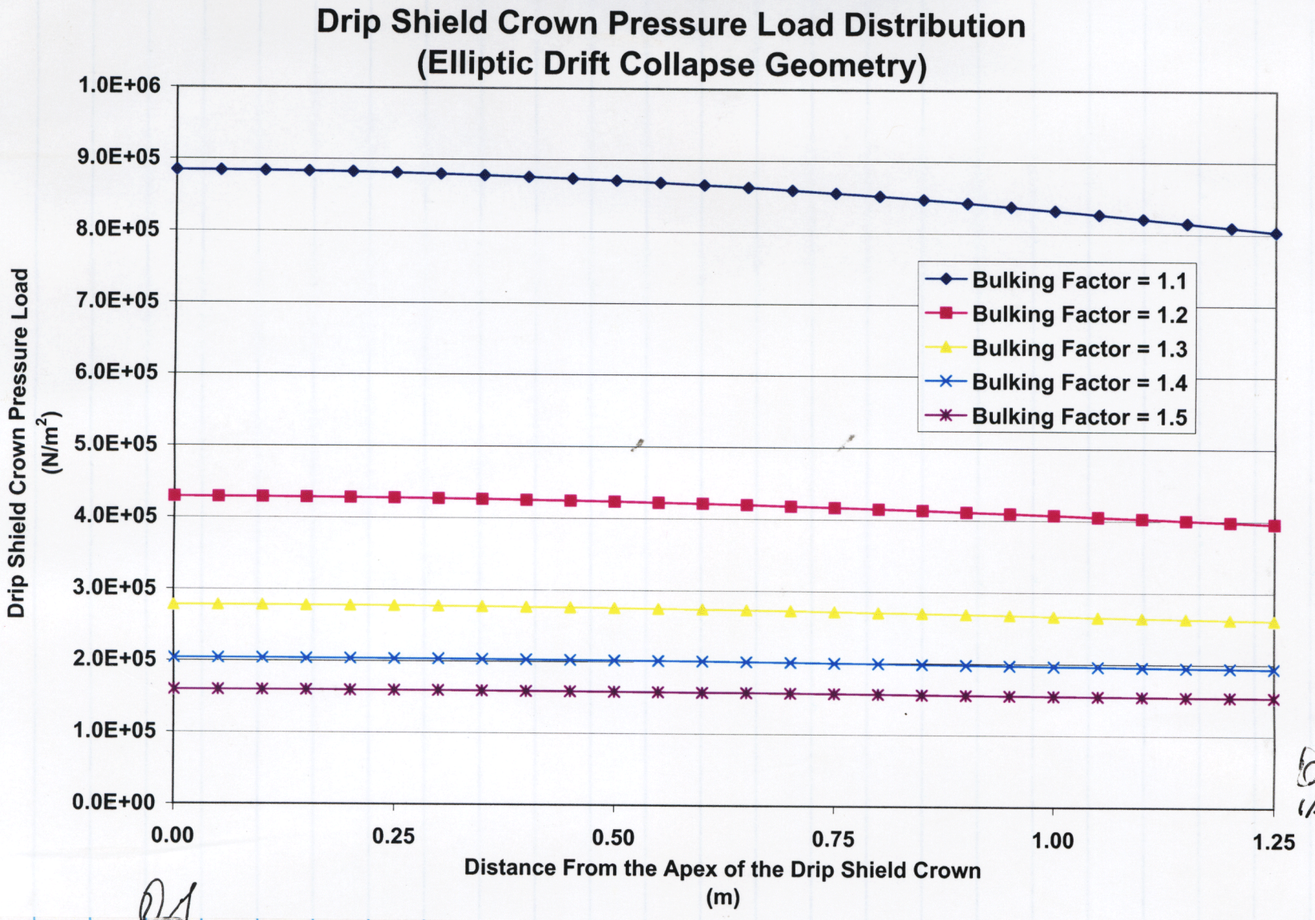
G. Douglas Gute GDG

Simon Hsiung

Kevin J. Smart KJS

Jan 28, 2004.

Drip Shield Loading from Accumulated Rockfall Rubble



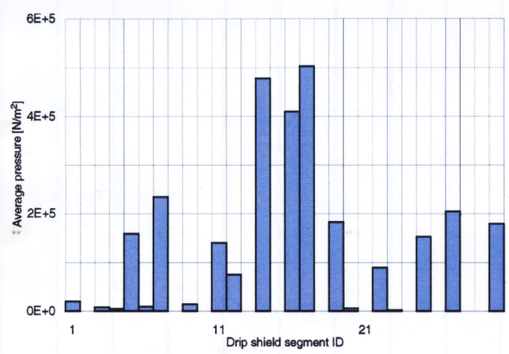
1/28/04

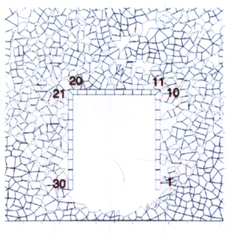
1/28/04

Calculations documented in the MECHFAIL report [MECHFAIL: A total System Performance Assessment Code Module for Evaluating Engineered Barrier Performance Under Mechanical Loading Conditions, CNWRA 2003-06] indicate that that drip shield in the DOE repository design may be subjected to the static rockfall loads displayed on p. 2. The calculation of the information on p. 2 is documented on p. 64 of CNWRA Scientific Notebook Number 409.

DOE calculated drip shield loads, (see plots below) are typically smaller than the drip shield loads illustrated on p. 2.

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Figure 138. Pressures on the Drip Shield Calculated from the Discontinuum Model: Case 4

Table 40. Summary of Pressures on the Drip Shield Calculated from the Discontinuum Model

Case	Block Size (m)	Pressure (kN/m²)			
		Left Side of Drip Shield	Top of Drip Shield	Right Side of Drip Shield	Bulking
1	0.3	105.4	107.3	72.9	0.37
2	0.3	10.4	119.9	220.8	0.30
3	0.2	142.7	172.2	37.7	0.17
4	0.2	62.6	179.2	44.8	0.16
5	0.2	107.8	145.1	49.2	0.17

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The pressures listed in Table 40 are averaged over two sides and the top of the drip shield. However the pressures are quite non-uniform as shown in Figure 138 for case 4. Note that the pressures shown in Figure 138 are forces averaged over 30 segments: 10 on each side and 10 on the top of the model. Details of drip shield pressures for each of the cases analyzed are provided in Attachment XVI.

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Jan 29, 2004

Thermal load data for Yucca Mountain repository design was extracted from TPA 5.0 input files. This thermal load data will be used as input for confirmatory thermal-mechanical analysis.

Data file name: frmTPA50HeatLoad.xls

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Blended thermal load, Watt per wastepackage, interpolated in TPA5.0.
Columns A and B extracted from spread sheet provided by R. Fedors (1/28/2004)
Column B includes 70% ventilation during first 50 yr.

Linear heat load based on: WP length = 5.06 m; spacing = 0.1 m

Time	heat load, W/WP	Time (yr)	Ventilated heat load (W/m)	Full heat load (W/m)
0	2190.3	2.00E-06	424.4767	1414.9225
2.3102	2107.6	2.3102	408.4496	1361.4987
4.6744	2025	4.6744	392.4419	1308.1395
7.094	1932.3	7.094	374.4767	1248.2558
9.5702	1848	9.5702	358.1395	1193.7984
12.104	1771.1	12.104	343.2364	1144.1214
14.698	1700.5	14.698	329.5543	1098.5142
17.352	1635.4	17.352	316.9380	1056.4599
20.069	1575.1	20.069	305.2519	1017.5065
22.849	1519.1	22.849	294.3992	981.3307
25.694	1455.4	25.694	282.0543	940.1809
28.605	1388.8	28.605	269.1473	897.1576
31.585	1327.1	31.585	257.1899	857.2997
34.635	1269.8	34.635	246.0853	820.2842
37.756	1216.5	37.756	235.7558	785.8527
40.95	1166.7	40.95	226.1047	753.6822
44.219	1120.1	44.219	217.0736	723.5788
47.564	1076.4	47.564	208.6047	695.3488
50.988	3451.3	50.988	668.8566	668.8566
54.492	3322.4	54.492	643.8760	643.8760
58.078	3200.9	58.078	620.3295	620.3295
61.747	3086.2	61.747	598.1008	598.1008
⋮	⋮	⋮	⋮	⋮
7913.7	133.78	7913.7	25.9264	25.9264
8101.3	132.35	8101.3	25.6492	25.6492
8293.3	130.94	8293.3	25.3760	25.3760
8489.7	129.55	8489.7	25.1066	25.1066
8690.8	128.17	8690.8	24.8391	24.8391
8896.6	126.81	8896.6	24.5756	24.5756
9107.2	125.46	9107.2	24.3140	24.3140
9322.7	124.13	9322.7	24.0562	24.0562
9543.3	122.81	9543.3	23.8004	23.8004
9769	121.5	9769	23.5465	23.5465
10000	120.12	10000	23.2791	23.2791

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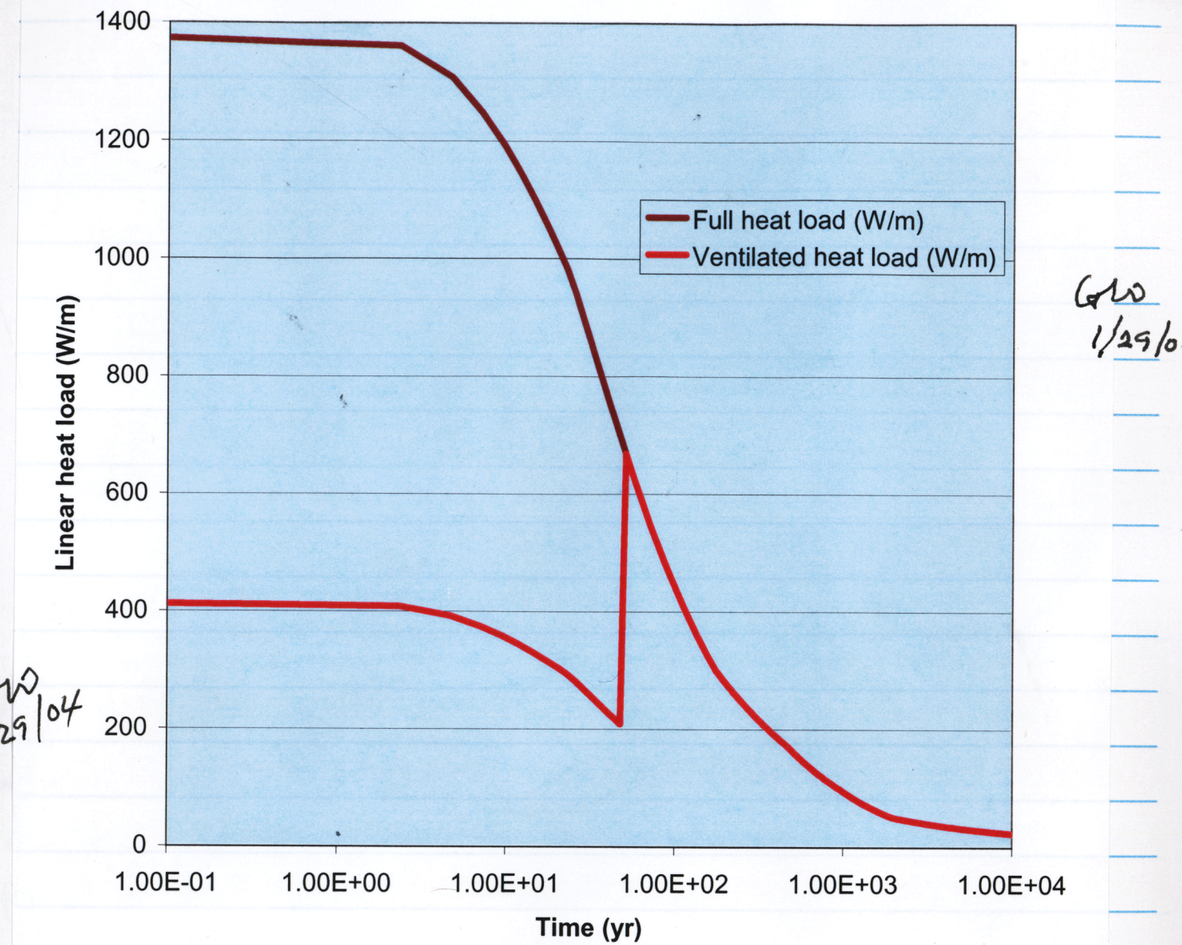
GW 1/29/04

GW 1/29/04

See electronic file for complete information.

GW 1/29/04

Plot of thermal load history (see .xls file on p. 4)



GW 1/29/04

GW 1/29/04

The ventilated thermal load (70% heat removed during first 50 yr) was used for analysis. The conversion of this thermal load history to an ABAQUS (Version 6.3) input block was performed using the calculation documented in the following pages

GW 1/29/04

GMO 1/29/04


```
/*********************************************************************
DrftTSrc (Drift Thermal Source Calculator)

This code prepares heat source history input for ABAQUS using tabulated
linear-heat-load history. The heat load is converted to a volumetric source
strength per unit volume of emplacement drift.

The input data are:

 1.          Linear heat load (W/m) file ventilatedHeatLoad.txt
 2.          Drift diameter (5.5 m)

Output:

Source-strength history (J/yr/m^3) output following ABAQUS input format.

Author:                         G. I. Ofoegbu
Date:                           Jan 28 2004
System:                         C++ compiler
                                (Code developed using Borland C++ Builder 6)
*********************************************************************/
//---------------------------------------------------------------------------

#include <stdio>
#include <iostream>
#include <iomanip>
#include <fstream>
#include <strstrea>
#include <math>
#include <string>
#include <conio>

#pragma hdrstop
#include <condefs>

using namespace std;

//---------------------------------------------------------------------------

#pragma argsused
int main(int argc, char* argv[])
{

// System constants

  float driftHeight = 5.5;
  float pi = 4.0*atan(1.0);
  float secPerYear = 365.25*24.0*60.0*60.0;
  char* outFileName= "d:\\TMResrs\\YMHeatLoad\\drftSrc.def";
  char* inFileName = "d:\\TMResrs\\YMHeatLoad\\ventilatedHeatLoad.txt";

// Open input and output files

  ofstream Fout(outFileName);
  if (!Fout){
    cerr << "Unable to open file " << outFileName << endl;
    cout << "Press return to end ";
    getch();
    return (1);
  }
  ifstream Fin(inFileName);
  if (!Fin){
    cerr << "Unable to open file " << inFileName << endl;
    cout << "Press return to end ";
    getch();
    return (1);
  }

// Prepare output files

  Fout << "***\n";
  Fout << "*** Heat source strength function for a "
       << setiosflags(ios::fixed) << setprecision(1)
       << driftHeight
       << "-m diameter drift"
       << resetiosflags(ios::fixed)
       << endl;
  Fout << "*** Includes 70% ventilation reduction for 50 yr"
       << endl;
  Fout << "*** t1,q1,t2,q2 ... etc\n";
  Fout << "*** t = time in yr; q = Joules/m^3/yr\n";
  Fout << "***\n";

// Read WP thermal-output history from file

  char buf[151];
  size_t nBuf = sizeof(buf);
```

GMO 1/29/04

See next page.

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```
  float yr,wpm;
  int onThisLine = 0;
  float srcStrength;
  float xSecArea = driftHeight*driftHeight*(pi/4.0);
  while (Fin){
    Fin.getline(buf,150);
    istrstream inpLine(buf,nBuf);
    inpLine >> yr >> wpm;
    if (inpLine.good()){
      srcStrength = wpm*secPerYear/xSecArea;

      if (onThisLine == 3){
        Fout << setiosflags(ios::scientific) << setprecision(3)
             << setw(12) << yr << ","
             << setprecision(5)
             << setw(12) << srcStrength
             << resetiosflags(ios::scientific)
             << endl;
        onThisLine = 0;
      }
      else{
        Fout << setiosflags(ios::scientific) << setprecision(3)
             << setw(12) << yr << ","
             << setprecision(5)
             << setw(12) << srcStrength << ","
             << resetiosflags(ios::scientific);
        onThisLine++;
      }
    }
  }

  cout << "Done ... Press return to end: ";
  getch();
  return 0;
}
```

Text file ventilatedHeatLoad.txt, which is documented partially on the right side, was extracted from the exel spread sheet on p. 4.

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D:\TMResrs\YMHeatLoad\ventilatedHeatLoad.txt

Time (yr)	Ventilated heat load (W/m)
2.0E-6	424.4767
2.3102	408.4496
4.6744	392.4419
7.094	374.4767
9.5702	358.1395
12.104	343.2364
14.698	329.5543
17.352	316.9380
20.069	305.2519
22.849	294.3992
25.694	282.0543
28.605	269.1473
31.585	257.1899
34.635	246.0853
37.756	235.7558
40.95	226.1047
44.219	217.0736
47.564	208.6047
50.988	668.8566
54.492	643.8760
58.078	620.3295
61.747	598.1008
⋮	⋮
7038.2	27.3508
7205.3	27.0601
7376.3	26.7713
7551.3	26.4864
7730.4	26.2054
7913.7	25.9264
8101.3	25.6492
8293.3	25.3760
8489.7	25.1066
8690.8	24.8391
8896.6	24.5756
9107.2	24.3140
9322.7	24.0562
9543.3	23.8004
9769	23.5465
10000	23.2791

} See electronic file for complete information

GMO 1/29/04

Feb. 04 2004

GLW 2/4/04

STRENGTH VERSUS STIFFNESS DATA FOR LITHOPHYSAL ROCK

Data defining the relationship between rock-mass strength and stiffness of the lithophysal rocks is one of the important inputs to the DOE assessment of thermally induced rockfall at the Yucca Mountain repository. This data is important because the rock-mass stiffness has a strong effect on thermal stress whereas the rock-mass strength determines the load-bearing capacity (resistance to thermal stress) of the rock. The occurrence or nonoccurrence of thermally induced rockfall, therefore, may be (inadvertently) prescribed by specifying a strength-to-stiffness relationship for the rock mass.

The DOE data describing such a relationship is provided in Table V-8 of the drift degradation report. The table and the DOE interpretation of the data are reproduced on p. 9 of this notebook. The DOE interpretation consists of representing the data as a best-fit straight line that is further divided into five segments. Each segment is represented by a value of unconfined compressive strength and a value of Young's modulus as provided in Table V-9 of the drift degradation report (see p. 9 of this notebook). The uncertainty in the DOE strength and stiffness data for lithophysal rocks is not adequately captured in this DOE interpretation of the data.

An alternative interpretation of the data, which was developed using the spread-sheet calculation documented on p. 10–11 of this notebook (file Lithophysal_Rock-Strength.xls), consists of defining the 95% confidence interval for the rock strength as a function of the rock stiffness. This interpretation indicates that the DOE data provides a 95% confidence that the value of unconfined compressive strength would lie within the limits identified in the following table for the specified values of Young's modulus.

Young's Modulus (GPa)	95% Confidence Limits for Unconfined Compressive Strength (MPa)	
	Lower Limit	Upper Limit
5.0	4.8	21.5
10.0	7.9	29.6
15.0	11.1	37.7
20.0	14.2	45.8

Analysis will be performed using the values in the above table to determine how the DOE assessment of thermally induced rockfall might have been affected by the uncertainty in the rock-mass strength-versus-stiffness relationship.

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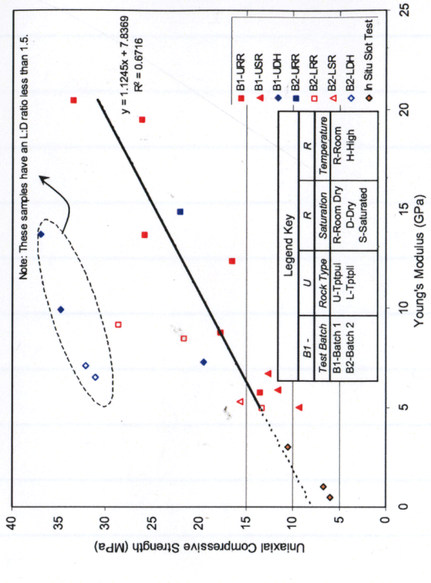


Figure V-3. Correlation of Young's Modulus and Uniaxial Compressive Strength from Large-Diameter Testing of Lithophysal Rock

DTNS: SN0208L0207502.001
SN0211L0207502.002
SN0208F4102102.002
SN0212F4102102.004
SN0301F4102102.006

NOTE: Both in situ test data and specimens with an L:D ratio less than 1.5 are excluded from the linear data fit.

Table V-9. Range of Mechanical Properties for Lithophysal Rock for Use in Rockfall Modeling

Category	Unconfined Compressive Strength (MPa)	Estimated Young's Modulus (GPa)	Cohesion (MPa)		Bulk Modulus, K (GPa)	Shear Modulus, G (GPa)
			ϕ=50	ϕ=45	ϕ=40	
1	10	1.9	1.82	2.07	2.33	1.07	0.80
2	15	6.4	2.73	3.11	3.50	3.54	2.65
3	20	10.8	3.64	4.14	4.66	6.01	4.51
4	25	15.3	4.55	5.18	5.83	8.48	6.36
5	30	19.7	5.46	6.21	7.00	10.95	8.21
6	6	1.0	1.09	1.24	1.40	0.56	0.42

NOTES: Categories 1 through 5 represent the range of unconfined compressive strengths in Table V-8, with values of Young's modulus calculated using Equation V-8. Category 6 is representative of the in situ slot test data.

Table V-8. Mechanical Properties of Lithophysal Tuff from Large-Diameter Samples

Test ID	Lithostratigraphic Unit	L:D Ratio[a]	Saturation	Temperature (C)	Ultimate Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Estimated Lithophysal Porosity[c]	DTN[b]
YMPLL49A	Tptpll	1.1 : 1	Dry	195	32.2	7.1	—	11.7	SN0211L0207502.002
YMPLL43A	Tptpll	1.1 : 1	Dry	200	31.1	6.5	—	20.3	SN0211L0207502.002
YMPLL23A	Tptpll	1.8 : 1	Room Dry	24	28.7	9.2	—	19.2	SN0211L0207502.002
YMPLL24A	Tptpll	1.8 : 1	Room Dry	24	13.3	5.0	—	22.2	SN0211L0207502.002
YMPLL46A	Tptpll	1.8 : 1	Room Dry	24	21.7	8.5	—	28.4	SN0211L0207502.002
YMPLL67A	Tptpll	1.9 : 1	Saturated	24	15.7	5.3	—	14.5	SN0211L0207502.002
YMPUL59B	Tptpul	1.2 : 1	Dry	190	19.6	7.3	—	39.4	SN0208L0207502.001
YMPUL67A	Tptpul	1.3 : 1	Dry	190	34.8	9.9	—	6.2	SN0208L0207502.001
YMPUL62B	Tptpul	1.0 : 1	Dry	200	37.0	13.7	—	19.3	SN0208L0207502.001
YMPUL50A	Tptpul	1.5 :1	Room Dry	24	22.1	14.9	0.21	28.5	SN0211L0207502.002
YMPUL59A	Tptpul	2.0 : 1	Room Dry	24	13.5	5.8	0.39	30.3	SN0208L0207502.001
YMPUL61A	Tptpul	1.9 : 1	Room Dry	24	17.7	8.8	—	23.9	SN0208L0207502.001
YMPUL62A	Tptpul	1.8 :1	Room Dry	24	25.9	13.7	—	12.7	SN0208L0207502.001
YMPUL64A	Tptpul	1.7 : 1	Room Dry	24	33.5	20.5	—	12.8	SN0208L0207502.001
YMPUL65A	Tptpul	2.0 : 1	Room Dry	24	26.2	19.5	—	11.9	SN0208L0207502.001
YMPUL66A	Tptpul	1.7 : 1	Room Dry	24	16.5	12.4	—	16.7	SN0208L0207502.001
YMPUL60A	Tptpul	1.8 : 1	Saturated	24	12.7	6.7	—	18.6	SN0208L0207502.001
YMPUL63A	Tptpul	1.9 : 1	Saturated	24	9.4	5.0	0.24	20.0	SN0208L0207502.001
YMPUL68A	Tptpul	2.1 : 1	Saturated	24	11.6	5.9	0.03	25.8	SN0208L0207502.001
1B	Tptpul	2.0 : 1	Saturated	23	14.5	—	—	17.3	MO0301RCKPRPCS.001
1D	Tptpul	2.0 : 1	Saturated	23	10.3	—	—	22.2	MO0301RCKPRPCS.001
2A	Tptpul	2.0 : 1	Saturated	23	12.4	—	—	14.1	MO0301RCKPRPCS.001
3A	Tptpul	2.0 : 1	Saturated	23	12.0	—	—	14.0	MO0301RCKPRPCS.001
8A	Tptpul	2.0 : 1	Saturated	23	18.2	—	—	13.5	MO0301RCKPRPCS.001
8B	Tptpul	2.0 : 1	Saturated	23	17.4	—	—	14.2	MO0301RCKPRPCS.001
8C	Tptpul	2.0 : 1	Saturated	23	18.5	—	—	17.9	MO0301RCKPRPCS.001
8D	Tptpul	2.0 : 1	Saturated	23	17.5	—	—	21.4	MO0301RCKPRPCS.001
8E	Tptpul	2.0 : 1	Saturated	23	13.8	—	—	19.3	MO0301RCKPRPCS.001
8F	Tptpul	2.0 : 1	Saturated	23	27.8	—	—	12.6	MO0301RCKPRPCS.001

NOTES: [a]Specimen length-to-diameter ratio.
[b]Specific data are located in rows 737 to 746 from DTN: MO0301RCKPRPCS.001. Additional test descriptions for the data in DTN: MO0301RCKPRPCS.001 are provided by Price et al. (1985).
[c]Lithophysal property data for tests documented in DTNs SN0208L0207502.001 and SN0211L0207502.002 are provided by DTN: SN0305L0207502.005. Lithophysal property data for tests documented in DTN: MO0301RCKPRPCS.001 are provided by Price et al. (1985, Table 4).

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Young's Modulus and Unconfined compressive strength data for lithophysal interval used in the Drift Degradation Analysis AMR (extracted from file "rock mass strength v1.xls"):

Laboratory Test Data from Large-Diameter Cores										
Test ID	Lithostratigraphic Unit	L:D Ratio[1]	Saturation	Temperature (C)	Ultimate Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Estimated Lithophysal Porosity[2]	DTN	Ratio of E to UCS
YMPLL49A	Tptpll	1.1 : 1	Dry	195	32.2	7.1	—	11.7	SN0211L0207502.002	220.50
YMPLL43A	Tptpll	1.1 : 1	Dry	200	31.1	6.5	—	20.3	SN0211L0207502.002	209.00
YMPLL23A	Tptpll	1.8 : 1	Room Dry	24	28.7	9.2	—	19.2	SN0211L0207502.002	320.56
YMPLL24A	Tptpll	1.8 : 1	Room Dry	24	13.3	5.0	—	22.2	SN0211L0207502.002	375.94
YMPLL46A	Tptpll	1.8 : 1	Room Dry	24	21.7	8.5	—	28.4	SN0211L0207502.002	391.71
YMPLL87A	Tptpll	1.9 : 1	Saturated	24	15.7	5.3	—	14.5	SN0211L0207502.002	337.58
YMPUL59B	Tptpul	1.2:1	Dry	190	19.6	7.3	—	39.4	SN0208L0207502.001	372.45
YMPUL67A	Tptpul	1.3:1	Dry	190	34.8	9.9	—	6.2	SN0208L0207502.001	284.48
YMPUL62B	Tptpul	1.0:1	Dry	200	37.0	13.7	—	19.3	SN0208L0207502.001	370.27
YMPUL50A	Tptpul	1.5 : 1	Room Dry	24	22.1	14.9	0.21	28.5	SN0211L0207502.002	674.21
YMPUL59A	Tptpul	2.0:1	Room Dry	24	13.5	5.8	0.39	30.3	SN0208L0207502.001	429.63
YMPUL61A	Tptpul	1.9:1	Room Dry	24	17.7	8.8	—	23.9	SN0208L0207502.001	497.18
YMPUL62A	Tptpul	1.8:1	Room Dry	24	25.9	13.7	—	12.7	SN0208L0207502.001	528.96
YMPUL64A	Tptpul	1.7:1	Room Dry	24	33.5	20.5	—	12.8	SN0208L0207502.001	611.94
YMPUL65A	Tptpul	2.0:1	Room Dry	24	26.2	19.5	—	11.9	SN0208L0207502.001	744.27
YMPUL66A	Tptpul	1.7:1	Room Dry	24	16.5	12.4	—	16.7	SN0208L0207502.001	751.52
YMPUL60A	Tptpul	1.8:1	Saturated	24	12.7	6.7	—	18.6	SN0208L0207502.001	527.56
YMPUL63A	Tptpul	1.9:1	Saturated	24	9.4	5.0	0.24	20.0	SN0208L0207502.001	531.91
YMPUL68A	Tptpul	2.1:1	Saturated	24	11.6	5.9	0.03	25.8	SN0208L0207502.001	508.62
				Mean (n=19) =	22.27	9.77	0.22	20.13		457.28
				Standard Deviation (n=19) =	8.76	4.75	0.15	8.00		161.04
				Median (n=19) =	21.70	8.50	0.23	19.30		429.63

Tests with ratios >= 1.5:1				
Ultimate Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Estimated Lithophysal Porosity[2]	Ratio of E to UCS
28.70	9.20	—	19.2	320.56
13.30	5.00	—	22.2	375.94
21.70	8.50	—	28.4	391.71
15.70	5.30	—	14.5	337.58
22.10	14.90	0.21	28.5	674.21
13.50	5.80	0.39	30.3	429.63
17.70	8.80	—	23.9	497.18
25.90	13.70	—	12.7	528.96
33.50	20.50	—	12.8	611.94
26.20	19.50	—	11.9	744.27
16.50	12.40	—	16.7	751.52
12.70	6.70	—	18.6	527.56
9.40	5.00	0.24	20.0	531.91
11.60	5.90	0.03	25.8	508.62
Mean (n=14) =	19.18	10.09	0.22	20.39	516.54
Standard Deviation (n=14) =	7.28	5.30	0.15	6.29	140.15
Median (n=14) =	17.10	8.65	0.23	19.60	518.09

SUMMARY OUTPUT -- Young's Modulus (GPa) versus Unconfinced compressive strength (MPa) -- 14 measurements with L:D >= 1.5

Regression Statistics	
Multiple R	0.645322999
R Square	0.416441774
Adjusted R Square	0.339518697
Standard Error	5.559020655
Observations	14

ANOVA

	df	SS	MS	F	Significance F
Regression	1	286.6883331	286.6883331	9.277126	0.010163027
Residual	13	401.7352384	30.90271064		
Total	14	688.4235714			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.0%	Upper 99.0%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.742820106	0.13140314	13.26315422	6.24E-09	1.458940936	2.026699275	1.346996684	2.138643528

RESIDUAL OUTPUT

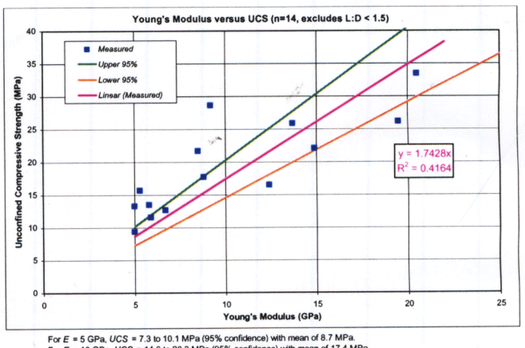
Observation	Predicted Y	Residuals	Standard Residuals
1	16.03394497	12.66605503	2.36447788
2	8.71410053	4.58589947	0.856088344
3	14.8139709	6.8860291	1.285472847
4	9.236946561	6.463053439	1.206512431
5	25.96801958	-3.868019578	-0.72207568
6	10.10835661	3.391643386	0.633146537
7	15.33681693	2.363183068	0.441155218
8	23.87663545	2.023364549	0.377718443
9	35.72781217	-2.227812172	-0.415884396
10	33.98499207	-7.784992066	-1.453289809
11	21.61096931	-5.110969314	-0.954107539
12	11.67688471	1.02310529	0.190991652
13	8.71410053	0.68589947	0.128042611
14	10.28263863	1.317361375	0.245922905

PROBABILITY OUTPUT

Percentile	Y
3.571428571	9.4
10.71428571	11.6
17.85714286	12.7
25	13.3
32.14285714	13.5
39.28571429	15.7
46.42857143	16.5
53.57142857	17.7
60.71428571	21.7
67.85714286	22.1
75	25.9
82.14285714	26.2
89.28571429	28.7
96.42857143	33.5

Using y-intercept of zero:

x	predicted	Upper 95%	Lower 95%
0	0.00	0.00	0.00
5	8.71	10.13	7.29
10	17.43	20.27	14.59
15	26.14	30.40	21.88
20	34.86	40.53	29.18
25	43.57	50.67	36.47



For E = 5 GPa, UCS = 7.3 to 10.1 MPa (95% confidence) with mean of 8.7 MPa.
For E = 10 GPa, UCS = 14.6 to 20.3 MPa (95% confidence) with mean of 17.4 MPa.
For E = 15 GPa, UCS = 21.9 to 30.4 MPa (95% confidence) with mean of 26.1 MPa.
For E = 20 GPa, UCS = 29.2 to 40.5 MPa (95% confidence) with mean of 34.9 MPa.

Regression Statistics	
Multiple R	0.819510696
R Square	0.671597781
Adjusted R Square	0.64423093
Standard Error	4.340505235
Observations	14

ANOVA

	df	SS	MS	F	Significance F
Regression	1	462.3437431	462.3437431	24.54056	0.000334214
Residual	12	226.0796283	18.83998569		
Total	13	688.4235714			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.0%	Upper 99.0%
Intercept	7.836930904	2.566584321	3.053447665	0.01002	2.244824152	13.42903766	-0.002798322	15.67666013
X Variable 1	1.124525265	0.227000602	4.953842652	0.000334	0.629933449	1.619117708	0.431143309	1.81790722

RESIDUAL OUTPUT

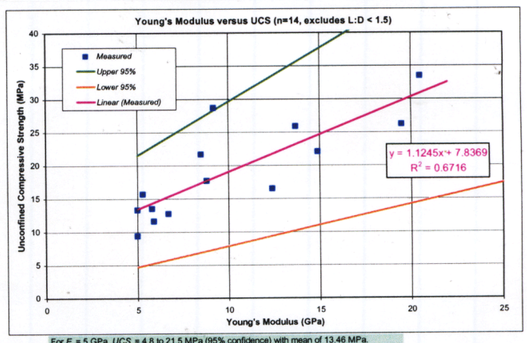
Observation	Predicted Y	Residuals	Standard Residuals
1	18.18256334	10.51743666	2.522032473
2	13.45955723	-0.159557226	-0.038261082
3	17.39539565	4.304604348	1.032224134
4	13.79691481	1.903085195	0.456350992
5	24.59235734	-2.492357345	-0.597655718
6	14.35917744	-0.859177438	-0.20602676
7	17.73275323	-0.032753231	-0.007854073
8	23.24292703	2.657072973	0.63715376
9	30.88969883	2.610301174	0.6259381
10	29.76517356	-3.565173562	-0.854912065
11	21.78104418	-5.281044184	-1.266369872
12	15.37125018	-2.671250176	-0.640553388
13	13.45955723	-4.059557226	-0.973462972
14	14.47162996	-2.871629964	-0.688603531

PROBABILITY OUTPUT

Percentile	Y
3.571428571	9.4
10.71428571	11.6
17.85714286	12.7
25	13.3
32.14285714	13.5
39.28571429	15.7
46.42857143	16.5
53.57142857	17.7
60.71428571	21.7
67.85714286	22.1
75	25.9
82.14285714	26.2
89.28571429	28.7
96.42857143	33.5

Using best-fit y-intercept:

x	predicted	Upper 95%	Lower 95%
0	7.84	13.43	1.62
5	13.46	21.52	4.77
10	19.08	29.62	7.92
15	24.70	37.72	11.07
20	30.33	45.81	14.22
25	35.95	53.91	17.37



For E = 5 GPa, UCS = 4.8 to 21.5 MPa (95% confidence) with mean of 13.46 MPa.
For E = 10 GPa, UCS = 7.9 to 29.6 MPa (95% confidence) with mean of 19.08 MPa.
For E = 15 GPa, UCS = 11.1 to 37.7 MPa (95% confidence) with mean of 24.7 MPa.
For E = 20 GPa, UCS = 14.2 to 45.8 MPa (95% confidence) with mean of 30.3 MPa.

Thermal Properties of Lithophysal Rocks

February 5, 2004

GW 2/5/04

Table V-1. Density Data for Various Thermal Mechanical Units and Associated Lithostratigraphic Units

Thermal Mechanical Unit	Stratigraphic Unit	Thickness[a] (m)	Bulk Density (kg/m³)	DTN[b]
TCw / PTn	Tpcpv3	0.0	2310	SN0303T0503102.008
	Tpcpv2	5.1	1460	
	Tpcpv1	2.4	1460	
	Tpbt4	0.5	1460	
	Tpy	3.8	1460	
	Tpbt3	3.8	1460	
	Tpp	5.1	1460	
	Tpbt2	8.3	1460	
	Tptrv3	1.9	1460	
	Tptrv2	1.2	1460	
	Mean (weighted by unit thickness)		*1460*	
TSw1	Tptrv1	1.2	2310	
	Tptrn	35.6	2190	
	Tptrl	6.1	2190	
	Tptpul	66.8	1834	SN0208T0503102.007
	Mean (weighted by unit thickness)		*1974*	
TSw2 / TSw3	Tptpmn	38.3	2148	
	Tptpll	95.6	1979	
	Tptpln	55.1	2211	
	Tptpv3	12.0	2310	
	Mean (weighted by unit thickness)		*2095*	
CHn1 / CHn2	Tptpv2	4.7	1460	SN0303T0503102.008
	Tptpv1	15.4	1460	
	Tpbt1	2.0	1460	
	Calico	45.5	1670	
	Calicobt	15.9	1670	
	Mean (weighted by unit thickness)		*1614*	

NOTES: [a]Thickness of units extracted from DTN: MO0012MWDGFM02.002. The details of this extraction are provided in Attachment XIII.
[b]Mean values are calculated in this report and not provided by the DTNs listed in this table. Data extracted from DTN: SN0208T0503102.007 are summarized in BSC 2002c, Table 7-10.

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Table V-16. Specific Heat for Various Thermal Mechanical Units and Associated Lithostratigraphic Units

Thermal Mechanical Unit	Stratigraphic Unit	Thickness[a] (m)	Specific Heat[b] (J/kg°K)			DTN[c]
			T ≤ 95°C	95°C<T<114°C	T > 114°C	
TCw / PTn	Tpcpv3	0.0	1246	8028	1000	SN0303T0510902.002
	Tpcpv2	5.1	1246	8028	1000	
	Tpcpv1	2.4	1291	8716	1000	
	Tpbt4	0.5	1291	8716	1000	
	Tpy	3.8	1291	8716	1000	
	Tpbt3	3.8	1291	8716	1000	
	Tpp	5.1	1291	8716	1000	
	Tpbt2	8.3	1291	8716	1000	
	Tptrv3	1.9	1291	8716	1000	
	Tptrv2	1.2	1291	8716	1000	
	Mean (weighted by unit thickness)		*1284*	*8607*	*1000*	
TSw1	Tptrv1	1.2	894	1770	1000	
	Tptrn	35.6	891	2649	990	
	Tptrl	6.1	891	2649	990	
	Tptpul	66.8	938	3453	990	
	Mean (weighted by unit thickness)		*920*	*3130*	*990*	
TSw2 / TSw3	Tptpmn	38.3	908	2962	990	
	Tptpll	95.6	926	3245	990	
	Tptpln	55.1	896	2756	990	
	Tptpv3	12.0	907	1697	1030	
	Mean (weighted by unit thickness)		*913*	*2965*	*992*	
CHn1 / CHn2	Tptpv2	4.7	1095	4880	1030	
	Tptpv1	15.4	1245	6174	1130	
	Tpbt1	2.0	1245	6174	1130	
	Calico	45.5	1402	9376	1125	
	Calicobt	15.9	1247	7297	1070	
	Mean (weighted by unit thickness)		*1323*	*8061*	*1110*	

NOTES: [a]Thickness of units provided in Attachment XIII.
[b]T = temperature.
[c]Mean values are calculated in this report and not provided by the DTNs listed in this table.

Table V-17. Thermal Expansion for Various Thermal Mechanical Units

Thermal Mechanical Unit	Thermal Expansion Coefficient (/°C)			
	25°C < T ≤ 50°C	50°C < T ≤ 75°C	75°C < T ≤ 100°C	100°C < T ≤ 125°C
TCw	7.09×10^{-6}	7.62×10^{-6}	8.08×10^{-6}	10.34×10^{-6}
PTn	4.46×10^{-6}	4.28×10^{-6}	-1.45×10^{-6}	-30.42×10^{-6}
TSw1	6.56×10^{-6}	7.32×10^{-6}	6.83×10^{-6}	6.92×10^{-6}
TSw2	7.14×10^{-6}	7.47×10^{-6}	7.46×10^{-6}	9.07×10^{-6}

NOTES: T = temperature. Source data provided by DTN: SNL01B05059301.006. The calculation of mean data is documented in Brodsky et al. (1995, Table 4-4).

GW 2/5/04

Table V-15. Thermal Conductivity for Various Thermal Mechanical Units and Associated Lithostratigraphic Units

Thermal Mechanical Unit	Stratigraphic Unit	Thickness[a] (m)	Thermal Conductivity[b] (W/m*K)		DTN[c]
			T ≤ 100° C	T > 100° C	
TCw / PTn	Tpcpv3	0.0	0.80	0.69	SN0303T0503102.008
	Tpcpv2	5.1	1.06	0.49	
	Tpcpv1	2.4	1.06	0.49	
	Tpbt4	0.5	1.06	0.49	
	Tpy	3.8	1.06	0.49	
	Tpbt3	3.8	1.06	0.49	
	Tpp	5.1	1.06	0.49	
	Tpbt2	8.3	1.06	0.49	
	Tptrv3	1.9	1.06	0.49	
	Tptrv2	1.2	1.06	0.49	
	Mean (weighted by unit thickness)		*1.06*	*0.49*	
TSw1	Tptrv1	1.2	0.80	0.69	
	Tptrn	35.6	1.81	1.30	
	Tptrl	6.1	1.81	1.30	
	Tptpul	66.8	1.77	1.18	SN0208T0503102.007
	Mean (weighted by unit thickness)		*1.77*	*1.22*	
TSw2 / TSw3	Tptpmn	38.3	2.07	1.42	
	Tptpll	95.6	1.89	1.28	
	Tptpln	55.1	2.13	1.49	
	Tptpv3	12.0	0.80	0.69	
	Mean (weighted by unit thickness)		*1.92*	*1.33*	
CHn1 / CHn2	Tptpv2	4.7	1.06	0.49	SN0303T0503102.008
	Tptpv1	15.4	1.06	0.49	
	Tpbt1	2.0	1.06	0.49	
	Calico	45.5	1.26	0.60	
	Calicobt	15.9	1.26	0.60	
	Mean (weighted by unit thickness)		*1.21*	*0.57*	

NOTES: [a]Thickness of units extracted from DTN: MO0012MWDGFM02.002. The details of this extraction are provided in Attachment XIII.
[b]T = temperature.
[c]Mean values are calculated in this report and not provided by the DTNs listed in this table. Data extracted from DTN: SN0208T0503102.007 are summarized in BSC 2002c, Table 7-10.

GW 2/5/04

Values of thermal properties for lithophysal rocks (tptpll) documented in DOE's drift degradation report (relevant tables reproduced on this page) will be used for the confirmatory analysis.

Density = 1979 kg/m³

Thermal conductivity:

= 1.89 W/m.K

for temperature ≤ 100°C

or 1.28 W/m.K

for temperature > 100°C

GW 2/5/04

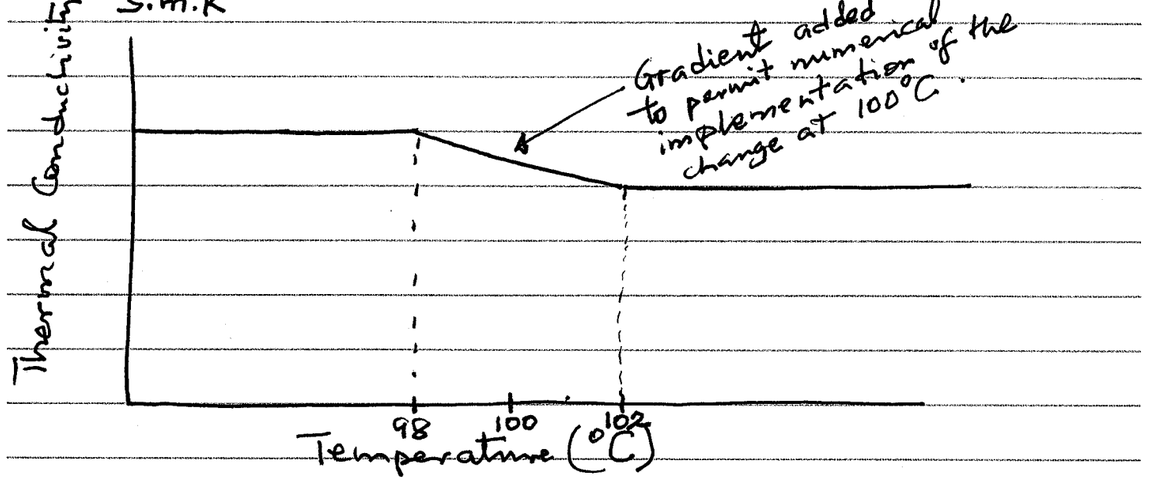
GW 2/5/04

Convert thermal conductivity to J/yr/m.K

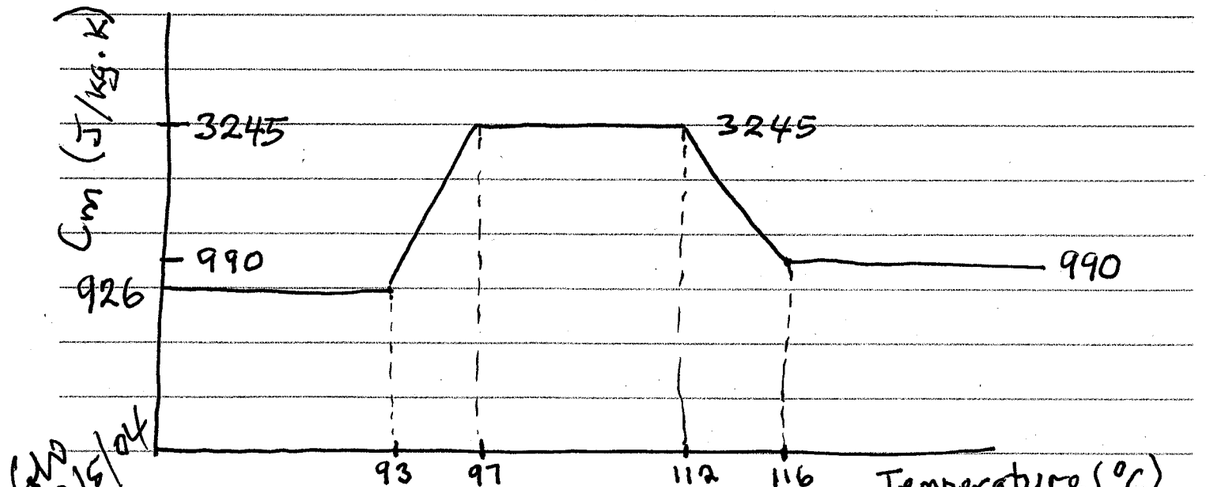
$$1.89\ \frac{J}{s\cdot m\cdot K}\times(365.25\times24\times60\times60)\ \frac{s}{yr}$$

$$= 5.964\times10^{7}\ J/yr/m\cdot K$$

$$1.28\ \frac{J}{s\cdot m\cdot K} = 4.039\times10^{7}\ J/yr/m\cdot K$$



Specific heat: Cm (J/kg.K)

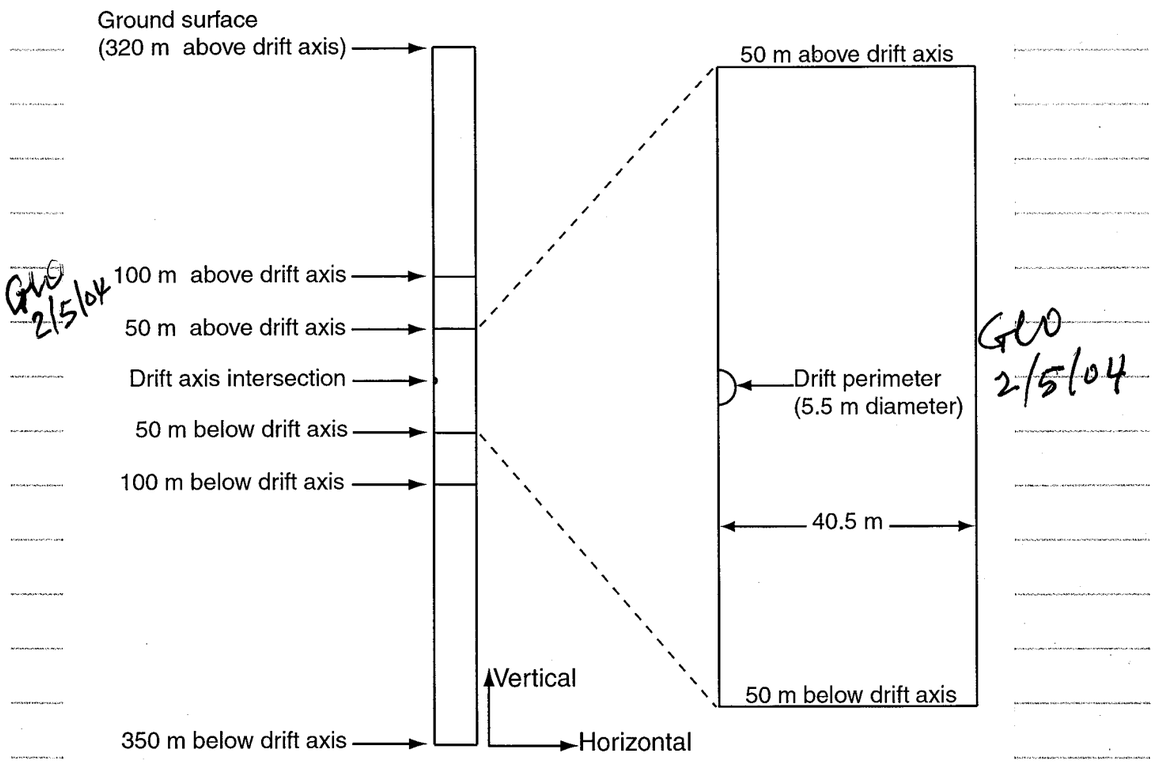


GW 2/6/04

Finite Element Model

February 05 2004

The finite element model geometry consists of a rectangular domain 40.5 m wide by 670 m high, as shown below:



GLO 2/5/04

The model represents the region between two emplacement drifts (including half of one drift) with an assumed vertical symmetry plane through the drift axis and midway between the two adjacent drifts. The following geometrical features are used:

GLO 2/5/04

Drift cross-section: Circular, 5.5 m diameter, horizontal axis

Center-to-center distance: 81 m

Depth to water table: 350 m below drift axis

Ground surface elevation: 320 m above drift axis.

Thermal Boundary Conditions:

Fixed temperature at water table (350 m below drift axis)

GLO 2/5/04

Fixed temperature at ground surface.

Zero heat flux (symmetry condition) normal to vertical boundaries.

Mechanical Boundary Conditions:

Zero vertical displacements at model base (350 m below drift axis)

Zero lateral displacement (symmetry condition) on vertical boundaries.

Free surface at the ground surface.

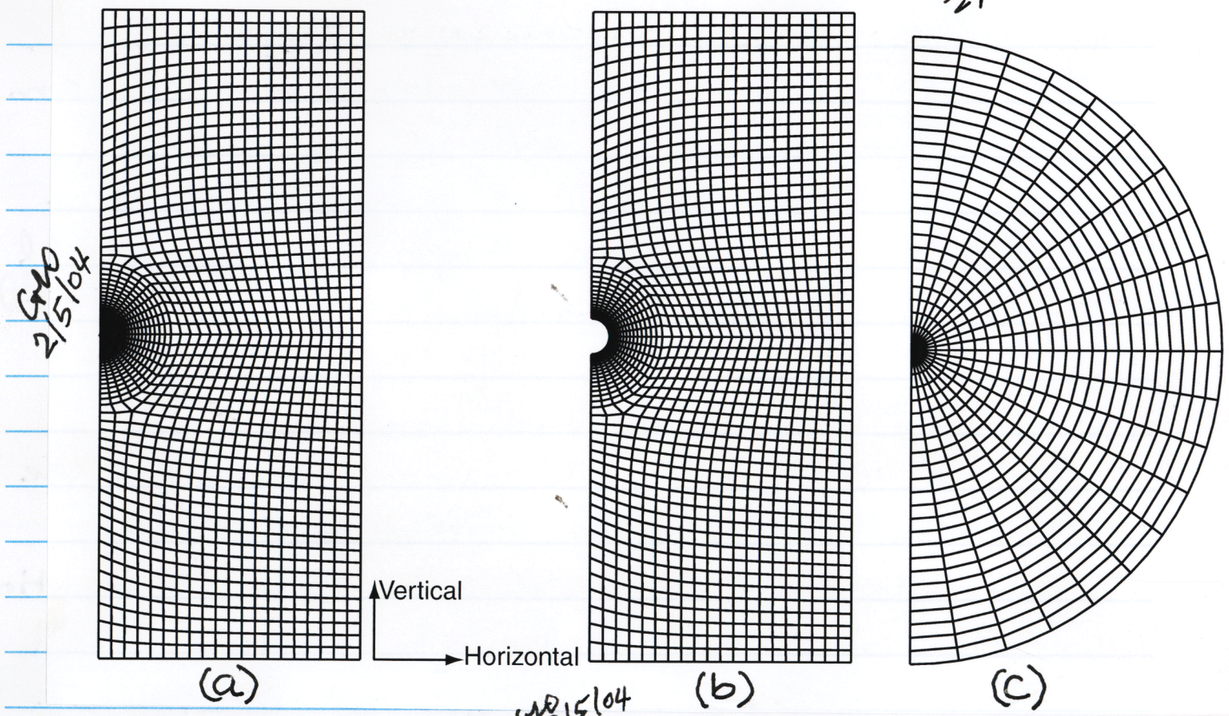
Initial Temperature: 18.7°C at the ground surface and increases with depth based on the geothermal gradient defined on p. 24 of Notebook 263.

Initial Stress: Based on an average vertical stress of GLO 2/5/04 that increases with depth

at a rate of 23.44 MPa/km, which gives a vertical stress of about 7.5 MPa at the depth of the drift axis. The ratio of horizontal to vertical stress is set at 0.25 to conform with $\nu/1-\nu$, where $\nu = 0.2$ is the Poisson's ratio.

GWD 2/5/04

GWD 2/5/04



GWD 2/5/04

Finite element mesh for model region between 50 m below and above the drift axis.

(a) Mesh for the domain including the drift before excavation

(b) Mesh showing excavated drift (simulated by removing elements)

(c) Mesh for zone inside the drift perimeter. The elements in (c) were assigned a volumetric heat

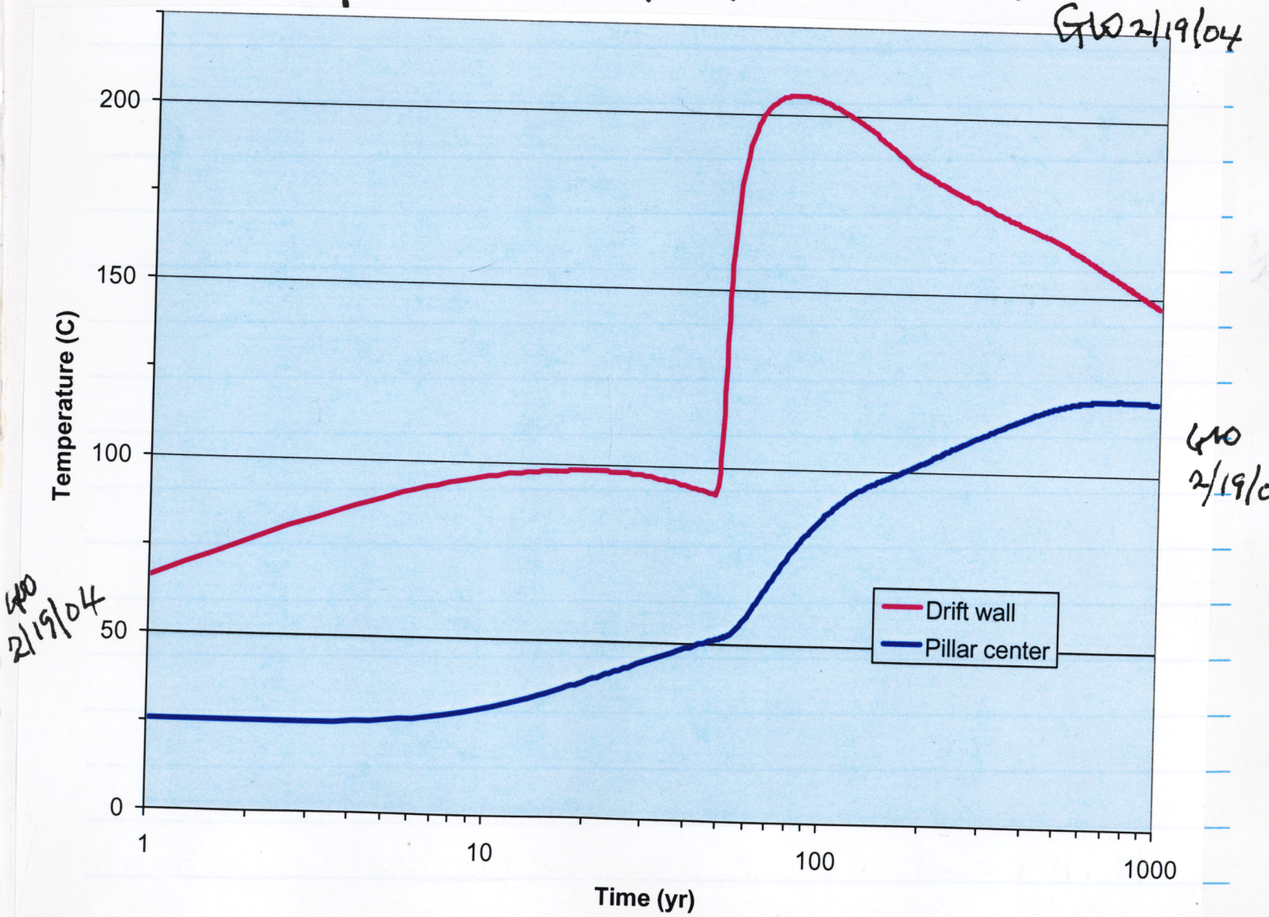
source, calculated as described on p. 6, to simulate heat from waste packages. The elements in (c) were removed in the second step of the mechanical model (after the initial static equilibrium state has been established) to simulate drift excavation.

GWD Dep 2/5/04

February 19 2004
Results of Heat Conduction Analysis

The calculated temperatures (below) are too high compared with temperatures given in figure 31 (p. 86) of the DOE report (cited on p. 4 of this notebook).

GWD 2/19/04

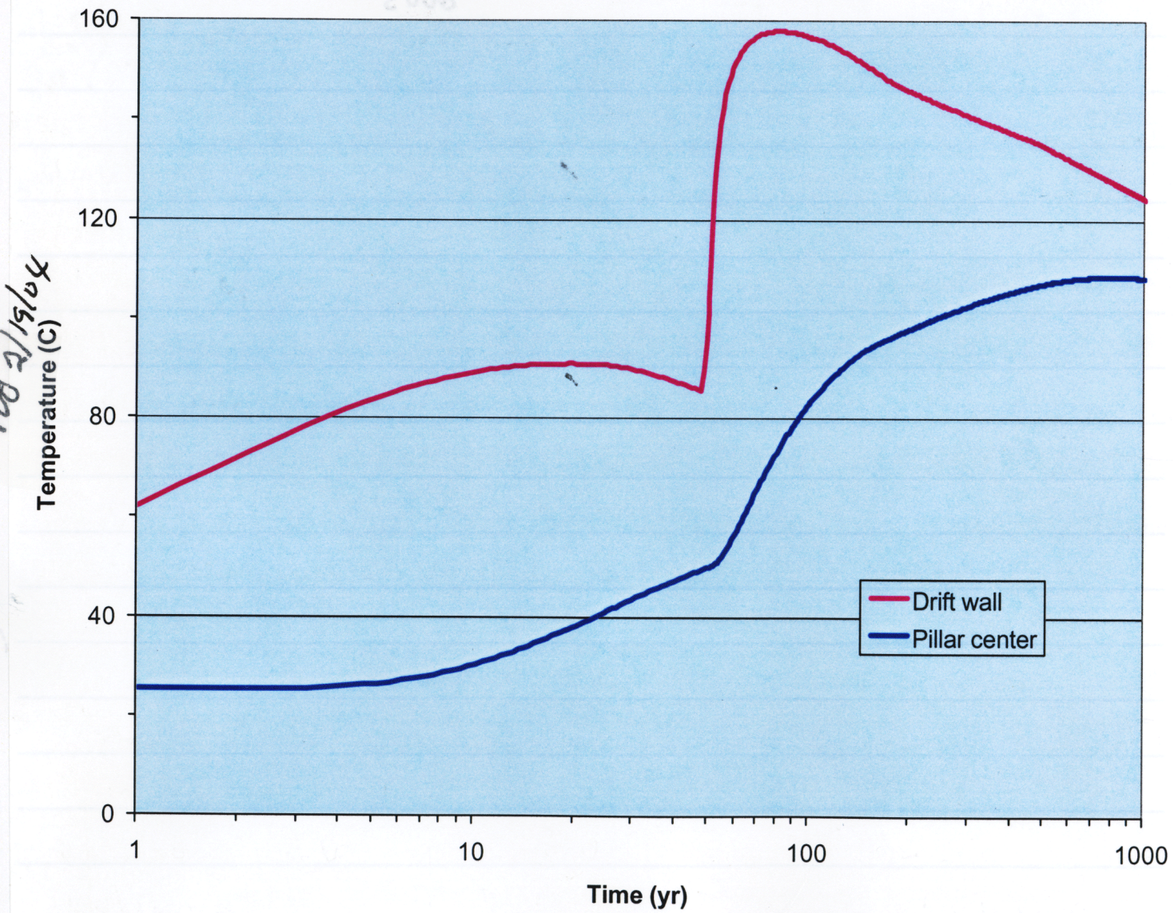


GWD 2/19/04

GWD 2/19/04

A second heat conduction analysis was performed using values of thermal properties described on p. 44-45 of Notebook #321 (instead of the values described on p. 13 of this notebook). The temperatures calculated in the second analysis (plotted below) agree reasonably with the temperature history provided by DOE on p. 86 of the drift degradation report.

GW 2/19/04



GW 2/19/04

GW 2/19/04

The input and output files for the heat conduction

analysis are located in subdirectory 2DTherm of the analysis subdirectory that will be provided later in this notebook. The following files are given in the subdirectory 2DTherm:

GW 2/19/04

Contents of 'D:\TMReviews\DrftDegAMR\2DTherm'

Name	Size	Type	Modified
allNodes.def	539KB	DEF File	2/28/2003 9:22 AM
drftSrc.def	6KB	DEF File	1/28/2004 2:32 PM
dt01.inp	10KB	INP File	2/5/2004 10:08 AM
dt01TempHist.pdf	10KB	Adobe Acrobat Doc...	2/6/2004 5:40 PM
dt01TempHist.txt	40KB	Text Document	2/6/2004 5:34 PM
dt01TempHist.xls	82KB	Microsoft Excel Wor...	2/6/2004 5:39 PM
dt03.inp	11KB	INP File	2/6/2004 5:05 PM
dt03TempHist.pdf	10KB	Adobe Acrobat Doc...	2/6/2004 4:54 PM
dt03TempHist.txt	30KB	Text Document	2/6/2004 4:22 PM
dt03TempHist.xls	81KB	Microsoft Excel Wor...	2/6/2004 4:53 PM
dt13.inp	11KB	INP File	2/11/2004 4:04 PM
ElemQuad8.def	276KB	DEF File	2/28/2003 9:54 AM
ElemTri3.def	4KB	DEF File	2/28/2003 9:58 AM
fullDrftSrc.def	6KB	DEF File	2/11/2004 3:58 PM
iniTemp.def	544KB	DEF File	3/3/2003 11:00 AM

GW 2/19/04

GW 2/19/04

Files associated with the analysis described on p. 17 are named with the prefix "dt01", and files associated with the second heat conduction analysis (p. 18) are named with the prefix "dt03". The files dt13.inp and fullDrftSrc.def were developed for another analysis case that will be described later if it is performed. All other files that don't have either the dt01 or dt03 prefix are common to the two heat conduction analyses. The temperature distributions calculated in the dt03 analysis were used for thermal-mechanical calculations.

February 19, 2004

Thermal Mechanical Analysis

Temperature:

Initial temperature —— file iniTemp.def (p.19)

Time zero — 1000 yr —— from ABAQUS output file dt03.fil from heat conduction analysis performed with dt03.inp.

Mechanical Properties

Thermal expansivity from Table V-17 on p.12.

Two linear-elastic analyses are performed as described below. An ABAQUS user-subroutine is provided to calculate stress-to-strength ratio using a rock strength defined through the Mohr-Coulomb failure criterion. Values of Young's modulus and unconfined compressive strength are taken from the plot on p.11. Friction angle of 40° is taken from Table V-9 on p.9.

	Case m01	Case m02
Young's modulus	5 GPa	20 GPa
Unconfined Compressive strength	4.8 MPa	14.2 MPa
Friction angle	40°	40°
Cohesion	1.12 MPa	3.31 MPa

Cohesion is calculated using the relationship (based on Mohr-Coulomb failure criterion)

$$Q_u = 2C \tan(45 + \phi/2)$$

Q_u = unconfined compressive strength

C = cohesion

ϕ = friction angle in degrees.

The user-subroutine used for stress/strength ratio calculation are given below.

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```
      SUBROUTINE UVARM(UVAR,DIRECT,T,TIME,DTIME,CMNAME,ORNAME,
     1           NUVARM,NOEL,NPT,LAYER,KSPT,KSTEP,KINC,NDI,NSHR,COORD,
     2           JMAC,JMATYP,MATLAYO,LACCFLA)
C
      INCLUDE 'ABA_PARAM.INC'
      CHARACTER*80 CMNAME,ORNAME
      CHARACTER*3 FLGRAY(15)
      DIMENSION UVAR(NUVARM),DIRECT(3,3),T(3,3),TIME(2)
      DIMENSION ARRAY(15),JARRAY(15),JMAC(*),JMATYP(*),COORD(*)

      Code M2D20LF
          for ABAQUS Version 6.3
          Date:     Feb 09, 2004
          Author:   G.I. Ofoegbu

      Computes safety factor (strength/stress ratio) for model m01
      following procedure documented in CNWRA Scientific Notebook
      #321, p. 87.

      Values of principal stress required for the calculation are
      obtained through ABAQUS user-interface subroutine GETVRM

      Externally supplied input parameter:

      FRIC          Friction angle (degrees);
      CPAR          Cohesion parameter (MPa);

      The reciprocal of the calculated safety factor
      is stored in vector UVAR as follows

      Location in UVAR              Stored Variable
      ----------------              ---------------
            1                           1/fs

      TOTIME = TIME(2)
      ZTIME = 2.0E-6
      IF (TOTIME .LT. ZTIME) THEN
        UVAR(1) = 0.0
        RETURN
      ENDIF
C
      FRIC = 40.0
      CPAR = 1.12
C
      PI = 3.141592654
      ALPHA = PI/4.0 + (FRIC/2.0)*(PI/180.0)
      TA = DTAN(ALPHA)
C
C     Obtain current values of principal stress components
C
      JRCD = 0
      CALL GETVRM('SP',ARRAY,JARRAY,FLGRAY,JRCD,JMAC,JMATYP,
     1            MATLAYO,LACCFLA)
C     IF (JRCD .NE. 0) THEN
C       WRITE(6,1000) NOEL,NPT,TIME(2)
C       RETURN
C     END IF
C
      PSMAX = -ARRAY(1)
      PSMIN = -ARRAY(3)
      FS = (2.0*CPAR*TA + PSMIN*TA*TA)/PSMAX
      curVAL = 1.0/FS
      preVAL = UVAR(1)
      IF (curVAL .GT. preVAL) THEN
        UVAR(1) = curVAL
      ENDIF
      RETURN
C
C----67--1---------2---------3---------4---------5---------6---------7-*
C
 1000 FORMAT(/,'ERROR IN UVARM-CALL FOR VARIABLE PE',/,
     1       10X,'FOR ELEMENT NUMBER = ',I5,/,
     2       10X,'INTEGRATION POINT  = ',I5,/,
     3       10X,'AT TIME            = ',E12.3)
      END
```

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```
      SUBROUTINE UVARM(UVAR,DIRECT,T,TIME,DTIME,CMNAME,ORNAME,
     1           NUVARM,NOEL,NPT,LAYER,KSPT,KSTEP,KINC,NDI,NSHR,COORD,
     2           JMAC,JMATYP,MATLAYO,LACCFLA)
C
      INCLUDE 'ABA_PARAM.INC'
      CHARACTER*80 CMNAME,ORNAME
      CHARACTER*3 FLGRAY(15)
      DIMENSION UVAR(NUVARM),DIRECT(3,3),T(3,3),TIME(2)
      DIMENSION ARRAY(15),JARRAY(15),JMAC(*),JMATYP(*),COORD(*)
C
C     Code M2D20LF
C         for ABAQUS Version 6.3
C         Date:     Feb 09, 2004
C         Author:   G.I. Ofoegbu
C
C     Computes safety factor (strength/stress ratio) for model m01
C     following procedure documented in CNWRA Scientific Notebook
C     #321, p. 87.
C
C     Values of principal stress required for the calculation are
C     obtained through ABAQUS user-interface subroutine GETVRM
C
C     Externally supplied input parameter:
C
C     FRIC          Friction angle (degrees);
C     CPAR          Cohesion parameter (MPa);
C
C     The reciprocal of the calculated safety factor
C     is stored in vector UVAR as follows
C
C     Location in UVAR              Stored Variable
C     ----------------              ---------------
C           1                           1/fs
C
      TOTIME = TIME(2)
      ZTIME = 2.0E-6
      IF (TOTIME .LT. ZTIME) THEN
        UVAR(1) = 0.0
        RETURN
      ENDIF
C
      FRIC = 40.0
      CPAR = 3.31
C
      PI = 3.141592654
      ALPHA = PI/4.0 + (FRIC/2.0)*(PI/180.0)
      TA = DTAN(ALPHA)
C
C     Obtain current values of principal stress components
C
      JRCD = 0
      CALL GETVRM('SP',ARRAY,JARRAY,FLGRAY,JRCD,JMAC,JMATYP,
     1            MATLAYO,LACCFLA)
C     IF (JRCD .NE. 0) THEN
C       WRITE(6,1000) NOEL,NPT,TIME(2)
C       RETURN
C     END IF
C
      PSMAX = -ARRAY(1)
      PSMIN = -ARRAY(3)
      FS = (2.0*CPAR*TA + PSMIN*TA*TA)/PSMAX
      curVAL = 1.0/FS
      preVAL = UVAR(1)
      IF (curVAL .GT. preVAL) THEN
        UVAR(1) = curVAL
      ENDIF
      RETURN
C
C----67--1---------2---------3---------4---------5---------6---------7-*
C
 1000 FORMAT(/,'ERROR IN UVARM-CALL FOR VARIABLE PE',/,
     1       10X,'FOR ELEMENT NUMBER = ',I5,/,
     2       10X,'INTEGRATION POINT  = ',I5,/,
     3       10X,'AT TIME            = ',E12.3)
      END
```

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