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date: 2 April 2007
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from: A. E. Ismail [signature] 4/9/07
B. Y. Park
subject: Revised permeability estimates for the Disturbed Rock Zone (DRZ)

The current Waste Isolation Pilot Plant Performance Assessment (WIPP PA) models assume that the permeability within the Disturbed Rock Zone (DRZ) around the repository rooms takes on a single, constant value for the entire 10,000-year time period simulated in BRAGFLO. However, it is known that healing will occur, changing a number of physical properties in the DRZ. To accommodate this behavior in the PA models, we are defining a new material, DRZ_2, which more accurately reflects the behavior of the DRZ after the completion of healing. This memo outlines the determination of the permeabilities, DRZ_2:PRMX_LOG, DRZ_2:PRMY_LOG, and DRZ_2:PRMZ_LOG, for the new material. Full details of the analysis will be provided in the Summary Report for Analysis Plan AP-133 (Park and Ismail, 2007).

As outlined in AP-133 (Park and Ismail, 2007), we used the sonic velocity data of Holcomb and Hardy (2001), taken from the S-90 drift at Location 1, to measure the dilatancy criterion constant *C*. This relationship was then used to define the onset of healing in the DRZ, using simulation results obtained from SANTOS. The official runs were performed on Warthog; the executables are located in the ACCESS_WARTHOG directory, while the output files are stored in the SANTOS_Analysis repository under Tests/Output/DRZ/ in the Concurrent Version System (CVS) repository.

The first part of the analysis determines the extent of the DRZ by using the ultrasonic wave velocity data of Holcomb and Hardy (2001) to determine the region in which the velocity profile changes with increasing depth from the rib. The results from SANTOS were stored in the files *rqad0p0.e* and *rqad0p0.ed*. Then, by computing the quantity $I_1/J_2^{1/2}$ (where I_1 is the first invariant of the stress tensor and J_2 is the second invariant of the deviatoric stress tensor) in ALGEBRA using the script *dpot.alg* (located in the Test/Input/DRZ directory), we can determine the constant C in the damage potential criterion $D = CI_1/J_2^{1/2} < 1$. Comparing the damage potential contours around the drift with the inferred DRZ depths from ultrasonic wave velocity measurements, we found that $C = 0.190$. (The calculation is carried out in Excel: see *Ultrasonic_velocity_data_for_Room_Q_access_drift.xls*; this file will be included with the final report for AP-133.) This criterion was then applied to the rock surrounding the rooms in the Waste Isolation Pilot Plant (WIPP) repository to define the DRZ. The resulting data indicates that the DRZ extends below the room to Marker Bed 139, and above the room up to Anhydrite "A". The DRZ also includes a region extending roughly 2 m from the side of the room.

We also need to determine the permeability range to be used by DRZ_2:PRMX_LOG, DRZ_2:PRMY_LOG, and DRZ_2:PRMZ_LOG. To calculate the permeabilities, the strain distributions around the room were computed using SANTOS; the volumetric dilatant strains were converted to permeabilities using the Peach model proposed by Chan *et al.* (2001):

$K_p = C_p\ (\varepsilon_{kk})^3$,

where K_p is the permeability, ε_{kk} is the dilatant strain, and C_p is a regression constant determined by Pfeifle *et al.* (1998) to be 2.13 x 10^{-8} m^2. The calculations were carried out using the ALGEBRA script *drz_lkp.alg* (located in the directory Test/Input/DRZ); the resulting plots were stored as *drz_lkp_curr_0p0.ps* and *drz_lkp_curr_1p2.ps* for gas generation rates $f = 0.0$ and $f = 1.2$. A Perl script, *avg_perm.pl*, was used to analyze the ALGEBRA output file *lkp_around_room_f0p0.dat* and *lkp_around_room_f1p2.dat* to find the minimum and maximum permeabilities; the script is included in Appendix A, while the *.dat* files are included in Tests/Support/DRZ. The list of cells comprising the DRZ was taken from the file *ele_num_around_current_room.pdf*, which is also stored in the directory Tests/Support/DRZ.

Examining the permeability range obtained for gas generation rates of $f = 0.0$ and $f = 1.2$, we find that the maximum permeability in the DRZ at time $t = 200$ years after completion of excavation is 2.09 x 10^{-18} m^2, while the minimum permeability is 3.24 x 10^{-23} m^2. In practice, however, it is difficult to measure permeabilities below about 10^{-21} m^2; additionally, the permeability of intact halite, as currently implemented in the PA Parameter Database (PDB) is from 10^{-24} m^2 to 10^{-21} m^2. Consequently, we propose using the maximum permeability of intact halite specified in S_HALITE:PRMX_LOG, 10^{-21} m^2, as the minimum value for the permeability of the DRZ. (Although at 10,000 years after closure, the maximum value of PRMX_LOG has decreased to -18.53, we use the maximum value at 200 years after closure to establish the overall range. We discuss the reasons for selecting 200 years after closure as the time to measure permeabilities below.)

Since permeability is entered into the PA PDB as a logarithmic quantity, we treat the log of the permeability as a uniform quantity, with maximum log (2.09 x 10^{-18}) = −17.68, and minimum log (10^{-21}) = −21.00. The resulting parameters are provided in the following table.

Table 1. Parameter Entry for DRZ_2 Permeabilities

Property	DRZ_2:PRMX_LOG DRZ_2:PRMY_LOG DRZ_2:PRMZ_LOG
Description	Log of intrinsic permeability, (x, y, z)-direction
Analysis	AP-133
Parameter Type	Conceptual
Distribution	Uniform
Units	m^2
Mean	−19.34
Median	−19.34
Deviation	0.958
Minimum	−21.00
Maximum	−17.68

For a uniform distribution defined on $a < x < b$, both the mean and median are specified by the midpoint $c = (a + b) / 2$. For the given permeabilities, the mean and median are therefore $c = (-21.00 + -17.68) / 2 = -19.34$. The deviation is found as the square root of the variance, which is given by:

$$\sigma^2 = \int_a^b \left(x - \langle x \rangle\right)^2 p(x)\,dx = \left(\frac{1}{b-a}\right)\int_a^b \left(x - \frac{a+b}{2}\right)^2 dx = \frac{1}{12}(b-a)^2.$$

The deviation is therefore equal to

$$\sigma = \sqrt{\frac{(b-a)^2}{12}} = \frac{b-a}{2\sqrt{3}} = \frac{-17.68-(-21.00)}{2\sqrt{3}} = 0.958.$$

The next step of the analysis was to find the time at which no further dilatancy of the DRZ is expected. Examining the DRZ extent graphs produced above, and using $C = 0.190$ to compute the evolution of the damage potential D with time, we find that for $t > 200$ years, essentially the entire DRZ has $D > 1$, which indicates very little change takes place after that time. We therefore will take $t = 200$ years to be the point at which DRZ_1 is replaced by DRZ_2.

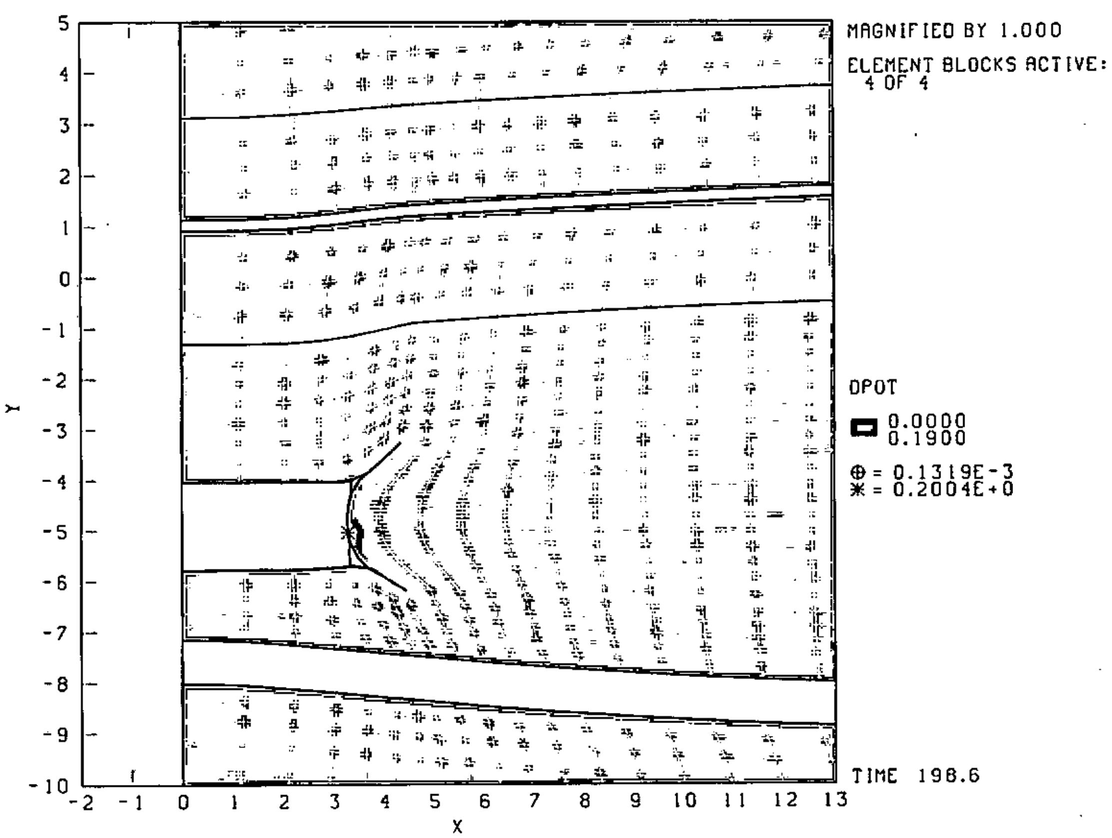

Figure 1 DRZ extent at time 200 years after closure of the WIPP repository. Only a small area (shown in white) near the repository has not healed by that time.

References

Chan, K. S., S. R. Bodner and D. E. Munson, 2001. Permeability of WIPP Salt during Damage Evolution and Healing, *Int. J. Damage Mech.* Vol. 10, 347-375.

Holcomb, D. and R. Hardy, 2001. *Status of Ultrasonic Wave Speed Measurements Undertaken to Characterize the DRZ in the Access Drift to Q Room.* Memorandum to F. Hansen, Sandia National Laboratories, 22 January 2001.

Park, B. Y. and A. E. Ismail, 2007. *Analysis Plan for Prediction of the Extent and Permeability of the Disturbed Rock Zone around a WIPP Disposal Room.* Analysis Plan AP-133. Carlsbad, NM: Sandia National Laboratories.

Pfeifle, T. W.; N. S. Brodsky; and D. E. Munson, 1998. Experimental Determination of the Relationship between Permeability and Microfracture-Induced Damage in Bedded Salt. *3rd North American Rock Mechanics Symposium. Cancun, Mexico, 3-5 June 1998*, USA-324-1, SAND98-0411C.

```
    # If cell corresponds to DRZ, compute permeability by
    # exponentiating.
    if (defined $drz{$id}) {
      <INPUT> for (0 .. $ARGV[1]);
      chomp (my $line = <INPUT>);
      my @entries = split " ", $line;
      $drz{$id} = (10**$entries[1]);
    }
  }
}

my $entries = 0;
my $perm = 0.0;

my $minp = 1;
my $maxp = -1;

# Find the maximum, minimum, and mean of the distribution.
for my $k (keys %drz) {
  $perm += $drz{$k};
  ++$entries;
  $minp = $drz{$k} if ($minp > $drz{$k} && $drz{$k} > 2e-23);
  $maxp = $drz{$k} if ($maxp < $drz{$k});
}

my $var = 0.0;

# Compute variance.
for my $k (keys %drz) {
  $var += ($drz{$k} - ($perm/$entries))**2;
}

printf "Average permeability = %e\n", $perm / $entries;
printf "Variance: %e\n"; $var / ($entries - 1);
printf "Maximum permeability = %e\n", $maxp;
printf "Minimum permeability = %e\n", $minp;
```

Appendix A *Perl script* avg_perm.pl *to determine maximum, minimum, and mean permeabilities from ALGEBRA output file.*

```
#!/usr/bin/perl

# A. E. Ismail
# SNL
# 22 March 2007

# Calculate average permeability of a block.

use strict;

# First, we need to create a hash storing the cells corresponding to the DRZ.

my @drz_list =
   (441, 442, 443, 444, 445, 446, 447,
    463, 464, 465, 466, 467, 468, 469,
    485, 486, 487, 488, 489, 490, 491,
    507, 508, 509, 510, 511, 512, 513,
    529, 530, 531, 532, 533, 534, 535,
    551, 552, 553, 554,
    566, 567, 568, 569,
    581, 582, 583, 584,
    596, 597, 598, 599,
    611, 612, 613, 614,
    626, 627, 628, 629,
    641, 642, 643, 644,
    656, 657, 658, 659,
    671, 672, 673, 674,
    686, 687, 688, 689,
    701, 702, 703, 704,
    716, 717, 718, 719,
    731, 732, 733, 734, 735, 736, 737,
    753, 754, 755, 756, 757, 758, 759,
    775, 776, 777, 778, 779, 780, 781,
    797, 798, 799, 800, 801, 802, 803,
    819, 820, 821, 822, 823, 824, 825,
    841, 842, 843, 844, 845, 846, 847,
    863, 864, 865, 866, 867, 868, 869,
    1435, 1436, 1437, 1438, 1439, 1440, 1441,
    1457, 1458, 1459, 1460, 1461, 1462, 1463,
    1479, 1480, 1481, 1482, 1483, 1484, 1485,
    1501, 1502, 1503, 1504, 1505, 1506, 1507
   );

# Next, create a hash table corresponding to the above elements.
my %drz;
$drz{$_} = 1 foreach (@drz_list);

# Read in entries from the data file. A second argument provided in
# the command line allows the user to skip a certain number of rows
# in the list of times, allowing for selection of an arbitrary time
# for the grid points.
open INPUT, "<$ARGV[0]" or die "Could not open $ARGV[0].\n";

while (<INPUT>) {
  if (/legend string/) {
    my @line = split '\"', $_;
    my @words = split ' ', $line[$#line - 1];
    my $id = $words[$#words];
```