Field Monitoring and Numerical Modeling of Gas Flow and Radon Emission Control in Waste Rock Dump 38neu, Germany

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Abstract
Since 1991, Wismut GmbH has been remediating uranium mining legacies in Eastern Germany. At the former Schlema-Alberoda mining site, waste rock dump 38neu was built along a natural slope on the edge of an inhabited valley. The dump has a 750 m width, a maximum thickness of 30 m and a total height of 100 m. Dump remediation involved surface resloping with benches and a 1 m thick soil cover. The dump characterization was focussed onthe soil cover:its air permeability, radon concentrations under the cover, and, across the soil cover, radon fluxes and differential pressures. In summer, relatively high radon concentrations and fluxes occur across the cover in the lower slope of the dump. Differential pressures indicate that gas flow is upward in the dump below the 9.5 ºC mean atmospheric temperature and downward otherwise. A numerical model using TOUGH AMD was validated against field measurements. Results indicate that gas flow is controlled by dump gas buoyancy relative to atmospheric air.Preferential gas entry and exit occur acrossthe dump lower slope where differential pressuresare highest, explaining the higher radon fluxes observed near the base of the dumpunder high atmospheric temperatures.

Key Words: uranium mining, covers, remediation, risk mitigation, sustainability

Introduction

Since 1991, Wismut GmbH (2011) has been remediating uranium mining legacies in Eastern Germany. At the former Schlema-Alberoda mining site, 23 mine dumps are located near residential areas. There, waste rock dump 38neu was built along a natural slope on the edge of an inhabited valley (Figure 1). Dump 38neu contains 4.7 Mm^3 of waste rock over a width of 750 m, with a maximum thickness of more than 30 m (Figure 2) and a total height of nearly 100 m between its top surface and toe (Figure 6).

Figure 1.View of waste rock dump 38neu of uranium mining in Bad Schlema, Wismut GmbH, Germany. Note proximity of housing developments near the dump toe (Photo courtesy of Wismut GmbH).

Investigations by Wismut GmbH of radon exhalation from uncovered mine dump surfaces revealed convective gas flow within the mine dump. The remediation of dump 38neu involved surface resloping with benches and adding a 1 m thick soil cover consisting of 0.2 m of organic soil over a 0.8 m radon barrier layer made up of fine soil. Following remediation and surface vegetation, the radon situation was monitored in dump 38neu. Under summer conditions, relatively high radon concentrations and radon fluxes still occurred across the cover in the lower slope areas near the toe of the dump.

The objectives of this study were to carry out numerical simulations representing gas flow in covered waste rock dump 38neu to develop an appropriate conceptual gas flow model and identify potential options to influence gas transport processes in order to mitigate radon liberation. The study was based ondata from field measurements and monitoring in order to improve the conceptual model of gas flow in dump 38neu, provide estimates of physical properties and serve as model calibration criteria.This paper documents the field characterization data and the results of the numerical model related to the representation of present-day gas flow conditions.

Field Characterization

Differential pressure measurements across the soil cover at different elevations on the dump slope were found to be powerful means to characterize the driving forces of air flow inside the dump, as hinted by previous studies (Phillip *et al*. 2009; Lahmira*et al*. 2009). Figure 2 shows measurement points (MP) on the surface of dump 38neu. These measurement points were concentrated along a line passing through the thickest part of the dump. The numerical model was also based on a vertical cross-section along this line (Figure 6) to facilitate the comparison of model results with field measurements. The thickness of waste rock was derived from the present topography of the dump surface and the former natural surface topography prior to the placement of the dump.

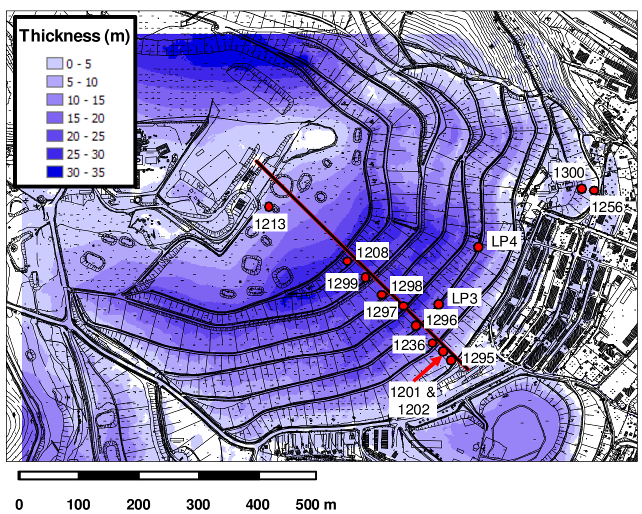


Figure 2.Map of waste rock dump 38neu, showing its thickness (levels of blue) and measurement points (MP) (red circles with MP numbers). Red line indicates location of cross-section shown on Figure 6.

The continuous monitoring of differential pressure across the soil cover was carried out by Wismut GmbH during July and August 2010. Differential pressures of dump gas relative to the atmosphere were measured through open tubes inserted through the soil cover that were screened at their base in contact with waste rock, open to the atmosphere at their exterior end and sealed at their perimeter to avoid preferential gas flow along tubes. Also, a weather station continuously monitors air temperature and atmospheric pressure. Measurements had already been made by Wismut GmbH on radon concentrations under the cover and radon fluxes at the cover surface from 2006 to 2008 at MP 1201 and 1202, which are located near the base of the dump. The air permeability of the soil cover was also measured in the field. Grain size distributions are also available on the soil cover material. Wismut GmbH also carried out gas tracer tests under winter conditions, which provided an estimate of gas flow velocity inside the dump.

Differential pressures were correlated to atmospheric temperature at each MP. Figure 3 illustrates two of these correlations for two MP located in the upper (1299) and lower (1295) parts of the dump slope, which exhibit inverse trends. A time lag of 70 minutes between differential pressure responses to changes in temperature was taken into account prior to making the correlations. For all MPs, there is zero differential pressure at a temperature of 9.5 ºC (Figure 3). This is the mean annual atmospheric temperature at the site and it is presumed to also be the mean internal temperature of the dump, as there is no exothermic sulphide oxidation in the dump. Differential pressures can thus be inferred to be driven by differences between the internal dump temperature (quite constant) and variable atmospheric temperatures.

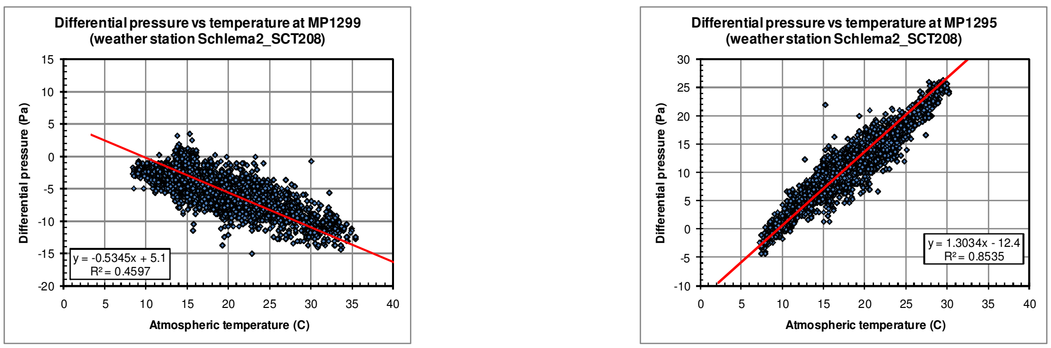


Figure 3.Correlation of differential pressures across the soil cover with atmospheric temperature for MP in the upper (1299 at 454 m) and lower (1295 at 413 m) slope (locations shown on Figure 2).

The correlations illustrated in Figure 3 provided mean values of differential pressure at 5 and 25 ºC at the elevations of each MP. These two values of temperature were used because they represent winter and summer (about min. and max.) conditions at the site. Figure 4 shows these mean differential pressures at the elevations of the MPs. There is a linear trend in differential pressures with depth, which is opposite at 5 and 25 ºC. There is a crossover at which there is no differential pressure at about 440 m (close to the elevation of MP 1298, which has low differential pressures poorly correlated with temperature). At a given elevation, the magnitudes of differential pressures at 5 ºC are lower than at 25 ºC because 25 ºC departs more from the mean dump temperature of 9.5 ºC.

The dashed lines on Figure 4 represent the theoretical differential pressure that would be present in a static gas column of the dump at 9.5 ºC isolated from the atmosphere by a perfectly sealing soil cover. The actual differential pressures on the dump surface are lower than these theoretical values, which indicate that there is gas flow in the dump leading to pneumatic potential (or pressure) losses. At 25 ºC, differential pressures indicate that the dump gas pressure is lower than the atmosphere in the upper slope of the dump, but higher than the atmosphere in the lower slope. There will thus be a tendency for air to enter in the dump through the soil cover in the upper part of the slope, whereas dump gas will tend to exit through the cover in the lower part of the slope. This implies that gas then flows downward through waste rock within the dump. The gas flow behavior is the reverse at 5 ºC. Higher differential pressures in the upper and lower parts of the dump imply that higher gas fluxes will occur through the soil cover at these locations, presuming that the soil cover air permeability is relatively uniform.

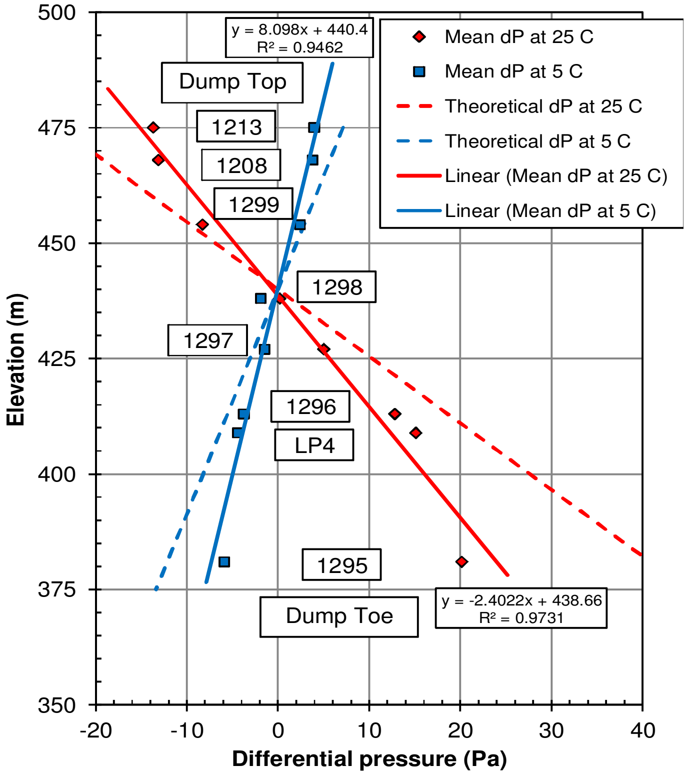
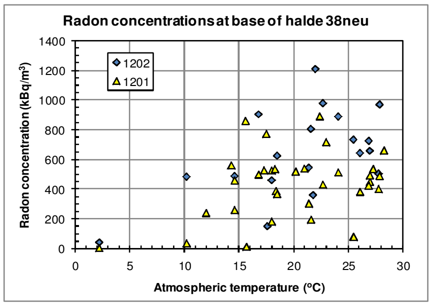


Figure 4.Mean differential pressures across the soil cover at 5 and 25 ºC at different elevations on the dump (negative values indicate a lower pressure in the dump than in the atmosphere).

As shown by Lahmira*et al*. (2009) for the analog conditions found at the Sullivan Mine, this gas flow behavior can be explained by the buoyancy of dump gas relative to the atmosphere. At relatively low atmospheric temperature (below 9.5 ºC), the dump gas phase has a lower density than atmospheric air, so dump gas tends to flow upward, whereas high atmospheric temperature leads to an atmospheric air density lower than dump gas, thus leading to the downward flow of dump gas. The later situation explains themore important radon gas fluxes observed in summer at the base of dump 38neu.

Figure 5 shows radon concentrations and fluxes made using gas flux chambers at MP 1201 and 1202, located close to the base of the dump (Figure 2). A representative radon concentration in the dump was estimated at about 1000 kBq/m^3at these locations (which were inferred to be represented by the highest measured concentrations). Maximum radon fluxes were respectively estimated at 5 and 25 $Bq/m^{2\cdot}s$ at MP 1201 and 1202. Simply using Darcy's Law for gas flow, Table 1 shows how values of radon concentrations and fluxes were used to estimate dump gas volumetric and mass fluxes as well as of the effective air permeability of the soil cover (between 10^{-12} and 10^{-11} m^2), which is consistent with field measurements of air permeability.



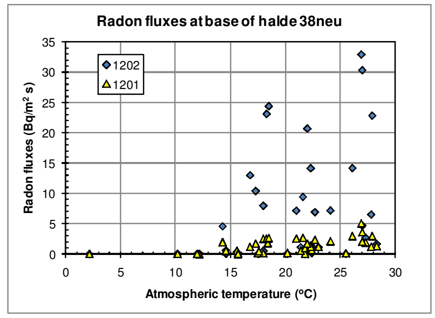


Figure 5.Observed radon concentrations (left) and radon fluxes (right) from 2006 to 2008 at measure points 1201 and 1202 located near the base of dump 38neu (Figure 2).

Table 1.Radon fluxes converted to gas fluxes to derive soil cover properties

Parameter	Units	Upper flux value (Typical of MP 1202)	Lower flux value (Typical of MP 1201)
Known parameter or parameter derived from onsite measurements			
Dump cover thickness	m	1.0	1.0
Differential pressure at the base of 38neu @ 25 ºC atmospheric temperature	Pa	20.5	20.5
Radon concentration in dump gas	kBq/m^3	1000	1000
Maximum radon flux	$Bq/m^2{\cdot}s$	25	5
Estimated dump gas properties at mean dump temperature			
Dump gas density at 9.5 ºC	kg/m^3	1.24	1.24
Dump gas viscosity at 9.5 ºC	Pa·s	$1.8x10^{-5}$	$1.8x10^{-5}$
Calculated gas flux			
Dump gas volumetric flux	$m^3/m^2{\cdot}s$	$2.5x10^{-5}$	$5.0x10^{-6}$
Dump gas mass flux	$kg/m^2{\cdot}s$	$3.1x10^{-5}$	$6.2x10^{-6}$
Calculated cover properties			
Effective air permeability of cover	m^2	$2.2x10^{-11}$	$4.3x10^{-12}$
Equivalent hydraulic conductivity of cover	m/s	$1.6x10^{-4}$	$3.3x10^{-5}$

Geometry and Material Properties

The numerical model is a 2D vertical section representing the surface and base topography of dump 38neu (Figure 6). The grid was designed to represent atmospheric boundary elements as well as the following materials (from top to base): soil cover, waste rock, basal waste rock boulder layer and materials underlying the dump. Actual data on grain size of waste rock types are not available. The nature of waste rock types was inferred from visual observations and information available on waste rock placement methods, which included conveyor belt dumping that create boulder layers.

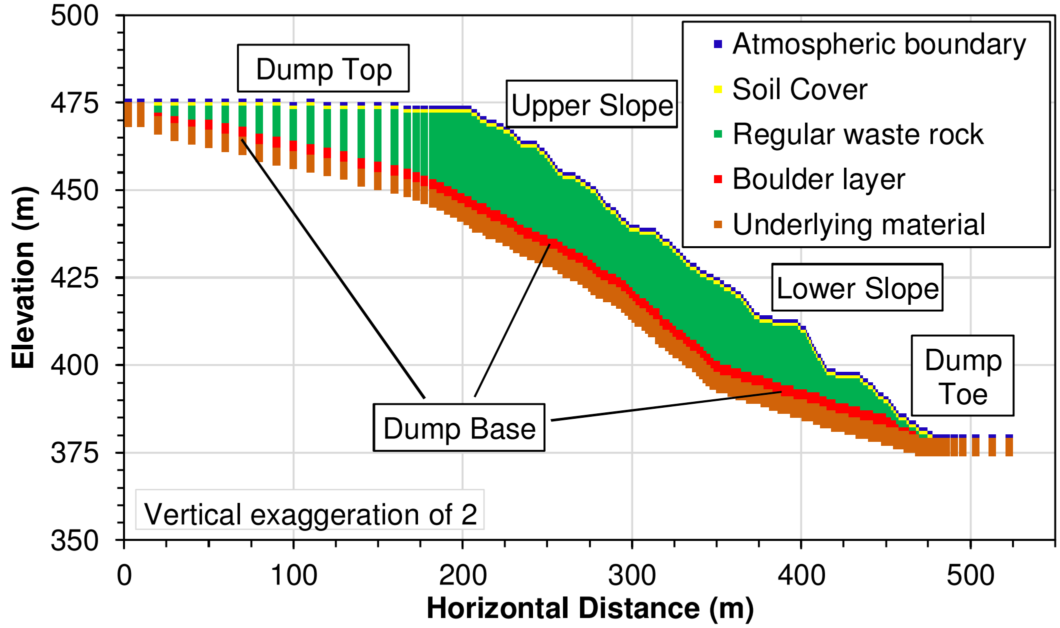


Figure 6.Cross section through dump 38neu showing materials and geometry(location in Figure2).

Table2summarizes the main properties of materials that were derived on the basis of available information and analog sites (Lefebvre *et al*. 2002; Lahmira*et al*. 2009). Two base case models were developed: 1) a simplified global base case considering only waste rock and a soil cover, and 2) a final base case considering two types of waste rock, including a coarse boulder layer at the base of the dump, and natural soil underlying the dump.

Table 2.Material properties used in the simulations

Materials	*Porosity*	*Water saturation*	*Air permeability*	*Range of air permeability*
	n **(-)**	S_w **(-)**	***k*** **(m^2)**	***k*** **(m^2)**
Simplified Global Base Case				
Soil cover	0.45	0.80	$5x10^{-12}$	$5x10^{-12}$and $5x10^{-11}$
Waste rock	0.34	0.44	$1x10^{-8}$	$1x10^{-9}$ to $5x10^{-8}$
Surface soil	0.34	0.44	$5x10^{-12}$	$5x10^{-12}$ and $5x10^{-11}$
Underlying materials	0.34	0.44	$1x10^{-8}$	$1x10^{-9}$ to $5x10^{-8}$
Final Base Case				
Soil cover	0.45	0.80	$1x10^{-11}$	$8x10^{-12}$ and $1x10^{-11}$
“Regular” waste rock	0.34	0.44	$8x10^{-10}$	$8x10^{-10}$ to $2x10^{-9}$
Boulder layer	0.34	0.44	$3.5x10^{-8}$	$3x10^{-8}$ to $3.5x10^{-8}$
Underlying materials	0.34	0.44	$1x10^{-10}$	$1x10^{-10}$ to $5x10^{-10}$

Numerical Modeling
The numerical simulator TOUGH AMD was used to develop models representing dump 38neu. TOUGH AMD represents multiphase transfer processes and reactions within acid-generating rock piles containing pyrite (Lefebvre *et al*. 2001a 2001b). It is based on the general multiphase non-isothermal and multicomponent simulator TOUGH2 (Pruess*et al*. 1999). The numerical simulator TOUGH AMD considers heat and three components: water and air subdivided in two components (oxygen and the other air gases). This model has been used to simulate acid rock drainage in mine rock piles at other mine sites (Lefebvre *et al*. 2001b 2002; Wels *et al*. 2003; Sracek*et al*. 2004).

Two numerical modelswere developed to represent steady state gas flow in dump 38neu under present-day conditions at atmospheric temperaturesof 5 and 25 ºC. These temperatures are in the lower and upper range of values recorded at the site. Therefore,modeling at these temperaturescan represent end-members of gas flow patterns occurring in dump 38neu. The internal dump temperature in the models was set at 9.5 ºC,which corresponds to the mean atmospheric temperature as confirmed by differential pressures(Figure 3). Atmospheric temperature was applied on boundary elements at the top surface of the dump. The base of the dump was assumed to be impermeable to gas flow.

Based on a previous simulation study representing a similar gas flow behavior at the Sullivan Mine in B.C. (Lahmira*et al*. 2009), some simplifying conditions were used in the numerical model: 1) heat transfer by conduction was not represented in the model, but the model considers different temperatures for the dump and atmosphere, 2) only gas flow was considered and water was set as immobile in the waste rock dump, and 3) the same constant gas composition was used for atmospheric air and dump gas since the waste rock is not acid-generating and thus does not consume oxygen.

The two base case models represent different materials in the dump (Table 2). A simplified base case simulation represented only the 1-m soil cover and underlying bulk waste rock. This model was developed to achieve an initial calibration of simulated conditions to differential pressures with simplified material distribution. After calibration of the simplified base case, a final base case model was then developed to represent the internal distribution of materials within the dump, including the presence of a boulder layer (Figure 6 and Table 2). The final base case model was calibrated and validated against 1) differential pressure measurements at different elevations along the surface of the dump, 2) radon flux and concentration measurements on the lower part of the dump slope that were used to estimateequivalent gas fluxes, 3) upward gas velocities at the upper base of the dump estimated by WismutGmbH on the basis of a gas tracer test made at “low” atmospheric temperature and 4) the elevation of the cross-over at which differential pressures are zero (i.e. about 440 m, Figure 4).

The simplified base case model was run at 5 and 25 ºC and calibrated against the field measurements of differential pressure (converted into pneumatic potentials – for details see Lefebvre et al., 2011a or 2011b). Figure 7 shows that there is a good match between simulated and measured pneumatic potentials at 25 ºC near the surface of the dump. This calibrated simplified base case used air permeability values of $5x10^{-12}$ m^2 for the cover and $1x10^{-8}$ m^2 for the bulk of waste rock (Table 2).

A final base case model was then developed by distinguishing “regular” waste rock, a waste rock boulder layer at the base of the dump and natural materials underlying the waste rock. The calibration and validation objectives were met using air permeabilities of $1x10^{-11}$ m^2, $8x10^{-10}$ m^2, $3.5x10^{-8}$ m^2 and $1x10^{-10}$ m^2, respectively, for the soil cover, “regular” waste rock, the boulder layer and the natural material underlying the dump (Table 2). This final base case reproduces the gas velocity of a tracer experiment as well as the radon fluxes measured at the base of the dump. However, the differential pressures are not matched as closely as with the simplified base case (Figure 7). The two base cases are considered representative of the range of possible internal material distribution in dump 38neu.

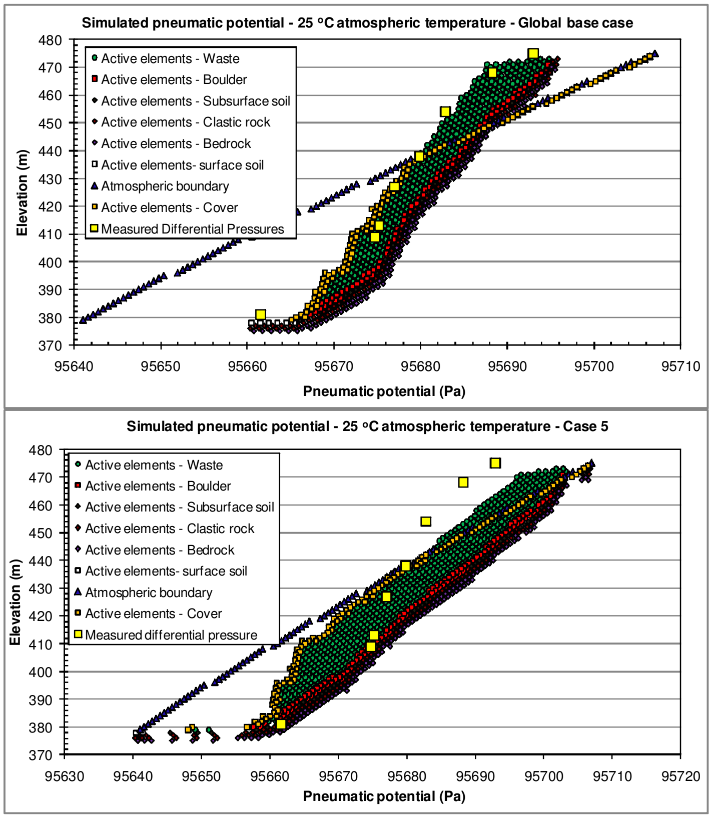


Figure 7.Simulated pneumatic potentials versus elevation at 25 °Cfor the simplified (top) and final (bottom).base cases. Simulated conditions for different parts of the dump are compared to measured differential pressures (yellow squares).

The air permeability of the cover used in the model is consistent with field measurements as well as the values derived from radon fluxes. At this air permeability, the soil cover limitsgas entry and exit in the dump to a certain extent, but its air permeability is much higher than what would be expected on the sole basis of the grain size of the material. It is presumed that vegetation growth, bioturbation and natural evolution of the material exposed to weather conditions have led to observed conditions. Based on WismutGmbH information concerning older dump cover, this evolution towards higher soil cover permeability is normal, so a further increase in soil cover permeability in the future is to be expected for dump 38neu as well. The consequence is that the soil cover does not totally impede gas flow through the dump, although its permeability is low enough to favor a long gas flow path through the entire length of the waste rock dump slope.

The air permeability of waste rock in the model that was needed to reproduce differential pressure measurements is much higher than field indications obtained from water infiltration tests. It is inferred that field measurements made in the upper layer of the dump may represent properties of crushed and compacted waste rock related to machinery traffic during resloping of the dump. It is also inferred that the end dumping and cone dumping construction of the dump may have induced high vertical permeability as well as potentially a boulder layer at the base of the dump that may explain the high air permeability.

Figure 8 shows the simulated gas flow patterns, both for the simplified and final base cases at 25 °C. Trends in pneumatic potentials with elevation (Figure7) and gas flow patterns (Figure8) are similar, but in opposite direction, for simulations made at 5 °C (not shown).

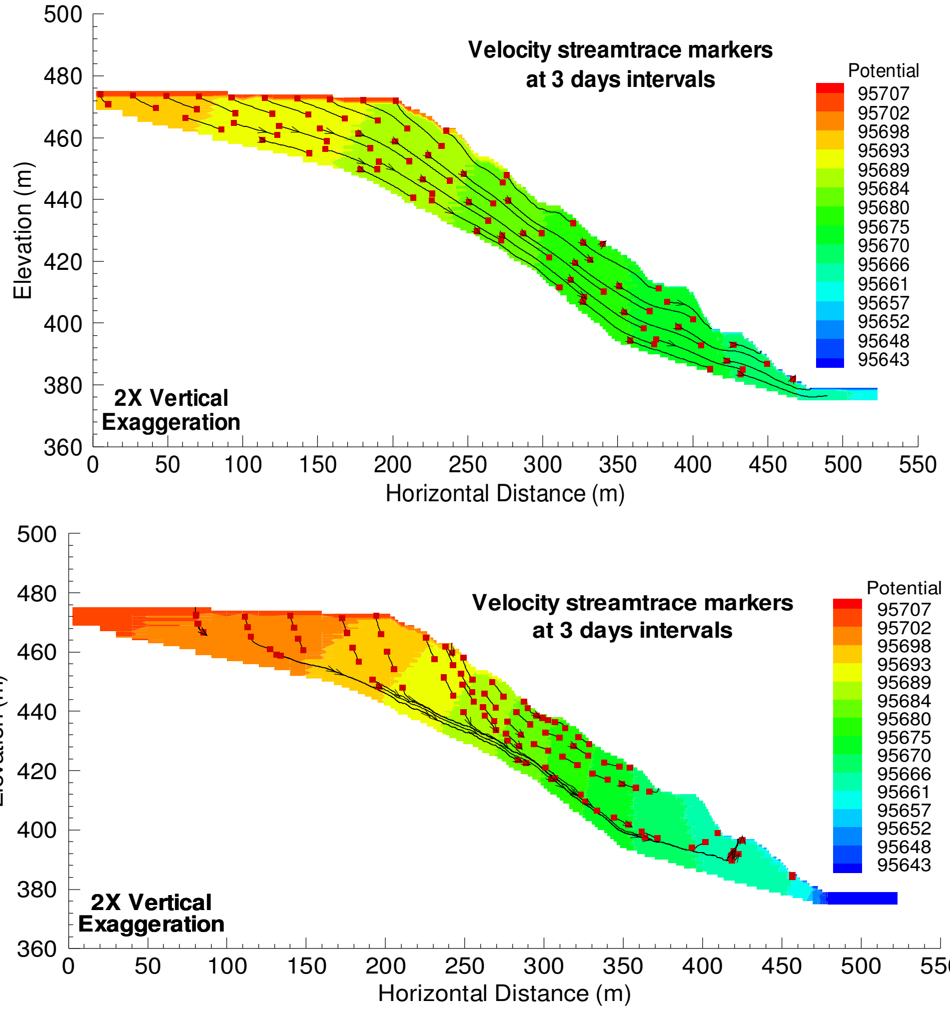


Figure 8. Pneumatic potential (Pa) and gas transit time along stream traces at 25 °C for the simplified base case (top) and the final base case (bottom).

Preferential gas entry and exit occur on the top surface of the dump and on its lower slope (Figures 8 & 9). Higher differential gas pressures between the atmosphere and the dump gas at the upper and lower limits of the dump promote more significant gas exchanges at these locations (Figures 4, 7, 8 and 9). The gas exchange across the top surface is also favored by its very large surface area compared to the rest of the dump, but fluxes are relatively small (Figure 9). However, the highest differential pressures are present near the base of the dump, thus favoring higher radon gas fluxes out of the dump at that location under high atmospheric temperatures (above 9.5 °C) (Figure 9). Along the dump slope, the portions of slopes just above benches are the locations of preferential gas entry or exit through the soil cover, whereas there are lower fluxes across the bench surfaces. This occurs because benches lead to discontinuities in the normal trend of pneumatic potential differences with elevation between dump gas and the atmosphere. These discontinuities in pneumatic potential gradients lead to the oscillations in gas fluxes between horizontal top surfaces and vertical faces of grid elements in the model. These oscillations are more important at higher gas fluxes, as seen between measure points 1236 and 1295, both for entering and exiting fluxes for simulations at 5 and 25 °C, respectively. Such a behavior was observed in previous numerical simulations at other sites (Lefebvre *et al*. 2001b 2002; Lahmira*et al*. 2009).

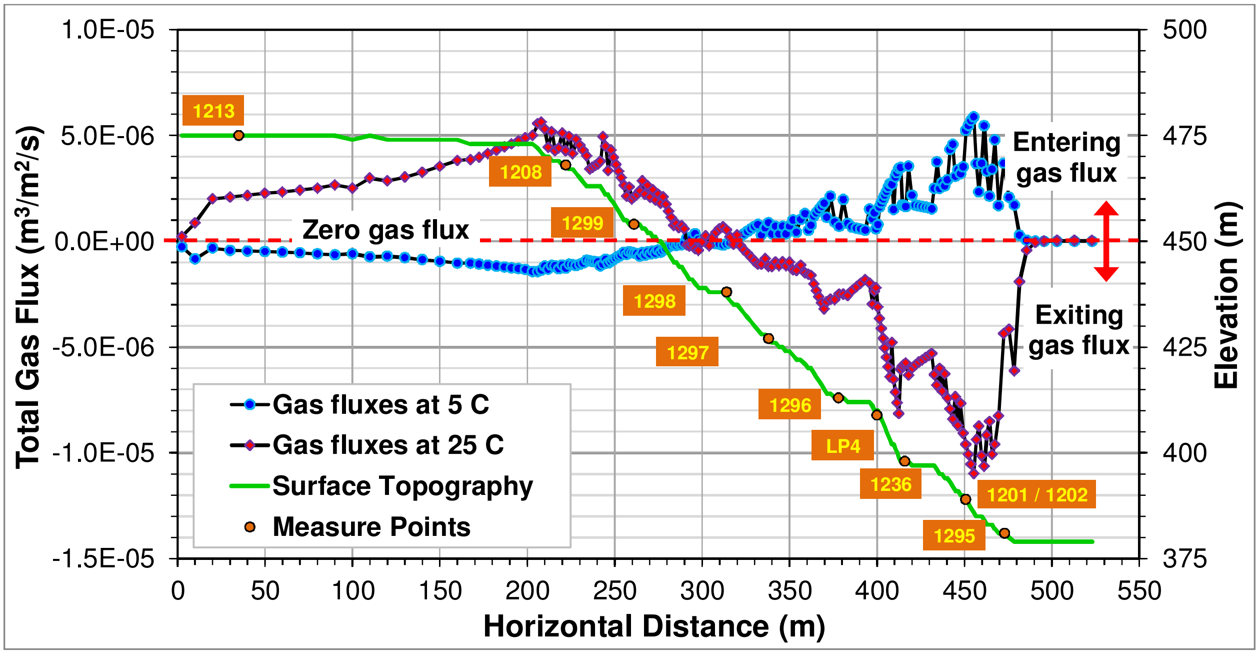


Figure 9. Simulated gas fluxes through the soil cover for the final base case at 5 °C and 25 °C.

Based on the observed and simulated behaviour of gas transfer in the waste rock dump, a range of radon flux mitigation options were considered and a numerical simulation program wascarried out to represent these options: 1) vertical barriers through theentire thickness of waste rock located at the toe or at the center of the dump; 2) enhancement ofthe soil cover over the top surface of the dump with a decreased air permeability; 3) openings inthe soil cover on benches along the dump slope; 4) the potential effect of long term degradationof the soil cover that would increase its air permeability; 5) gas venting wells screened at thebase of the dump in the boulder layer under different benches; and 6) the effect of long termdegradation of the soil cover on gas venting wells at the most efficient location. These options aimed either to reduce gas fluxes, by limiting their entry or impeding their flow in the dump, or controlling the points of gas outflow in areas representing a lower risk of exposure. A discussion of the methods and results of this modeling program are however beyond the scope of this paper. Interested readers are referred to the reportsdocumenting radon flux mitigation simulations (Lefebvre et al., 2011a and 2011b).

Conclusions

The differential pressure and radon flux measurements made by Wismut GmbH on dump 38neu provide a novel and powerful way to understand gas flow and calibrate the numerical modeling of gas flow in a waste rock dump, without the need to drill observation boreholes. The data are consistent and provide clear indications of gas flow conditions in the dump. In the particular case of dump 38neu, radon gas concentrations and fluxes can also be used to further constrain the model and provide another estimate of the air permeability of the soil cover that is coherent with field measurements.

A simplified base case model representing only the bulk waste rock properties under the soil cover was used to develop a base case simulation that could be calibrated against the differential pressure measurements. A final base case model was then developed by distinguishing “regular” waste rock, a high permeability waste rock boulder layer at the base of the dump and natural materials underlying the waste rock. This final base case reproduces the gas velocity of a tracer experiment as well as the radon fluxes measured by Wismut GmbH at the base of the dump.

Modeling shows that preferential gas entry and exit occur on the top surface of the dump and on its lower slope. However, the highest differential pressures are present near the base of the dump, thus favoring higher radon gas fluxes out of the dump at that location under high atmospheric temperatures. This explains the observed higher radon gas fluxes near the base of the dump in summer months. Within the dump, there is preferential flow and higher gas velocities in the boulder layer. These key features of gas flow have to be taken into account in the design of radon flux mitigation approaches.

Acknowledgements
Wismut GmbH is acknowledged for supporting this work and granting permission to publish. From Wismut GmbH, J. Regner, Ch. Schramm, M. Speer, Dr. P. Schmidt and Dr. M. Paul directly contributed to this work.

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Acronyms

MP: Measure point