ONTARIO POWER GENERATION

Albert Sweetnam
Executive Vice President

Nuclear Projects

700 University Avenue, Toronto, Ontario M5G 1X6

Tel: 416-592-7537
albert.sweetnam@opg.com

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Dr. Stella Swanson
Chair, Joint Review Panel
Deep Geologic Repository Project

c/o Canadian Nuclear Safety Commission
280 Slater Street
Ottawa, Ontario
K1P 5S9

Dear Dr. Swanson:

<u>Deep Geologic Repository Project for Low and Intermediate Level Waste – Submission for the October 11, 2012 JRP Technical Information Session #2</u>

References:

1. OPG Letter from Albert Sweetnam to Dr. Stella Swanson, "Deep Geologic Repository Project for Low and Intermediate Level Waste – Submission for JRP's Technical Information Session #2", August 27, 2012, CD# 00216-CORR-00531-00135.

2. JRP Letter from Dr. Stella Swanson to Albert Sweetnam, "Modelling Technical Information Session", September 10, 2012, CD# 00216-CORR-00531-00139.

The purpose of this letter is to provide OPG's revised written submission and presentation material to the Joint Review Panel (JRP) for the October 11, 2012, Technical Information Session. These materials were revised to incorporate the JRP's feedback on OPG's August 27 submission (Reference 1) received on September 10 (Reference 2).

OPG's revised written submission and revised slides for the oral presentation are attached to this letter as Attachments 1 and 2, respectively.

If you have questions on the above, please contact Mr. Allan Webster, Senior Manager, Licensing, at (905) 839-1151, ext. 6051.

Sincerely,

<original signed by>

Albert Sweetnam
Executive Vice-President
Nuclear Projects
Ontario Power Generation

Attach

cc. Dr. J. Archibald – Joint Review Panel c/o CNSC (Ottawa)
Dr. G. Muecke – Joint Review Panel c/o CNSC (Ottawa)
P. Elder – CNSC (Ottawa)
F. King – NWMO (Toronto)

ATTACHMENT 1

Attachment to OPG letter, Albert Sweetnam to Dr. Stella Swanson, “Deep Geologic
Repository Project for Low and Intermediate Level Waste – Submission for the
October 11, 2012 JRP Technical Information Session #2”

October 3, 2012

CD#: 00216-CORR-00531-00142

OPG’s Written Submission for JRP’s Technical Information Session #2 on October 11, 2012

Written Submission

Contents

1.0 INTRODUCTION

This written submission is being provided to the Joint Review Panel in support of OPG’s oral presentation at the Technical Information Session #2 to be held on October 11, 2012. Due to numerous references to the slides in the oral presentation provided in Attachment 2, this written submission should be read in conjunction with the accompanying presentation slides.

2.0 GEOSCIENCE MODELLING

2.1 3-DGFM

The three-dimensional geological framework model (3-DGFM) is a regional-scale realization of the bedrock stratigraphy that is linked to historical well log data and is consistent with recent stratigraphic interpretations. It was developed, in part, to provide a conceptual 3-dimensional model of bedrock stratigraphy, which is necessary to establish regional scale hydrostratigraphy and to assess long-term groundwater system behaviour and characteristics, including Paleohydrogeologic response to future glacial events. Given the nature and spatial distribution of the historic well logging information, the model derived is not intended to establish a basis for an interpretation of regional bedrock structure.

The boundary of the approximately 35,000 km^2 3-DGFM, overlain on the bedrock geology of southern Ontario and defined as the ‘Regional Study Area’, is shown on the lower left-hand side of slide #3. The bedrock geology map also indicates the location of the cross-section, A-A’, which is shown on the lower right-hand side of slide #3. This cross-section, with 50 times vertical exaggeration, was generated from the 3-DGFM. It illustrates the lateral extent and traceability of individual stratigraphic units across the model domain in a location proximal to the Bruce nuclear site that passes through the Texaco #6 exploratory borehole, 2.9 km east of the site.

2.1.1 3-DGMF – Model Methodology

The methodology for the 3-DGFM development, including a description of the data sets used, is described in the Three-Dimensional Geologic Framework Model report (ITASCA CANADA and AECOM 2011) that supports the DGR Geosynthesis (NWMO 2011). Several key data sets, as listed on slide #4, were used to constrain the model during its development. The primary data set used to generate the model was the Ontario Oil, Gas and Salt Resources Library (OGSRL) Petroleum Wells Subsurface Database, which includes borehole well records from 1930 to the present day. The majority of the boreholes were drilled as exploration wells for oil and gas hydrocarbons, targeting Cambrian, Ordovician and Silurian formations. A total of 341 well records existed for the Regional Study Area at the time of model development in 2008. In some cases, these well records include historic borehole geophysical survey logs. Additional data sets include the Ontario Geological Survey (OGS) Seamless Digital Bedrock Geology compilation map, and OGS Open File Report 6191, entitled “An updated guide to the Paleozoic stratigraphy of southern Ontario”, by Armstrong and Carter (2006, 2010). Reference wells included within this open file report were used as a primary basis to develop the stratigraphic model, as was the standardized stratigraphic nomenclature. The model also incorporated information for 76 petroleum wells from the Michigan Department of Natural Resources and

Environment, Petroleum Well Database, as well as information on ground surface topography, bedrock surface topography, glacial drift thickness and Lake Huron bathymetry.

The historical drilling records used to develop the stratigraphic model were verified by a screening process to check and assure data reliability. As indicated on slide #5, the data screening and verification process included three primary checks. Firstly, the historical well logs were screened for obvious errors, which could include a complete lack of data, incorrect stratigraphic contact elevation, or incorrect collar ground surface elevation. Secondly, the recorded stratigraphic relationships were compared between adjacent wells to determine the degree of stratigraphic consistency and lateral traceability, as well as to verify the distribution of stratigraphic features such as pinnacle or barrier reef complexes. And, thirdly, in the event of inconsistency in drilling logs, geophysical well logs, if available, were compared against the reference geophysical logs described by Armstrong and Carter (2010).

The result is that 299 wells from the 341 total wells in the OGSRL database were deemed acceptable and used in the creation of the 3-DGFM. All data sets, including the original and the vetted, with explanations as to why well data were removed, are documented in Appendix C of the 3-DGFM report (ITASCA CANADA and AECOM 2011). The illustration on the right-hand side of slide #5 shows the distribution of screened wells across the Regional Study Area, colour-coded to indicate the lowermost geological unit encountered in each well.

The diagram on the left-hand side of slide #6 illustrates the work flow for developing the 3-DGFM. The process may be best described as numerical estimation of formation surface, augmented by manual interpretation to ensure geologic knowledge regarding bedrock stratigraphy was preserved. In brief, the screened data was input into the model and formation top surface and thickness maps were generated in the GoCad environment. Where available, geophysical well logs were re-examined to assure established formation contacts were selected. As well, bedrock formation projections to the digitally constrained bedrock surface were checked for consistency against published formation outcrop/subcrop mapping. The result of the manual refinement was a stratigraphic model that was linked to, and reflected, the geological understanding in the published literature. The final step was the completed 3-dimensional realization of the fully screened and tested data set.

All structural contours for the individual formation surfaces, which show both wells and well identifiers, are provided in Appendix A of the 3-DGFM report (ITASCA CANADA and AECOM 2011). Also available are oblique renderings of each of the individual surfaces showing the well constraints (Appendix B of the 3-DGFM report). The illustration on the right-hand side of slide #6 shows the isopach (total thickness) map for the entire Ordovician shale interval, which includes the Blue Mountain, Georgian Bay and Queenston formations, generated from the 3-DGFM data set.

2.1.2 3-DGFM – Model Testing

The 3-DGFM was tested at both the regional and site scales for consistency between observed and modelled data. Slide #7 shows an overview of such a test involving the Sherman Fall Formation, which directly underlies the Cobourg Formation, the proposed DGR host rock. For this test, a formation surface was generated using 67% of the wells intersecting the Sherman Fall Formation, and then the remaining 33% of the wells were input into the test model to compare the goodness of fit between actual well log data and predicted formation depths.

Overall, the difference between predicted and observed formation depths, at model control points, was on the order of metres.

The 3-DGFM also underwent a blind depth test at the site scale. In this test, the 3-DGFM model was used to predict formation contacts and depth at the location of DGR site investigation borehole DGR-4. The table shown in slide #8 lists, from left to right, the stratigraphic units encountered beneath the Bruce nuclear site, the 3-DGFM predicted formation tops, the observed formation tops within DGR-4 (base on core logging) and the variance between the 3-DGFM predicted and observed formation top depths. Note that all units are in metres. The results indicate that the 3-DGFM estimated the DGR-4 formation contacts to within metres. One obvious error was in the estimation of the formation top depth for the Kirkfield Formation. The error occurred as a result of a change in the selection of the formation top pick criteria for the Kirkfield during core logging workshops, which included participation by industry, government and academic experts.

2.1.3 Confidence Assessment

Slide #9 lists the six primary reasons that speak to confidence in the bedrock stratigraphy as realized in the 3-DGFM. Firstly, the reliability of the well log data was screened and verified, including a check against a set of established reference wells. The well logs were then checked for internal consistency against stratigraphic relationships and traceability. This led to a model that was consistent with present stratigraphic understanding and nomenclature. The model was calibrated at both the regional and site scales, with a resulting fit that is within metres at control points. The DGR drill core formation picks were determined based on the results from four core workshops, which included participation from industry, academic and government experts. In addition, all data sets and formation surface contour maps are provided for independent assessment and review. The methodology is described in three reports, the Regional Geology – Southern Ontario report (AECOM and ITASCA CANADA 2011), the 3-DGFM report (ITASCA CANADA and AECOM 2011) and the Geosynthesis report (NWMO 2011). Finally, all geoscience data incorporated into the model are publicly available for revision and/or alternate interpretation.

As seen of slide #10, overall there is a high level of confidence that the 3-DGFM model has been developed and applied appropriately for the assessment of the DGR system at the site scale.

2.2 FRAC3DVS-OPG

The purpose of this modelling work program was to conduct hydrogeologic analyses at different scales to develop and test the understanding of long-term shallow, intermediate and deep groundwater system properties and behaviour relevant to illustrating DGR safety.

An issues-based approach was adopted in this modelling program to explore and examine groundwater system evolution and the impact, if any, of system property uncertainty on the performance of the DGR. The analyses approach involved the investigation of the long-term behaviour of the groundwater system as constrained by both local-scale and regional-scale observation data sets. Specific simulations included the investigation of density-dependent flow at both the regional-scale and site-specific scale and the investigation of two-phase gas and water flow in one-dimensional columns representing the DGR site. In Paleohydrogeologic analyses, the impact of glacial ice-sheet perturbations on groundwater system stability and resilience was examined.

2.2.1 FRAC3DVS-OPG – Fundamental Aspects

FRAC3DVS was first released to the public in 1995. The model has been the subject of many journal and conference papers. The model has a large user base that includes universities, consultants and government agencies throughout the world. In 2001, OPG began to support the development of the model through contracts with both the University of Waterloo and with Laval. The OPG version of FRAC3DVS has a comprehensive user manual. Quality assurance and quality control of the code is facilitated by a version-control system at the University of Waterloo. There are 35 verification tests for the code.

FRAC3DVS-OPG simulates three-dimensional density-dependent flow and solute transport in variably saturated porous media. Solute transport processes include advection, mechanical dispersion and diffusion. The impact of mechanical loading on groundwater flow is included in the model using the literature standard for glaciation studies that assumes that loads are areally homogeneous. The performance measures in the model include the water Mean Life Expectancy (MLE).

2.2.2 Modelling Approach – Issue Based

The steps of the modelling process are outlined on slide #14. All modelling problems follow 5 basic steps. The first step is the selection of the computational model that is capable of representing the processes occurring. Model uncertainty is related to the physics described by this computational model. The remaining 4 steps in the development of a numerical model are: i) the specification of geometry, in the case of the DGR this is the 3-DGFM stratigraphy; ii) the selection of parameters and constitutive laws that represent the system; iii) the specification of the boundary conditions and in the case of transient problems, the specification of the initial conditions; and iv) the use of appropriate discretization for both space and time.

In the DGR study, the FRAC3DVS-OPG computational model was applied following an issues-based approach for data analysis, the synthesis of data that cannot be measured directly and for hypothesis testing (slide #15).

Confidence in the hydrogeologic modelling study using FRAC3DVS-OPG is provided by the use of two different computational models so that model uncertainty could be addressed. In addition to FRAC3DVS-OPG, the two-phase gas and water compositional model TOUGH2-MP was also used in the study. FRAC3DVS-OPG was used with and without mechanical coupling.

Parameter uncertainty was investigated using sensitivity analyses that explored the parameter space. “What if” or hypothetical scenarios were also developed. The important part of the work is estimating the degree to which the uncertainty in a given parameter impacts the performance measures for the DGR. An example performance measure includes the solute transport processes in the Ordovician sediments at the DGR and Mean Life Expectancy. Confidence was also developed through sensitivity analyses for the boundary conditions selected for the description of the flow domain. The hydrogeologic modelling study describes 36 scenarios that were used to explore the groundwater system parameter space, boundary conditions and physics.

2.2.3 Modelling Study Design

The design of the hydrogeologic modelling study is described in slides #16 and #17. Data synthesis was an important aspect of this issues-based approach. An important component of the work is the synthesis of the vertical hydraulic conductivities for the Ordovician sediments. The measured pressures in the DGR boreholes were used to guide the work.

The depth of penetration of glacial meltwater was investigated in paleohydrogeologic simulations that included a comprehensive parameter sensitivity analysis.

The study design investigated the cause of the abnormal pressures observed in the Ordovician sediments. The computational model FRAC3DVS-OPG was used to simulate saturated flow while TOUGH2-MP was used to investigate the impact of the presence of an immiscible gas phase.

FRAC3DVS-OPG was used in numerical experiments to investigate “what if” scenarios, for example, to assess the impacts of enhanced Precambrian surface hydraulic conductivities on DGR and groundwater system performance measures.

The impact of boundary condition conceptualization on DGR performance measures was specifically investigated (slide #17). Two conceptual models were used for the work with multiple scenarios being developed for each. The boundary conditions for site scale analyses were defined using both the embedment and the nested model approaches. Both lateral and surface boundary conditions were varied in the study.

The site-scale analyses were developed to investigate the impact on the DGR of hypothetical transmissive fractures that vertically connect the permeable Cambrian sandstone and the Niagaran dolomite. Data for the DGR site were used to guide the work.

The study design also included parameter sensitivity studies to explore the impact of parameter perturbations on groundwater system barrier and repository performance.

2.2.4 Hydrogeologic Model – Spatial Scales

The four conceptual models that were developed in the study design are highlighted in slide #18. The conceptual models include a regional-scale domain of more than 18,000 km^2 that extends from the deepest parts of Lake Huron and Georgian Bay to the eastern edge of the surface water basin in which the DGR is located. The site-scale model has an area of approximately 400 km^2 and a finer spatial discretization. The Michigan Basin cross-section extends from the Algonquin Arch to Wisconsin and includes the deepest layers in the basin. The fourth conceptual model investigated fluid flow and solute transport in one-dimensional columns representing the DGR site (TOUGH2-MP only).

The numerical model discretization shown in a block cut view on the right-hand side of slide #19 explicitly used all of the 31 stratigraphic layers identified in the 3-DGFM shown on the left-hand side of the slide. The result is a reasoned representation of the regional hydrostratigraphy

2.2.5 Uncertainty Assessment

An important aspect of the design of the numerical modelling study was the use of the laboratory and field data gathered at the DGR site to constrain and guide the selection of model parameters. This minimizes the impact of parameter uncertainty on the study performance measures. Important parameters include the horizontal hydraulic conductivities estimated from in-situ straddle packer tests in the DGR boreholes as summarized on slide #20. These results from these tests provide confidence in the hydraulic conductivities used in the model.

The simulation of density-dependent flow requires estimates of the total dissolved solids (TDS) distribution in all of the hydrostratigraphic layers. TDS data were obtained from the DGR rock core pore fluid analyses and groundwater sampling. The measured TDS distribution for the DGR is shown on slide #21. The methodology used to calculate fluid densities minimizes the impact of parameter uncertainty on the system performance measures.

Further minimization of the impact of parameter uncertainty was provided by using the geomechanical properties for the various horizons occurring at the DGR. Young’s moduli and Poisson’s ratios obtained from geomechanical tests were used to estimate storage coefficients and the one-dimensional loading efficiency that is used to simulate the hydro-mechanical effect of glacial loading on fluid migration.

Tortuosity is an important parameter in the estimation of solute diffusion. Data from the University of New Brunswick diffusion experiments were used to estimate tortuosities and effective porosities of the rock.

The observed formation pressure profile in the DGR boreholes, shown on slide #22, was used to estimate vertical hydraulic conductivities for the Ordovician sediments. The vertical line in the figure is the head expected based on the surface elevation at the DGR site. Heads greater than this expected value, as occur in the Cambrian sandstone, indicate over pressurization. Heads less than the expected value, as occur in the Ordovician sediments that are the host rock for the DGR, indicate under pressurization.

2.2.6 Model Simulations – Solute Transport

All scenarios of the study design investigated porewater migration within in the Ordovician sediments. Peclet numbers for each scenario support the conclusion that solute transport in the Ordovician sediments is diffusion dominant. Mean Life Expectancies, which is a measure of the time that it will take a solute to migrate to a discharge point, were greater than 100 million years. The MLE for the regional-scale model are illustrated on slide #23. Confidence in the assessment that solute transport in the Ordovician sediments is diffusion dominant is provided by the sensitivity analysis developed in the study design.

2.2.7 Calibration – Hydraulic Gradients

Confidence in the study results is provided in calibration whereby model results are compared to observed data such as the formation pressures in the DGR boreholes and environmental tracer concentrations from core analyses. An upward gradient is observed in the Shadow Lake, Gull River and Coboconk units. This gradient cannot be preserved for more than 10,000 years unless the vertical hydraulic conductivity for the units is less than 10^{-14} m/s. Solute transport for such values is diffusion dominant.

The preservation of the observed under-pressures also requires low vertical hydraulic conductivities. The dissipation of the under-pressures with time is shown in slide #24 for an analysis that assumed saturated flow. It will take millions of years for full dissipation to occur. Solute transport remains diffusion dominant throughout the Ordovician sediments.

2.2.8 Calibration – Paleohydrogeologic

The results for the ten paleohydrogeologic simulations included in the study design are shown on the right-hand side of slide #25. Also included in the slide are the observed pressures in the DGR boreholes. The left-hand side figure is the 120,000 year glaciation realization from the University of Toronto Glacial Systems Model that includes the variation of ice thickness and the depth of permafrost formation. The 3-dimenisonal paleohydrogeologic model was unable to generate the observed formation under-pressures within the Ordovician sediments. Confidence in this conclusion is provided by the 10 simulations developed in the study design. The hydrogeologic modelling study calibration investigation showed that the under-pressures could be described by the presence of a gas phase.

2.2.9 Calibration – Anomalous Formation Pressures

The simulated environmental and freshwater heads at the location of the DGR-2 borehole from the cross-section analysis of saturated flow in the Michigan Basin are shown on slide #26. The physics represented in the model does not permit the simulation of the under-pressures. Confidence in the conclusion that the over-pressures in the Niagaran and the Cambrian are related to topography, geometry and fluid density variation in the basin is provided by the fit of the model to the measured heads. The Niagaran is point A in the figure. The Cambrian is point B.

2.2.10 Calibration – Hypothetical Fracture

Hypothetical vertical fractures proximal to the DGR that connect the Cambrian sandstone and the Niagaran sediments were found to be inconsistent with the pressures observed in the DGR boreholes. As shown in slide #27, the observed upward gradient between the Cambrian and Niagaran would result in flow to the Niagaran (point A) from the Cambrian in the hypothetical fracture and the prediction of higher pressures in the Niagaran than those observed at the site. Consistent with literature, the anomalous pressures require low vertical hydraulic conductivities. The presence of transmissive fractures is inconsistent with this observation.

The comparison of the model results with observed data provides calibration.

2.2.11 Confidence Assessment

The confidence assessment for the design of the hydrogeologic modelling study that used FRAC3DVS-OPG is listed on slide #28.

Model uncertainty was investigated using two different computational models: FRAC3DVS-OPG was used for the simulation of saturated density-dependent flow with and without mechanical coupling; TOUGH2-MP was used to investigate water and gas flow (discussed in Section 2.2.2).

The impact of parameter uncertainty on performances measures such as advective velocity, mean life expectancy and Peclet number was investigated by sampling the parameter space and by the investigation of alternate conceptual models and alternate descriptions of the model boundary conditions.

The hydrogeologic modelling study was designed using an issues-based approach that addressed hypotheses and “what if” scenarios. At all stages of the work, the study outcomes were compared to the field and laboratory derived data for the DGR site to establish confidence in the interpretation of groundwater system understanding and behaviour.

Finally, confidence in the overall modelling study outcome is provided by independent multiple lines-of-evidence (geology/hydrogeochemistry/geomechanics) described in the DGR Geosynthesis that are directly used to constrain, check and assess the reliability of the modelled scenarios and their contribution to groundwater system understanding.

Slide #29 presents a table that summarizes evidence from the approach and design of the modelling study that has contributed confidence to an understanding of groundwater system properties and behaviour relevant to DGR safety. A key finding is that mass transport within the Ordovician sediments that host the DGR has remained diffusion dominated.

2.3 TOUGH 2-MP

The purpose of this model work program was to test the hypothesis that the observed formation under-pressures in the Ordovician sediments can be described by the presence of an immiscible gas phase in the low-permeability rock (slide #31). To test the hypothesis, sensitivity analyses were performed that included the investigation of alternate conceptual models to constrain an understanding of the gas and water phenomena and the system attributes that are necessary to generate and preserve the under-pressures in the Ordovician sediments observed in instrumented DGR boreholes.

The TOUGH2-MP computational model describes multi-phase, multi-compositional flow in porous and fractured media (slide #32). The phases that are considered are water and gas as described in the equation-of-state module EOS3. Groundwater flow is considered density independent for the analyses.

As stated in the lower half of slide #32, the TOUGH model, developed by Karsten Pruess of the Lawrence Berkeley Laboratory, was released in 1991. TOUGH2-MP is the parallelized version of the code. The state-of-the-art model is used extensively worldwide for the analysis of multi-phase flow. It is the model of choice for nuclear waste isolation studies that include a separate gas phase. Lawrence Berkeley Laboratory has verified the model and continues to develop and support the TOUGH family of codes.

2.3.1 Modelling Approach

In the hydrogeologic modelling study, TOUGH2-MP was used to evaluate water and gas flow in a one-dimensional column between the Cambrian sandstone aquifer and the Niagaran aquifer. The bedrock stratigraphy matches that observed in borehole DGR-2. The permeability for the sedimentary rock was defined using the DGR straddle packer hydraulic conductivity estimates and the fluid densities estimated using laboratory-derived pore fluid TDS concentrations in the

Ordovician and Silurian rock. The capillary pressure versus saturation relationships were developed for each rock type from the petro-physics tests of the DGR cores. The figure on slide # 33 depicts these relationships. It is significant that the Ordovician sediments have high entry pressures for the drainage curves shown. The design of the study minimizes the impact of parameter uncertainty.

Other important parameters are the rock dependent diffusion coefficients and tortuosities. These were developed from the University of New Brunswick diffusion studies. Higher values will allow the gas to dissipate more quickly both in the gas phase and in solution. The presence of a gas phase acts as a natural analogue for the diffusion process.

In summary, the TOUGH2-MP analyses used the data of the DGR field and laboratory studies as described in the DGR Descriptive Geosphere Site Model (INTERA 2011).

2.3.2 Hypothesis Testing – Multiple Scenarios

As stated in slide #34, the single hypothesis tested in the study is that "the under-pressures observed in the Ordovician sediments are the result of the presence of an immiscible gas phase in the low-permeability, low-porosity rock matrix". Supporting the presence of a gas phase are the geochemical data indicating that solution methane concentrations are either at or near saturation concentrations in some horizons in the Ordovician sediments.

Four scenarios were developed to explore and test the hypothesis. These scenarios involved two different mechanisms for the source of the gas. The first is the assumption of initial gas saturation and its redistribution in the column in geologic time. The second source model considers that the gas was slowly generated in geologic time between the Coboconk and the Queenston Formations and redistributed in the column. Each source model also investigated the occurrence of a discontinuity of the capillary pressure versus saturation relationship in the rock. The design of the study provides a model uncertainty analysis.

Confidence is provided by comparing the simulated heads with the measured values – the essence of model calibration. The best-fit results between the measured pressures in the DGR boreholes and the results for the analysis of an initial gas saturation of 17% that has been redistributed (slide #35). As geologic time progresses, all of the gas would eventually diffuse from the column. The time for the complete removal of all of the gas is dependent on both the gas and the water phase diffusion coefficients.

Slide #36 presents the best-fit results for the testing of the hypothesis with a gas generation source. As in the previous case, the model calibration fit between the measured pressures and the TOUGH2-MP simulated pressures supports the hypothesis that the presence of a gas phase could lead to under-pressures. As in the previous case, the dissipation of the gas is sensitive to both the rock mass permeability and gas diffusion coefficients. As stated previously, higher values of both lead to quicker dissipation of the gas to the Cambrian and the Niagaran. A gas phase can only occur for long periods of time if transport processes are minimized.

In the final case shown (slide #37), the observed pressures are compared in model calibration to the case where there is a discontinuity in the rock of the capillary pressure versus water saturation relationship. That is, different relationships are assumed for adjacent layers of the rock. A gas phase will more readily enter the rock if the air entry pressure is lower. This results in the accumulation and trapping of gas in pockets that have a lower capillary pressure and hence higher water pressure as shown by the spike to the right in the figure. The occurrence of pockets of trapped gas is important as they would lead to further impede vertical migration of solutes.

2.3.3 Confidence Assessment

A confidence assessment for the TOUGH2-MP groundwater system analysis is provided in slide #38. The model outcome is a comparison of the model results to observed under-pressures in the Ordovician sediments. Confidence is provided by the study design and in model calibration by comparing the model results to the measured pressures in the DGR boreholes. The four scenarios investigated using the state-of-the-art computational model TOUGH2-MP support the hypothesis that the presence of a gas phase can provide an explanation for the under-pressures observed in the Ordovician sediments. It is important to note that a gas phase of only a few percent saturation is sufficient to preclude glaciation as an explanation of the under-pressures. The FRAC3DVS-OPG study design and published literature support this conclusion. Slide #39 presents a table that summarizes the contribution to confidence that is provided by the multiple lines of evidence.

2.4 MIN3P

This section describes numerical modelling efforts taken to develop and test an interpretation, or conceptual model that can explain the natural environment tracer profiles (slide #41) observed within the sedimentary sequence beneath the Bruce nuclear site. Studying the distributions of these tracers in the groundwater and porewater provides a site-specific natural analogue for solute-transport processes that have been operative in the system over geologic time. The natural tracers examined include chloride and bromide ions, and the oxygen and hydrogen isotopes that form part of the water molecule.

The assessment of the geologic, hydrologic and geochemical data indicates that solute transport in the Ordovician stratigraphic units enclosing the repository level has been controlled by diffusion. The purpose of the MIN3P modelling was to provide a quantitative assessment of this hypothesis. The principal objective of the modelling was to develop an understanding of the time scale required to generate the natural tracer profiles by diffusion.

2.4.1 Fundamental Aspects of the Model

The MIN3P model was developed by Professor Ulrich Mayer during his PhD research program at the University of Waterloo (slide #42). Dr. Mayer is now a professor at the University of British Columbia, Department of Earth and Ocean Sciences. It is a numerical finite-volume model for simulating transport and reaction processes in groundwater. It can solve problems in one, two or three dimensions. Dr. Mayer first published details of the model development in 2000 and it has been under continuous development since that time. The current version is MIN3P v NWMO. The model has a broad list of capabilities that can be broadly categorized into physical and chemical processes. The integration of physical and chemical processes allows simulation of solute transport coupled with geochemical reaction processes – generally known as reactive transport.

The present use of MIN3P for simulating non-reactive tracer diffusion is a relatively simple application and does not require the full model capabilities.

The academic community requiring the use of high-end reactive transport modeling is small, but since 2000, over 50 peer-reviewed journal papers have been published with MIN3P (slide #43). In addition there are many peer-reviewed conference papers, book chapters and graduate theses. Worldwide, there are now over 20 research groups using MIN3P.

2.4.2 Model Verification

Model verification is conducted with a set of standard problems for which output from MIN3P is compared to published results from the literature, or output from established analytical or numerical models (slide #44). For each MIN3P code enhancement, new verification examples are added. After each code enhancement, the complete set of verification problems is retested to confirm code behaviour.

At several stages of MIN3P’s development, Dr. Mayer has participated in international benchmarking exercises (slide #45). During the initial stages of development, Dr. Mayer participated in an international workshop at Pacific Northwest National Labs. In 2008, with the support of the NWMO, he participated in a reactive transport workshop in Strasbourg, France. He is planning to participate in the 2nd Subsurface Environmental Simulation Benchmarking Workshop in Taiwan later this year. MIN3P was successful at all of these events, and it is worth noting that MIN3P was the only model to successfully complete the benchmarking exercises in Strasbourg.

2.4.3 Modelling Approach

In the present context, MIN3P has been used for testing conceptual models by exploring the fit between the natural tracer data and the model output for variable diffusion times (slide #46). There is no effort to calibrate the model by adjusting formation parameters to achieve a fit to the measured data – the diffusion coefficients are included as measured. Also, it should be noted that the model has not been used for prediction of future system behaviour. The scientific method is at work here in that a hypothesis is developed based on consistency with prior information and the site characterization data. The hypothesis, as it relates to the diffusion time scale, must then be tested, and one way to do that quantitatively is to use the numerical model. After repeated testing, a hypothesis is gradually refined with the goal of arriving at a robust interpretation, or conceptual model to explain the natural tracer data.

In this layered stratigraphy with significant lateral continuity and large distances from side boundaries, diffusion simulations are conducted with a vertical 1-D domain. Numerical simulations of diffusive transport require a discretized domain with specific grid spacing; in this case 5 m spacing was used – a value chosen to be small relative to the formation thicknesses.

The model domain must be assigned one or more diffusion coefficients. In this case the diffusion coefficients were assigned as shown in slide #47 in order to capture the stratigraphic variability manifest in the laboratory measured dataset. These diffusion coefficients are very low in the international context, yet they are conservative in the sense that they are measured under ambient laboratory pressures and do not account for the in-situ confining pressure. Recent research indicates that confining pressure would cause a further 20 to 40% decrease in D_e values.

The numerical model requires the assignment of boundary and initial conditions for the natural tracers. Examples are provided in slide #48 for chloride and ^{18}O. The description that follows provides an explanation of the approach using the chloride tracer as an example. Knowledge of the geologic evolution of the basin tells us that halite-containing evaporite rocks have been present in the Salina Formation since the Silurian – approximately 430 million years ago. Accordingly, in the Silurian and above initial and boundary conditions were established with porewater chloride concentrations at saturation with respect to halite. Similarly, there is geologic knowledge suggesting that the Ordovician sediments accumulated under conditions with normal marine salinity. This knowledge constrains the initial chloride concentration as shown for the Ordovician portion of the stratigraphy. There is no knowledge of the initial chloride concentration in the underlying Precambrian, but it is assumed that the dense brine from the basin invaded to some depth in the crystalline rocks. A zero flux boundary condition is established 750 m deep in the shield – a depth sufficient to prevent an influence from the boundary condition on the simulation results in the Ordovician region of interest.

2.4.4 Assessment of Uncertainty

The time scale for diffusion as indicated by the modelling is obtained by running MIN3P within a parameter estimation code called PEST (slide #49). PEST runs MIN3P numerous times while systematically changing the diffusion time scale. A least squares approach is used within PEST to obtain the diffusion time that provides the best fit to the tracer data profiles. There is some uncertainty in the choice of diffusion coefficients, initial and boundary conditions. This uncertainty is addressed by conducting sensitivity analyses, which allows us to investigate the range of possible values for each parameter. Examples of the analysis of sensitivity to the initial conditions and lower boundary condition for ^{18}O are shown in slide #49.

With regard to the influence of uncertainty on confidence in the results, it is important to make a distinction between confidence in the model results and confidence in the overall system interpretation. The confidence table on slide #50 therefore shows one column for each.

In terms of confidence in the numerical model results, the principal sources of uncertainty are the designation of the initial and boundary conditions, and the in-situ diffusion coefficients. An attempt is made to minimize these uncertainties by constraining these parameters with many laboratory measurements (for diffusion coefficients) and by consideration of additional lines of evidence (for initial and boundary conditions).

The overall interpretation of the system is not based solely on numerical model results. The model results are considered to carry less weight than other lines of evidence such as hydraulic and geochemical properties of the system. Consistency between the model output and all other contributing data is considered the most important factor leading to confidence in the proposed conceptual model.

3.0 REPOSITORY EVOLUTION MODELLING

3.1 FLAC3D

One purpose of FLAC3D analysis of the repository evolution was to investigate performance of the shaft seals and evolution of the excavation damage zone (or EDZ) around the shaft for the time frame of 1,000,000 years subjected to perturbations such as glaciations, seismic events, gas generation from corrosion of waste packages and likely and conservative combinations of loading scenarios (slide #52). The analysis was carried out, using numerical code FLAC3D, for critical sections of the proposed DGR shaft and designed to explore and provide insight into: i) short- and long-term rock mass behaviour; ii) specific seal behaviour; and iii) the extent of the excavation damage zone.

3.1.1 FLAC3D – Fundamental Aspects

FLAC stands for Fast Lagrangian Analysis of Continua. The three-dimensional version of the code, FLAC3D V3.1 was used in the shaft seal and EDZ analysis (slide #53). FLAC3D is a widely used, explicit, finite difference three-dimensional code for advanced geotechnical analysis of soil, rock and structural response and design in geotechnical, civil, petroleum and mining engineering. FLAC, which is the two-dimensional version of the code, has 3687 users in 67 different countries and FLAC3D was developed and has been commercially available since 1994.

FLAC3D V2.1 was qualified in 2002 by U.S. DOE for use on Yucca Mountain project, U.S. program for geological disposal of high-level nuclear waste. The code has also been applied by a number of other international nuclear waste management programs, including France (ANDRA), Sweden (SKB), Finland (Posiva), Switzerland (NAGRA), Germany and Belgium (ONDRAF/NIRAS).

3.1.2 Modelling Approach

The bedrock stratigraphy intersected by the DGR shafts and the geometry and positioning of seal materials is provided in slide #54. The shaft seal system consists of one asphalt column (S1), three concrete bulkheads (B1, B2 and B3) and four bentonite/sand backfill columns. The analyses were conducted for the selected horizons, including those incorporating concrete bulkhead B1 and the asphalt column S1. Those horizons were selected as representative of the worst conditions for EDZ formation based on the rock unit’s thickness, physical properties and the in-situ stress, to which the unit is subjected. The geometry of the FLAC3D model for concrete seal B1 is illustrated in the expanded view in slide #54. Quarter symmetry is used for all loading scenarios except for the seismic loading. The size of the quarter-symmetrical model was 60 m × 60 m in plan-view and 80 m high.

In terms of the modelling approach adopted for the shaft seal and EDZ assessment, the FLAC3D analyses incorporated the following: i) Accredited laboratory data used to develop rock mass parameters for the shaft analysis; ii) Conservative assumption on long-term rock strength and concrete bulkhead seal degradation over a period of 100,000 years; and iii) Conservative assumption with respect to seal degradation, stabilizing confinement due to swelling pressure from geological units and backfill materials was excluded in the analysis. Further considerations included the following:

Constitutive and Time Degradation Models

Failure envelope for different formation/unit was developed and based on extensive laboratory testing data using GSI (Geological Strength Index) approach resulting in prediction of lower strength than that predicted by DISL (damage initiation and spalling) approach (slide #55).

Also, long-term strength degradation was developed based on static-fatigue tests on Lac du Bonnet granite and verified by long-term strength test data for Cobourg limestone. The approximation of the time-dependent strength degradation curve used in the model is shown in slide #55. It is conservatively assumed that the long-term strength, which is indicated by the vertical asymptote in the figure, is 0.40 of the unconfined compressive strength (UCS).

In-situ Stress

Horizontal in-situ stress for the entire profile was deduced from modelling with conservative assumptions. The model and predicted stress magnitudes were calibrated with stress measurements at the Norton mine (Barberton, Ohio) at depth of 670 m. The predicted stress profile for the maximum horizontal stress is shown in slide #56. The stress at the Norton mine is indicated as the blue dot. The predicted stress magnitudes are in line with and sometimes even exceeding the upper bound values interpreted from borehole observations where no borehole breakout was encountered. They also exceed the regional stress data. The approach produces conservative estimate of in-situ stress based on observed Bruce nuclear site borehole information.

Effective Stress – (Pore Pressure Evolution)

Effective stress calculation was conducted in which the pore pressure affects the strength of the rock. Pore pressure build-up due to gas generation (Base Case) from waste degradation was considered. The pore pressure data (Base Case) at various distances from the shaft center and as a function of time, as calculated in the repository-scale two-phase model, were input into the FLAC3D model. The considered pore pressures profiles at different times are shown in slide #57. The negative pressures are conservatively ignored.

Glacial Loading

Glacial loading was one of the loading scenarios considered in the analysis. A time history of the glacial event with maximum vertical ice loading of 30 MPa was selected from a series of 8 possible ice-sheet loading histories derived from the University of Toronto Glacial System Model (Peltier 2011). The time history is shown in slide #58. It is assumed that the next glacial event will occur 60,000 years in future. Horizontal-stress increase incorporated Poisson's effect and crustal bending under glacial loading. The analysis has shown that an increase in EDZ due to glacial loading is relatively small because of the confining effect of the shaft seals.

Seismic Loading

The shaft and the EDZ were analyzed for seismic ground motions (slide #59). Uniform Hazard Spectra were developed for ground motion for probability of 10^{-5} p.a. as base case and 10^{-6} p.a. as extreme case (AMEC GEOMATRIX 2011). Three combinations of the earthquake magnitude and distance were used to generate ground motions that match the uniform hazard spectra at each probability level. Each ground motion matches the uniform hazard spectra in different frequency ranges. The time histories of the ground motions for low, middle and high frequency ranges are shown on the left. For each seismic event, three orthogonal components of the ground motion were used for the model analysis. The shaft was analyzed for 10^{-6} p.a. events only.

Bounding Scenarios

A suite of 38 numerical simulations was conducted to cover expected and bounding load combinations and scenarios for different shaft sections. Predictions of the performance of shaft seals and extent of EDZ are provided for the following scenarios:

i) Time-dependent strength degradation (Base Case)
ii) Base Case + glacial loads
iii) Base Case + glacial loads + water/gas pressure
iv) Base Case + glacial loads + seismic loads

The shaft geological profile, the layout of the shaft seal arrangement, and shaft sections that were investigated for different load combinations and scenarios is shown in slide #60.

3.1.3 Confidence Assessment

The following are the reasons for the confidence in the FLAC3D results (slide #61):

Validation and Calibration (Model and Inputs)
i) In-situ stresses calibrated to observed borehole behaviour
ii) High glacial and seismic loading based on historical models
iii) Conservative constitutive models and lower bound strength based on sample test data and rockmass characterization
iv) Weakening behaviour with strain and time based on literature and test data.

Verification (Correctness of Code)

i) FLAC3D has extensive verification suite linked to known solutions
ii) Results verified by comparison to other codes (PHASE2).

Reliability (Management of Uncertainty)

i) Concrete assumed to degrade over 100,000 years
ii) Backfill stabilization ignored
iii) Combined loading cases considered
iv) Stabilization due to swelling ignored.

Another element of conservatism relates to the implementation of the FLAC3D results within Safety Assessment (SA) analyses. In SA analyses, the EDZ is assumed to have the maximum extent as predicted for the Cabot Head Formation along the entire length of the vertical shaft. As illustrated by the FLAC3D analyses, the extent of the EDZ varies along the length of the shaft. In this situation where the EDZ pathway is connected in series, it will be the lower bound estimate not the upper bound of EDZ geometry that governs vertical mass transport and system performance.

To further gain confidence in the model results, the FLAC3D results were compared with the results of another numerical code (Phase 2) and empirical estimates of breakout depths around the tunnels or shafts based on elastic stresses developed by Dr. Derek Martin, University of Alberta. The extent of the EDZ calculated using FLAC3D and depth of damage or breakout depth using other approaches are shown in slide #62. Comparison shows that FLAC3D results are in agreement or exceed the predictions using other approaches.

As shown on slide #63, overall there is a high level of confidence that the FLAC3D model has been developed and applied appropriately for the assessment of the DGR system.

3.2 FRAC3DVS-OPG

FRAC3DVS-OPG (version 1.3) simulates groundwater flow and the transport of contaminants, in this case radionuclides, through geologic media. In the Postclosure Safety Assessment, FRAC3DVS-OPG has been used to support the development of the AMBER and T2GGM assessment models.

For the postclosure safety assessment, FRAC3DVS-OPG was used with both triangular and brick-shaped elements. Adaptive time-stepping was used to reduce computation time.

FRAC3DVS-OPG is an OPG QA controlled version of the FRAC3DVS code. The development history and status of the model have previously been covered in the Geoscience Modelling presentation.

Slide #66 shows the main processes included in FRAC3DVS-OPG. It provides a stylized illustration of the site in the future for postclosure safety assessment. The FRAC3DVS-OPG model domain extends up to the water table as shown. The models simulate all significant groundwater transport pathways for dissolved radionuclides. These include diffusive transport in the low-permeability deep and intermediate bedrock and in the sealed shaft, as well as advective-dispersive transport in the higher permeability shallow bedrock.

Two different model discretizations were used in the assessment as shown in slide #67.

The primary model is a detailed 3-D model that includes a repository representation consistent with the preliminary repository design (referred to as the “3DD” model). The model extends vertically from the top of the Cambrian formation to the top of the Salina G and thus includes all the Ordovician and Silurian units at the site. Hydraulic gradients are predominantly vertical within this domain, with horizontal gradients indicated only within three thin permeable units (Cambrian, Guelph, and Upper Salina A1).

The second model is a 3-D model of the surface units (referred to as the “3DSU” model) where flow is horizontal, driven by hydraulic gradients towards Lake Huron. The model includes the Devonian bedrock units, but not the surface till. It also includes a water supply well located down-gradient from the shaft. This model was used to determine the well capture percentage for any radionuclides transmitted through the shaft to the surface system.

The 3DD model is shown in the figure in slide #68. It contains several simplifications of the preliminary repository design:

- The ventilation and main shaft have been combined to form a single shaft of equal cross-sectional area.
- The emplacement rooms have been combined to form connected panels of equal volume.
- The ventilation and access tunnels have been schematically straightened to be generally orthogonal.
- Details around the shaft station have not been included.

These changes simplify the numerical modeling, but are not expected to have any influence on the results.

The access tunnels and waste panels are vertically extended 10 m to include rockfall. Conservatively, this has been assumed to occur instantaneously at closure rather than coincident with a future glacial event. Rockfall does not occur over the area supported by the concrete monolith extending from the shaft. There is, however, a higher-permeability damaged rock zone present surrounding the monolith.

The figure in slide #69 portrays the 3DSU model domain for the shallow groundwater system model. The horizontal extent in the X direction originates 500 m up-gradient of the shaft and extends approximately 2 km to just beyond the Lake Huron shoreline, covering the shallow flow system that would be impacted in any radionuclide release from the shaft.

The water supply well extends to a depth of 100 m and is located 500 m down-gradient from the nominal shaft location. At greater depths, the water becomes brackish and not potable. The downstream distance from the shaft was selected to capture contaminants from the expanding plume as it moved downstream, should there be release through the shaft.

The upper shaft itself is not explicitly incorporated in the model as it has a hydraulic conductivity similar to that of the upper rock formations.

Boundary head conditions are specified to force a groundwater flow direction parallel to the X axis and towards Lake Huron. Hydraulic and transport properties of each formation and head gradients were as specified in the Descriptive Site Geosphere Model.

Slide #70 shows the key initial conditions assumed in the 3DD model - in particular, the rock formation hydraulic conductivities and the initial head conditions. The data are derived directly from the site characterization program, especially the Descriptive Geosphere Site Model (INTERA 2011). The figure shows that all the rock formations within the model domain are included within the model.

Hydraulic pressures measured at site have been converted into environmental head to account for the effect of the fluid column density variations on hydraulic head gradients. An under-pressure in the middle of Ordovician rock formations is apparent, as is the Cambrian formation over-pressure at the bottom of the model.

Fixed pressure boundary conditions at the top and bottom of the model were specified based on the measured Cambrian and Salina G heads respectively. The side boundary conditions were set to “no flow”. These boundary conditions support a vertical gradient in this system, and maximize the potential impacts at the site.

There were no model calibration parameters. All variables affecting flow and transport within the rock mass are derived directly from site characterization results, specifically the Descriptive Geosphere Site Model (INTERA 2011) and supporting reports. In particular:

- Formation hydraulic conductivity values were derived from formation averages calculated from straddle packer testing in boreholes DGR1 through DGR6.
- Porosity and diffusion measurements are formation averages of testing on rock cores from DGR boreholes. Storage coefficients were calculated from formation average porosities and rock compressibilities calculated from measured geo-mechanical parameters
- Initial heads are the pressures measured at site in the Westbay system, converted to environmental head.

The figures on slide #72 present example results for the NE-RC (or reference case simulations). The figures portray the concentration of Chlorine-36 at various times. This is a potentially important radionuclide since it is long-lived and non-sorbing. The concentration in the repository at closure is calculated assuming all Cl-36 present in the waste dissolved instantaneously in a fully-saturated system.

The 3-D figure on the left-hand side shows the extent of transport at 1 Ma. This concentration contour is approximately equivalent to an annual 1 μSv dose if it was used for drinking water. This is much less than criteria, and also this water is too saline to drink. The figures on the right show a vertical cross-section through the repository and shaft and the associated concentrations at 50 ka, 100 ka, 500 ka, and 1 Ma. In all cases it is clear that radionuclides have not travelled far from the repository, due to the almost total lack of advection in the system. Diffusion is the dominant transport mechanism. This is consistent with the conclusions from the Geosynthesis for the host rock.

Confidence in the FRAC3DVS-OPG model has been described in the previous presentation on this code in the Geoscience Modelling presentation. Slide #73 describes confidence in the modelling of the DGR.

Numeric testing was performed to determine appropriate model convergence criteria. Mass balances of simulation results were calculated to ensure the simulation results were numerically correct.

QA procedures were applied to model input data. Parameter values in model input files were compared to source values by checkers who were not involved in creation of the input files. Reports and approaches were peer reviewed.

Finally, simulation results were compared to spreadsheet calculations for simple cases.

The figures in slide #74 compare head profiles for steady-state (NE-SBC) and transient (NE-RC) flow models as calculated by T2GGM and by FRAC3DVS-OPG. Steady-state results are identical. Transient results are shown at 100 ka in the bottom figure. The results differ at the top of the figure only, due to the different vertical extent and top boundary condition of the two models. Within the Ordovician below the Manitoulin formation, the results are very comparable.

Sources of uncertainty in the FRAC3DVS-OPG modelling can be categorized as related to:

1. the model parameterization;
2. the repository conceptual model; and
3. the geosphere conceptual model.

For the most part uncertainties are addressed by using conservative assumptions and sensitivity cases. The categories are dealt with on slides #75 and #76.

The parameter uncertainties are largely addressed by sensitivity cases. These are summarized in Figure 3-1 of the Postclosure Safety Assessment: Groundwater Modelling report (GEOFIRMA 2011). Key parameter uncertainties are addressed as follows:

- First, the geosphere formation permeabilities are derived from the measurements in boreholes DGR-1 through DGR-6. One sensitivity case evaluated the impact of 10x higher vertical permeability.
- Second, the excavation damaged zone or "EDZ" serves as a potential path for radionuclide transport from the repository to the biosphere. The radial extent of the EDZ is conservatively set equal to the shaft radius based on FLAC3D model results as presented earlier in this Technical Information Session. It is subdivided into two zones, an inner and outer EDZ with permeability multipliers of 100x and 10x the rock permeability, respectively. There is a sensitivity case (NE-EDZ1) where higher multipliers are used, including 10,000x for the inner EDZ.
- Radionuclide transport is diffusion dominated in the low-permeability host rocks. A sensitivity case with increased diffusion (NE-AN2) addresses uncertainty in this parameter.
- The characteristics of the seal materials have been selected from the lower end of the expected performance range, i.e., the upper end of range of permeabilities. Additional sensitivity cases with higher permeabilities have been simulated. A disruptive scenario with a much higher permeability than would be expected has also been tested.

The repository conceptual model uncertainty refers to the imprecise knowledge of the conditions within the repository. These are addressed through conservative assumptions as follows:

- First, since the timing of the rockfall within the repository is uncertain, it is assumed to occur immediately upon closure, even though it is most likely to occur at much later time. The main effect of this is to increase the effective height of the repository and tunnels.
- Within this FRAC3DVS-OPG model, the repository evolution is not modelled in detail. The entire waste inventory is assumed to dissolve instantly in a fully-saturated repository upon closure. Although most of the waste is containerized when placed in the repository, there is no credit given to the container for isolation. This maximizes the potential for release of radionuclides into the water and for their groundwater transport from the repository.
- For the normal evolution cases, gas generation is expected to substantially delay resaturation and thus limit the opportunity for waste to dissolve in liquids and be made available for groundwater transport. Gas generation impacts are addressed comprehensively in the T2GGM modelling.

The geosphere conceptual model uncertainty refers to the imprecise knowledge of the conditions that may affect fluid flow and radionuclide transport within the geosphere. These uncertainties are discussed and evaluated within the site Geosynthesis. The postclosure safety assessment modeling is based on the reasoned expectations described within the Geosynthesis documents. Particular aspects that could impact the FRAC3DVS-OPG results include:

- Ordovician underpressures - Pressures measured in the DGR boreholes indicate that the Ordovician system is under-pressured relative to hydrostatic. This under-pressure is believed to be remnant from historical processes as described in the Geosynthesis. The reference case (NE-RC) assumes that the under-pressures are present and will dissipate towards a steady-state system with time. The simplified base case (NE-SBC) conservatively assumes that the system at repository closure will be in a steady-state, and the under-pressure has fully dissipated.
- Cambrian over-pressure – This pressure is specified as constant on the basis of Michigan-basin-wide modeling results from the Geosynthesis program.
- Gas saturations in Ordovician rock – Testing on DGR cores has indicated that the Ordovician formations may contain free-phase gas at saturations approaching 20%. Gas saturations are not included in the fully liquid saturated FRAC3DVS-OPG simulations, but are included in the T2GGM simulations described in a subsequent presentation.
- Regional flow in permeable units – Hydraulic heads measured within the permeable units (the Cambrian, Guelph, and Salina A1 Formations) show gradients that indicate the presence of slow regional flow. These flows would serve to divert any radionuclides transported up the shaft and prevent them from reaching the biosphere. They have been conservatively ignored in the reference case and simplified base case. A sensitivity case (NE-HG) evaluates the effect of these horizontal flows.

Results of all sensitivity cases are compared in slide #77. In these cases, Cl-36 was modelled as it is a potentially important radionuclide. With one exception, all sensitivity cases show the flux of Cl-36 to the shallow groundwater system is less than the background rate of Cl-36 deposition to surface from natural sources. The exception is a very unlikely disruptive event case where an exploration borehole penetrates the repository and the underlying pressurized Cambrian formation, and is then not properly sealed.

More generally, the sensitivity case results show that transport is diffusion dominated in the deep rock formations, consistent with evidence from site characterization. Therefore, release to surface requires an enhanced permeable pathway such as a borehole. The detailed results also showed that the underpressure in the Ordovician sediments acted to reduce the flow of any radionuclides to surface.

In summary, FRAC3DVS-OPG has been used to model groundwater and contaminant transport in the repository, shaft and geosphere. The model does not include gas generation or transport, and so is not a primary code for postclosure assessment, but provides support to the primary T2GGM and AMBER codes.

Confidence in the model and results is provided by:

- use of the widely-accepted FRAC3DVS code.
- use of input data derived from the site characterization program.
- development under a formal QA system, with peer review at interim and final stages

- comparison of model results with other codes.
- uncertainties have been addressed using conservative assumptions and over 16 sensitivity case calculations.

Overall, there is a high level of confidence t that the FRAC3DVS-OPG model has been developed and applied appropriately for the assessment of the DGR system..

3.3 T2GGM

The T2GGM code has been developed to provide an integrated approach to modelling gas generation and consumption reactions in the repository, and the flow of gas and groundwater in the geosphere and engineered barrier system. Results include repository and shaft saturation.

T2GGM combines TOUGH2 and GGM. TOUGH2 is an industry standard numeric code for two-phase (gas and liquid) flow while GGM is a DGR-specific code.

TOUGH2 uses an integrated finite difference method approach to spatial discretization of the domain. GGM treats the repository as a single compartment model. GGM is a code module that is linked into and runs under TOUGH2.

Slide #82 illustrates the linkage between the TOUGH2 and GGM codes. TOUGH2 models the entire geosphere and repository domain. It calculates gas and groundwater movement in the shaft and geosphere, and the geosphere and repository pressures and saturations. TOUGH2 treats the repository as a single compartment.

The average repository pressure and saturations are passed to GGM at the beginning of a time step. GGM calculates gas generation and water consumption that will occur over the following time step according to the waste inventory and reaction conditions. The gas and water flow rates are then returned to TOUGH2 where they are incorporated in the pressure and saturation calculations for the time step.

TOUGH2 is a multi-phase and multi-component flow code. It includes advection and diffusion transport, and can be isothermal or nonisothermal.

It consists of a main program which is linked with an Equation of State module which defines the processes included. T2GGM uses EOS3, the module for water and air. There are single processor and multiple processor solver versions of the code. The multiprocessor code TOUGH2-MP was described earlier in the Geoscience Modelling presentation. The single processor version was used here in T2GGM. Apart from the solver approach, the single processor and multiprocessor codes are functionally identical.

TOUGH2 is provided in source code form that allows modification by the user. In addition to integrating GGM, EOS3 was extended to work with gases other than air, and a 1-D Hydro-Mechanical capability was added. This Hydro-Mechanical module was implemented using an approach similar to that in FRAC3DVS-OPG.

A fundamental assumption with TOUGH2 is Darcy flow of gases and liquids - i.e., non-turbulent flow of gas and liquids defined by permeability and pressure gradient. It also assumes a capillary pressure relationship between gas and liquid pressures, where capillary pressures are a function of saturation. This results in a non-linear system of equations.

GGM models gas generation reactions that are expected to occur within the repository. The repository is modelled as a single, fully connected, void of specified volume.

It is focused on the key processes that are potential sources of gas due to microbial and corrosion reactions. It also tracks water consumption. Microbial processes include the generation and decay of biomass.

At repository closure, the GGM is provided with an initial inventory of waste and package materials. Reactions proceed as conditions allow. For example, some reactions occur only when sufficient water or water vapour (as indicated by relative humidity) is present.

GGM tracks the amount of waste material, corrosion products and gases within the repository to ensure mass balance. It accounts for gas and water flows to and from the repository, into either the geosphere or shaft.

GGM includes over 30 reactions. The reactions and kinetics are described in detail in the T2GGM Software Documentation (QUINTESSA and GEOFIRMA 2011).

The key processes in the DGR are exothermic (i.e., energy releasing) reactions that occur under anaerobic conditions. These are as noted qualitatively on slide #85:

- Microbial degradation of organic waste materials yielding CH_4 and CO_2;
- Methanogenesis consuming H_2 and CO_2 and yielding CH_4;
- Anaerobic metal corrosion yielding H_2; and
- Enhanced corrosion of carbon steel in the presence of high-levels of CO_2, yielding H_2.

The T2GGM models simulate all significant transport pathways for bulk and dissolved gas. Bulk gas movement is limited primarily to the repository and engineered barrier system. Dissolved gas also diffuses into the low-permeability deep and intermediate bedrock.

In the modeling presented in the Postclosure Safety Assessment, T2GGM was only applied in the intermediate and deep geosphere. Gas transport in the in the higher permeability shallow bedrock was included in the AMBER DGR model.

Three different T2GGM model spatial discretizations were used, as shown in slide #87.

The primary model is a detailed 3-D model that includes a repository representation consistent with the preliminary repository design (referred to as the “3DD” model). A second 3-D model included a simplified representation of the repository that was used for certain sensitivity cases and to verify the detailed model (it is referred to as the 3DSRS model). The 3-D models extend vertically from the top of the Cambrian formation to the Guelph Formation, and thus include all the Ordovician units at the site. This range provided sufficient discretization to model transport in the low-permeability formations, while avoiding computation time issues associated with including the permeable Guelph and Upper Salina A1.

The lateral extent of the model was approximately 5 by 4 km, so extends well beyond the repository boundary. The rock formations were modelled as horizontally flat, consistent with the low slope of the stratigraphy, and the importance of vertical over horizontal transport from the repository.

The 2-D shaft model encompasses the entire Ordovician and Silurian sequence, up to the shallow groundwater system. This model was used to determine the fate of gas in the shaft for any cases that showed gas flow up the shaft. As a 2-D model, it contained a significantly reduced number of nodes compared to the 3-D models and therefore was not subject to the same computation time limitations.

The 3DD model is shown in the figure in slide #88. It contains several simplifications of the preliminary repository design:

- The vent and main shaft have been combined to form a single shaft of equivalent cross-sectional area.
- The emplacement rooms have been combined to form connected panels of equivalent volume.
- The ventilation and access tunnels have been schematically straightened to be generally orthogonal.
- Details around the shaft station have not been included.

These changes simplify the numerical modeling, but are not expected to have any influence on the results. In all cases, the void volume associated with these features has been incorporated to ensure correct gas pressure calculations.

The access tunnels and waste panels were vertically extended 10 m to include rockfall. Conservatively, this has been assumed to occur instantaneously at closure rather than coincident with a future glacial event. Rockfall is not included over the area supported by the concrete monolith extending from the shaft. There is however a higher-permeability damaged rock zone present above and below the monolith.

Slide #89 shows more detail of the shaft model. These two figures present a vertical cross-section through the repository. The left figure is to scale; it also shows the vertical limits of the 3DD model domain to the Guelph formation. Note that although four colors are used to illustrate the formations, all individual rock formations are actually present in the discretization and have separate property assignments.

The expanded scale on the right figure uses 10:1 horizontal exaggeration to clarify the shaft seal and excavation damaged zone (or “EDZ”) details. The EDZ is implemented as two rings surrounding the shaft, an inner EDZ and an outer EDZ. Permeabilities in the inner EDZ are increased by a factor of 100 relative to the intact rock, while outer EDZ permeabilities are increased by a factor of 10. The extent of the EDZ is illustrated by shading in the figure, and is conservatively modelled as equal in thickness to the shaft radius, throughout the entire shaft column.

Slide #90 shows the key initial conditions assumed in the 3DD model, in particular, the rock formation hydraulic conductivities and initial pressure conditions. The data are derived directly from the site characterization program, especially the Descriptive Geosphere Site Model (INTERA 2011). The figure shows that all the rock formations within the model domain are explicitly included in the model.

Hydraulic pressures measured at site have been converted into environmental head to account for the effect of the fluid column density variations on hydraulic head gradients. An under-pressure in the middle of Ordovician rock formations is apparent, as is the Cambrian formation over-pressure at the bottom of the model.

Fixed pressure boundary conditions at the top and bottom of the model were specified based on the measured Cambrian and Guelph pressures respectively. The side boundary conditions were set to “no flow”. These boundary conditions support a vertical gradient in this system, and maximize the potential impacts at the site.

The repository and shaft were fixed at atmospheric pressure for the first 60 years, representing the operating period, and then were allowed to evolve naturally.

There were no model calibration parameters. All variables affecting flow and transport within the rock mass are derived directly from site characterization results, specifically the Descriptive Geosphere Site Model (INTERA 2011) and supporting reports. In particular:

- Permeability measurements were derived from formation averages calculated from straddle packer testing in boreholes DGR-1 through DGR-6.
- Porosity, diffusion, rock density and pore compressibility measurements are formation averages of testing on rock cores from DGR boreholes.
- Two-phase flow parameters were calculated from parameter estimation routines applied to the van Genuchten equations on core petrophysics data.

Slide #92 presents example results for the reference case simulations. The upper figure shows gas partial pressures within the repository and the total gas pressure. The figure shows the long-term evolution of the repository gases towards methane-dominated conditions.

The second figure shows the mass balance of carbon in the system. This figure illustrates the long-term conversion of carbon, primarily from organic wastes, into methane gas.

Within the geosphere, gas and liquid move according to pressure gradients and permeabilities. Slide #93 shows details of the gas saturation, liquid pressure and flow directions around the shaft at 1000 years.

At this time, the shaft has nearly fully resaturated (full liquid saturation is shown as white) with the exception of the lower shaft and repository. Gas originally entrained in the shaft sealing materials at placement is moving down towards the low-pressure repository. There is liquid flow within the geosphere immediately adjacent to the shaft and repository driven by the high gradient between formation pressures and shaft pressures. Within the rock mass, there is virtually no flow due to the extremely low permeability.

Slide #94 describes the rationale for confidence in the code implementation.

The T2GGM code is largely based on TOUGH2, a widely-used code for modeling these phenomena. Within the radioactive waste community, TOUGH2 is the code of choice for modelling two-phase flow, and for assessing gas transport in DGRs. The background of TOUGH2 was described previously in the Geoscience Modelling part of this Technical Information Session.

Our confidence in T2GGM is also based on the processes used to implement and integrate GGM with TOUGH2. This work was conducted under ISO 9001:2008 registered quality assurance programs, with specific procedures to govern software development and numeric modelling. There are numerous unit test cases designed to verify GGM operation and integration with TOUGH2. QA procedures were applied to model input data. Parameter values in model input files were compared to source values by checkers who were not involved in creation of the input files. Finally, the reports and approaches were peer reviewed.

The NWMO is using T2GGM (primarily the gas transport TOUGH2 component) in a number of additional projects as described in slide #94. These comparisons with experiments and other computer codes provide further confidence in T2GGM.

Numeric testing was performed to determine appropriate model convergence criteria. Mass balances of simulation results were calculated to confirm that the results were numerically correct

Simulation results were compared to spreadsheet calculations for simple cases. This included pressures due to gas generation and flow rates for gas through unsaturated media.

Slide #95 shows the results of a comparison of the GGM module to the Finnish Gas Generation Experiment. This was a 10-year field study of gas generation from waste packages.

This figure shows the total gas generation with time from cellulosic wastes. The results showed that within a range of short-term cellulose degradation rates, reasonable agreement was obtained with experiment results for gas generation rate and composition.

Further confidence building exercises include comparison of results from different implementations and from other models.

In slide #96, the top figure compares T2GGM results for the detailed 3DD and simplified 3DSRS discretization models for three cases (NE-RC, NE-SBC, and NE-GG1). Each case is a different color. The two models are shown as a dashed and solid line, respectively. Results from the two models are very similar in each case, since the dashed and solid lines in each color (i.e., each case) largely overlap.

The lower figure compares T2GGM results with those from the FRAC3DVS-OPG code. Hydraulic head profiles for the transient (NE-RC) flow model at 100 ka are shown. They differ at the top of the T2GGM domain only due to the different vertical extent and top boundary condition of the two models. Within the Ordovician below the Manitoulin Formation, the results are very comparable.

Sources of uncertainty in the T2GGM modelling can be categorized as related to:

1) the gas generation model;
2) the repository model;
3) gas and water transport within the geosphere; and
4) the geosphere conceptual model.

The treatment of uncertainties with each category is addressed on slide #97 and following slides.

For the most part, uncertainties are dealt with by using conservative assumptions and sensitivity cases. The set of sensitivity cases is summarized in Figure 3-1 of the Postclosure Safety Assessment Gas Modelling report (GEOFIRMA and QUINTESSA 2011).

For the gas generation model, T2GGM uses simplifying but conservative assumptions that maximize gas generation. That is, rather than representing the full complexity of microbial and degradation reactions including interim products, the model focuses on the total degradation of the waste inventory into elemental gases. This is because of the importance of gas as a potential release pathway from the DGR.

An appropriate microbial population is assumed to be present within the repository environment at closure; either indigenous or resident in the wastes. In effect, it is assumed that if energy sources exist, microbes will take advantage of them. The impact of no microbial activity leading to methanogenesis is tested with a sensitivity case (NE-NM). The sensitivity to the reaction rates is tested by increasing and decreasing them in the NE-GG1 and NE-GG2 cases.

Most analyses have been run with reaction water consumption turned off (i.e., the Non-Water-Limited, or NWL cases). This conservatively assumes that more water is available to support the reaction than is calculated from the low-permeability rock.

Simulations with all gas generation processes turned off have also been performed; repository resaturation occurs within approximately 500 ka.

With respect to the repository model uncertainties:

- The potential effects of seismicity and glaciation loads are accounted for through rockfall, which is assumed to occur immediately upon closure and increase the vertical extent of the repository and tunnels.
- Although most of the waste is containerized when placed in the repository, there is no credit given to the container for isolation. The entire waste inventory is available for degradation immediately upon closure.
- The characteristics of the seal materials have been selected from the lower end of the expected performance range (i.e. the upper end of range of permeabilities). Additional sensitivity cases with further reduction in performance have been simulated. A disruptive scenario with a much higher permeability than would be expected has also been tested.

Another class of uncertainties is related to the parameterization of gas and liquid flow properties. Two-phase flow properties include both the choice of function describing capillary pressure and relative permeability and the parameterization of the function. Van Genuchten functions are widely used for low-permeability sedimentary rocks and are the most commonly used in international radioactive waste repository programs such as in Switzerland and France. The values used in the current work are derived from estimates obtained from inverse modelling where parameters are adjusted to fit curves to laboratory data obtained from DGR rock cores. A number of sensitivity cases were performed to determine the impact of variation in these values.

As mentioned previously, formation permeabilities are derived from the testing program in boreholes DGR-1 through DGR-6. A sensitivity case (NE-AN3) evaluated the impact of higher vertical permeability in all rock formations.

The excavation damaged zone or “EDZ” serves as a potential path for radionuclide transport from the repository to the biosphere. The radial extent of the EDZ is conservatively set equal to the shaft radius based on FLAC3D model results as presented earlier in this Technical Information Session. It is subdivided into two zones, an inner and outer EDZ with permeability multipliers of 100x and 10x the rock permeability, respectively. There is a sensitivity case (NE-EDZ1) where higher multipliers are used, including 10,000x for the inner EDZ.

The geosphere conceptual model uncertainty refers to the imprecise knowledge of the conditions that may affect gas and fluid flow within the geosphere. These uncertainties are discussed and evaluated within the site Geosynthesis report. The T2GGM postclosure safety assessment modeling is based on the reasoned expectations described within the Geosynthesis.

Essentially, the models are based on a reference case (NE-RC), which is based on the best understanding of the geosphere, or a simplified base case (NE-SBC), which is based on some conservative simplifications of the geosphere. In particular, the reference case includes the Ordovician under-pressures and the presence of some partial gas saturation in the Ordovician rocks. The simplified base case has no under-pressure (only over-pressure) and a fully saturated geosphere, conditions that tend to promote vertical transport.

In all cases, the Cambrian over-pressure is specified as constant in the models on the basis of Michigan basin-wide modeling results from the Geosynthesis.

Regional flow in permeable units – Pressures measured within the permeable units in the DGR boreholes show gradients that indicate the presence of slow regional flow. These flows would serve to divert any contaminants transmitted up the shaft, and have been conservatively ignored in this assessment. The importance was tested with a sensitivity case.

Vertical fault near repository – The Geosynthesis presents several lines of evidence that show that a conductive vertical fault near the repository is not consistent with site information. Consequently, such a fracture has not been included in the reference geosphere model. However, a “what if” scenario including a fracture has been evaluated separately with the FRAC3DVS-OPG code.

Some of the sensitivity results are illustrated in slide #100. This shows the repository pressure results from all Non-Water-Limited (NWL) cases. Although the timing varies, the peak pressures fall within a relatively narrow range near the steady-state formation pressure at the repository horizon. The main effect of the various uncertainties is in the timing of the pressure.

Another key result of the sensitivity analyses (not shown) is that there is some gas flow up the shafts at long times for certain sensitivity cases, notably those with higher gas generation or more permeable shaft seals. However, this does not move beyond the permeable Guelph Formation under Normal Evolution Scenarios. The impacts of this gas are included in the postclosure safety analyses conducted with the AMBER DGR code described later.

In summary, T2GGM modeling has been used to couple repository gas generation and liquid and gas flow within the geosphere and shaft to present a simulation of overall system performance to support the postclosure safety assessment.

Confidence in the model and results is provided by:

- the use of the widely-accepted TOUGH2 code as base;
- addition of a waste corrosion and degradation model with emphasis on gas generation;
- use of input data derived from site characterization;
- development under a formal QA system, including peer review of interim and final results;
- comparison of model results with other codes.
- comparison of results from different discretizations, and
- uncertainties have been addressed in a comprehensive manner with conservative assumptions and over 20 sensitivity case calculations.

Overall, there is a high level of confidence that the T2GGM model has been developed and applied appropriately for the assessment of the DGR system.

3.4 AMBER

The AMBER code is a general-purpose compartment modelling code that is developed and maintained by Quintessa Ltd. (UK). It provides a numerical framework for the user to implement their own specific model. It does not have a hard-wired model. The code is typically used to develop models of contaminant release, migration and impact in environmental systems. A DGR-specific model was developed for this project in Version 5.3 of the AMBER code.

The code adopts a compartment modelling approach, in which the system to be modelled is represented using a series of user-defined compartments. Contaminants are transferred between the compartments according to user-defined algebraic expressions. The code has two solvers for first order differential equations:

- a Laplace transform solver, suitable for use for models with non time-dependent transfers; and
- a time-step solver, for models with time-dependent transfers.

The AMBER code was first developed in 1993 and is now a widely-used, commercially-available code.

The key features of the code are as follows:

- It provides the user with the flexibility to specify the contaminants and compartments to be modelled.
- It allows the user to input their own algebraic expressions to represent:
    - time-varying properties and transfers;
    - contaminant concentrations and fluxes; and
    - the exposure of humans and other biota to contaminants.
- It also has an in-built ability to represent radioactive decay and ingrowth. The chain members and decay rates are input by the user.

- In addition, the AMBER code can be used to undertake probabilistic calculations and to analyze the associated results. Either Latin Hypercube Sampling or Monte Carlo Sampling can be used.

There are a number of factors that build confidence in the AMBER code.

- It has been managed and developed under Quintessa’s ISO 9001:2008 registered Quality Assurance system that incorporates the requirements of the UK TickIT software quality system.
- Each release of the code has been extensively tested against a broad set of verification tests which are documented in an associated report and provided with the code.
- The code is now used by over 85 organizations in more than 30 countries and there are more than 100 publications describing assessments in which AMBER has been applied, including:
    - international exercises involving code intercomparison, such as ISAM and BIOPROTA; and
    - other assessments of geologic repositories, such as the Swedish nuclear regulator’s (SKI) review of the safety assessment of the Swedish Nuclear Fuel and Waste Management Company’s Forsmark facility for the disposal of low and intermediate level radioactive waste. The models are documented in SKI Reports (Maul and Robinson 2002, Maul et al. 2004).

Documentation describing the AMBER code is available from Quintessa’s website (www.quintessa.org/software/amber).

A specific model has been implemented in Version 5.3 of the AMBER code to represent the postclosure contaminant release, migration and impacts from OPG’s DGR. This model is referred to here as AMBER DGR.

The implementation of the DGR model in AMBER has been supported by the FRAC3DVS-OPG and T2GGM detailed models, which were used:

- to identify contaminant transport pathways to be represented in the AMBER DGR model; and
- to quantify saturation profiles, gas composition, groundwater and gas fluxes, and well capture fraction used in the AMBER DGR model.

The AMBER DGR model is documented in:

- the Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario report (QUINTESSA 2011); and
- the Postclosure Safety Assessment: Analysis of Human Intrusion and Other Disruptive Scenarios report (QUINTESSA and SENES 2011).

Slide #107 summarizes the main repository, geosphere and surface environment (biosphere) processes and exposure mechanisms included in the AMBER DGR model for the Normal Evolution Scenario. It shows:

- the gradual resaturation of the repository;
- the partitioning of contaminants between liquid and gas phases in the repository;
- the diffusion of contaminants into the surrounding rocks;

- the diffusion/advection of contaminants into the shaft;
- the migration of the contaminants into the shallow groundwater system due to diffusion through the rocks, and diffusion and advection in the shafts;
- the release of contaminants into the surface environment via well pumping, groundwater discharge to the lake and gas flux; and
- the subsequent exposure of humans via ingestion, inhalation and external irradiation.

The key waste and repository assumptions in the model are:

- the repository resaturation rates are taken directly from T2GGM;
- no credit given to waste packaging as a physical or chemical barrier;
- instantaneous release of contaminants occurs on contact with water for all LLW and most ILW wastes;
- H-3 and C-14 are also released as gas due to waste degradation;
- there is no sorption of contaminants within the repository; and
- there is no solubility limitation except for carbon.

The key geosphere and shaft assumptions in the AMBER DGR model are:

- water and gas fluxes in shaft are taken from FRAC3DVS-OPG and T2GGM;
- transport is by diffusion in the geosphere;
- there is sorption of only certain elements (Zr, Nb, Cd, Pb, U, Np, Pu); and
- there is no solubility limitation of contaminants.

The key biosphere assumptions are:

- contaminants are released via:
    - well pumping from the shallow aquifer;
    - groundwater discharge to the near-shore lake bed; and
    - in certain cases, gas flux from the shafts into a house and surrounding soil
- a self-sufficient family farm is located on repository site using the well water and farming all their own food.

Within the model, the DGR system has been discretized to represent its key components, i.e.:

- the wastes - 21 compartments are used to represent the various low and intermediate waste categories;
- the repository – 50 compartments are used to represent the emplacement rooms, access tunnels, monolith, and rock damaged zones;
- the shafts – 69 compartments are used to represent the shaft seals and the rock damaged zones associated with the shafts;
- the geosphere – 188 compartments are used to represent the four groundwater zones; and
- the biosphere – represented by 7 terrestrial and 8 lake compartments.

Slide #111 provides an overview of the discretization of the wastes and repository, and the associated contaminant release and migration processes. Contaminants are released into the DGR’s two panels from the 21 waste categories in either gaseous or aqueous form. Once in the panels the contaminants are partitioned between gas and water. There is free mixing of gas and water between the panels and their associated access tunnels. Contaminants in water can migrate into the damaged zone surrounding the panels and tunnels, and into the concrete monolith and its damaged zone, and then into the shafts. Gas can migrate directly from the access tunnels into the shafts.

Slide #112 provides an overview of the discretization of the shafts and geosphere, and the associated contaminant migration processes. Four bedrock groundwater zones are explicitly represented, as is the combined shaft and its inner and outer damaged zones. Contaminants can potentially migrate via the shaft (and its damaged zones) and the geosphere, although the AMBER DGR model only considers gas migration via the main pathway identified by T2GGM, i.e., the shaft (and its damaged zones). Any contaminated groundwater that reaches the Shallow Bedrock Groundwater Zone can discharge to the biosphere via a well and via the lake; any contaminated gas can discharge to a house and to soil located directly above the shaft.

Slide #113 shows the dynamic biosphere model and its associated contaminant migration processes. Contaminant releases can occur to the terrestrial environment (on the left-hand side of the figure) and to the lake environment (on the right-hand side of the figure). A number of processes result in the migration of contaminants from the terrestrial to the lake system (such as erosion, interflow, airflow and stream flow).

AMBER DGR model has not been calibrated in the strict sense of the word since no free parameters have been adjusted to calibrate the model. However, it has been ensured that the model's input data are:

- mainly derived from and traceable to DGR waste and site characterization programs;
- the groundwater and gas transport data are imported directly from the FRAC3DVS-OPG and T2GGM models; and
- many biosphere data are taken from CSA publication N288.1-08.

The AMBER DGR model has been verified using a number of approaches.

First, the model uses the AMBER code which is a numerically robust and well-verified code suited for the development of models of radioactive waste disposal systems.

Second, the model has been implemented in an iterative manner under the project's quality management system with:

- checking of model and data implementation;
- mass balance checks to ensure that mass has not been generated or lost from the system due to numerical instabilities; and
- peer review of models and results, including the review of interim results by an International Peer Review Team. The interim and final models and results have been presented at international conferences.

In addition, the results from the AMBER DGR model have been compared with those from other models. First, the key contaminants identified by the model have been compared with those identified in simplified scoping calculations. Second, Cl-36 fluxes through the shaft and geosphere calculated by the AMBER DGR model have been compared with those calculated by the FRAC3DVS-OPG model. Cl-36 was examined since it can be an important radionuclide in the groundwater pathway from the DGR. As shown on slide #116, the AMBER DGR results are consistent with but more conservative than those calculated using the more accurate

FRAC3DVS-OPG code. This is expected, and is due to the coarser discretization of the diffusion-dominated system in AMBER DGR.

Uncertainties in a postclosure safety assessment can be classified into three sources:

- uncertainties associated with the future evolution of the system;
- uncertainties associated with the conceptual and mathematical models; and
- uncertainties associated with data.

These three sources of uncertainty have been addressed in the AMBER DGR model in the following ways:

- Future evolution uncertainties have been addressed by implementing and evaluating the Normal Evolution Scenario and four Disruptive Scenarios in the same AMBER DGR model.
- Model uncertainties have been addressed by implementing a range of sensitivity cases, for example, cases with or without Ordovician under-pressures, cases with immediate or gradual repository resaturation, and cases with or without horizontal flow in the Guelph and Salina A1 upper carbonate formations.
- Data uncertainties have been addressed by:
  - taking the data for the model from DGR waste and site characterization programs, augmented by national/international sources (e.g., the Canadian Standards Association, the International Atomic Energy Agency, and the International Commission on Radiological Protection);
  - undertaking multiple deterministic sensitivity calculations with alternative sets of parameter values (e.g., waste inventory, corrosion and degradation rates, shaft seal permeabilities); and
  - undertaking probabilistic sensitivity analysis in which key radionuclide release and transport parameters are assigned distributions for Normal Evolution Scenario's reference case.

In addition, model and data uncertainties have been addressed using conservative reference case assumptions, e.g.:

- instantaneous release of contaminants from all LLW and most ILW waste streams on contact with water;
- no sorption of contaminants in the repository;
- no solubility limits for contaminants in the repository except for C-14, which is constrained by carbonate equilibrium due to the surrounding limestone rock;
- no sorption for most contaminants in the shafts and geosphere;
- no solubility limits for contaminants in the shafts and geosphere;
- no significant groundwater flow in the Guelph and Salina A1 upper carbonate formations; and
- a self-sufficient, family farm located on the repository site which uses well water pumped from the Shallow Bedrock Groundwater Zone for domestic and agricultural purposes.

Slide #119 summarizes the results from the reference and sensitivity calculations for the Normal Evolution Scenario analyzed with AMBER DGR. This figure shows the maximum calculated effective dose on a logarithmic scale. From comparing the maximum doses for the reference case and the various sensitivity cases, it can be seen that the gas generation and shaft seal performance assumptions are the most important factors. However, note that all cases are orders of magnitude below the dose criterion of 0.3 mSv/yr. In particular, all these results are within the grey shaded region which corresponds to essentially trivial doses of less than 1 nSv/yr. That is, the reference and sensitivity cases all show very low impacts from the DGR. These sensitivity results also show that the calculated doses are most sensitive to the gas generation and shaft seal parameters.

In addition to the deterministic sensitivity calculations, probabilistic calculations were undertaken for leading radionuclides (C-14, Cl-36, Zr-93 and I-129) to investigate sensitivity of consequences to their release and transport parameters. The effect of varying the sampled parameters on the maximum calculated concentration in the well water is shown on slide #120, as this is a key factor in determining calculated dose rates in the biosphere. The results shown demonstrate that the concentration of leading radionuclides in well water may increase by up to about two orders of magnitude when the Reference Case parameters are varied over plausible ranges. However, the very small calculated impacts indicate that the safety of the system is not sensitive to variations in these parameters.

To summarize, AMBER DGR is an OPG DGR-specific model of postclosure contaminant release, migration and impact.

Confidence in the AMBER DGR model, and its evaluation that impacts will be low, has been built by:

- the use of the AMBER code which is quality assured and widely used;
- the use of standard conceptual / mathematical models such as those of the Canadian Standards Association;
- the use of input data derived from DGR-specific waste and site investigation programs and detailed models;
- the development of the model under a quality management system, with peer review at interim and final stages;
- the comparison of results from the AMBER DGR model with those from other codes; and
- the large safety margin in results.

Uncertainties have been addressed in the AMBER DGR model by:

- assessing five scenarios;
- using conservative assumptions; and
- undertaking deterministic and probabilistic sensitivity analyses.

Overall, there is a high level of confidence that the AMBER model has been developed and applied appropriately for the assessment of the DGR system.

4.0 RADIATION DOSE MODELLING

This part of the presentation describes dose models used to estimate doses in the DGR’s operational period in two categories - dose to people and dose to biota.

The first category is the radiation dose models for workers and public. The codes used in the DGR project are MicroShield, MicroSkyshine and MCNP. These models are used to calculate external (gamma radiation) exposure.

MicroShield is the primary radiation dose code used in the DGR project.

It is supported by MicroSkyshine and MCNP for specific analyses. In particular, MicroSkyshine was used to check the importance of the “skyshine” pathway, which is the scattering of gammas from air.

MCNP was used to check the significance of gamma scattering from walls in an underground emplacement room. MCNP also provided a cross-check of MicroShield.

A separate radiation dose model was used for non-human biota, which included internal exposure and external exposure.

4.1 MicroShield

MicroShield is a photon shielding and dose assessment program. MicroShield version 8.02 was used in the DGR project for gamma dose rate calculations and preliminary shielding design.

With respect to its numerical approach, MicroShield uses the point-kernel method. In this method, a volume source is treated as a number of point sources. The direct photon flux from each point source to the dose point is calculated analytically, including attenuation and buildup along each path.

MicroShield comes with a variety of defined geometries for the source and for the shields. Two examples are illustrated in slide #125 – a cylindrical source and shield, and rectangular source and shield. Also as shown in this slide, there can be multiple shield layers. Self shielding within the source itself is included. MicroShield assumes that the source concentration is uniform. It uses a buildup factor approach to account for additional scattering from the source and shield to the dose point.

MicroShield was not calibrated in this application. The input parameters are fully defined based on the source and shield properties.

MicroShield version 8.02 is the latest in a series of codes, going back to ISOSHLD, which was created by the US Pacific Northwest National Laboratory in 1966. The basic algorithms have been in use for decades. It comes with a built-in library that provides standard reference values for various key inputs, including the radionuclide data, material attenuation and buildup factors, and dose conversion factors.

MicroShield is a widely-used code, including use by OPG, CNSC, IAEA, US Nuclear Regulatory Commission, industry, and universities. It has been cited in about 200 papers. It has been used in support of licence applications and regulatory decisions. For example, it has been used by OPG in the assessment of the used fuel dry storage buildings at OPG’s Darlington and Western Waste Management Facilities.

Slide #128 shows two examples of tests of the accuracy of MicroShield. The top figure compares MicroShield results with those calculated for a standard source and 5 cm of steel shielding. The results show good agreement at various photon energies.

The bottom figure on this slide shows the results from application to a standard radiation transport problem from ANSI Standard 6.6.1. Again, the MicroShield results are in good agreement with other reference code results for this problem.

Slide #129 shows results from a comparison of MicroShield with the code MCNP in a specific DGR application - the dose to a forklift driver in a DGR emplacement room. The driver is exposed to an array of three ILW resin liner shields. In this case, MicroShield is more conservative than MCNP, i.e., it has overestimated the dose rate.

Overall, MicroShield is a very fast and convenient code for gamma dose rate estimates, but it must be used within its range of applicability. This was followed in the DGR calculations. First, MicroShield was used to estimate doses from L&ILW packages, where gamma radiation is the dominant dose. Second, Microshield was used to calculate the direct dose through simple shielding geometries. And third, it was used with common radionuclides, with photons within the MicroShield range.

Uncertainties in use of MicroShield include the source term, the shielding materials and geometry, the receptor, and the contribution of scattering.

With respect to the source term, generally higher dose rate packages were considered in the DGR analysis. Also many calculations were made with two different LLW or ILW packages, which tested the sensitivity of conclusions to variations in dose rate, source radionuclides and package design.

With respect to shielding, generally the analyses used standard shielding materials - concrete and steel for example. Custom materials were primarily used for the source materials to represent the various wastes. Conservative buildup factor materials were used.

The analyses did not credit any package internal structure for its contribution to shielding. This would be particularly relevant when modeling an array of packages.

With respect to the receptor, the analyses placed the dose point at a close position, but consistent with the scenario being analyzed. Doses were assessed for the antero/posterior basis, which means for a person facing the source.

MicroShield does not calculate scattering to the dose point from skyshine or from surround walls and floors. Therefore, the potential contribution from these to the total dose was calculated using separate codes - MicroSkyshine and MCNP - for the relevant scenarios.

4.2 MicroSkyshine

The purpose of MicroSkyshine is to calculate dose from overhead scattered gamma radiation. The code uses an analytic solution method based on use of "beam functions" for a point source. These beam functions were developed from more detailed Monte Carlo calculations. Microskyshine is a commercially available code.

It may be helpful to first define what is meant by “skyshine”. This is illustrated in the figure on slide #132. In this figure, there is a source and a receptor, separated by a shield that stops any direct dose to the receptor. However, structures often have thinner roofs than walls, and some gammas emitted from the source will escape into the air. Most of these would harmlessly dissipate. However, some fraction may be scattered towards the receptor. Although this may be a small fraction of the total flux from the source, it could be the dominant dose contribution at the receptor if the wall shield is very effective.

For the DGR, the possible skyshine was assessed from waste packages in the Waste Package Receipt Building through the roof and scattered towards non-Nuclear Energy Workers on the Bruce nuclear site but outside of the DGR site, or to public outside of the Bruce nuclear site.

The main relevant features of MicroSkyshine are as follows:

- standard source geometries
- standard source and shield materials (i.e., air, water, iron, etc.)
- the scattering medium is air
- the vertical wall is a perfect shield (i.e. the direct dose through the wall is not calculated).

MicroSkyshine version 2.10 is a commercial code. It comes with a built-in library that provides standard reference values for key inputs, including the radionuclide data, material attenuation and buildup factors, and dose conversion factors.

MicroSkyshine is recognized by regulators such as the CNSC and the US Nuclear Regulatory Commission. It has been used in support of licence applications. For example, it has been used by OPG in the assessment of the used fuel dry storage buildings at OPG’s Darlington and Western Waste Management Facilities. In the US, it has also been used to evaluate dry storage facilities.

MicroSkyshine was not calibrated in this application. The input parameters are fully defined based on the source and shield properties.

Slide #135 shows an example of a test of MicroSkyshine, based on the Standard Problem I.2 in the ANSI Standard 6.6.1. The right-side figure compares the code results with those calculated using other standard codes for a simple rectangular roofless building as shown in the left-side figure. The results show good agreement at various distances.

Slide #136 shows an example of another test of MicroSkyshine. In this case, the code results are compared with measurements from a Co-60 gamma source in a concrete shield with various roof thicknesses. The results are in good agreement.

The application of MicroSkyshine to the DGR is conducted under appropriate conditions for its applicability:

- Standard radionuclides, with photon energies from 0.1 to 2 MeV;
- Source-to-receptor distance of 80 m and 1100 m; and
- Waste Package Receipt Building (WPRB) roof thickness less than 6 mean-free-paths.

It was applied assuming there was the maximum number of packages stored in the WPRB. The skyshine was conservatively assessed at the closest distance to the source for the two receptors considered - non-nuclear workers at the DGR site fence line and public at the Bruce nuclear site fence line.

Sensitivity analyses were not carried out since the results showed that the skyshine dose rate at these locations was low.

4.3 MCNP

MCNP was developed for more accurate modelling of neutron, photon and electron transport. It is used in the DGR for gamma dose calculations to evaluate the importance of gamma scattering from walls in an underground emplacement room. This also provided a cross-check of MicroShield results for the same case.

MCNP uses the Monte Carlo numerical method. In this method, the random walk of individual particles is simulated. The results are statistical averages over many particles.

MCNP is a widely-used, commercially-available code.

Key features of MCNP relevant to the DGR are as follows:

- It is applicable to gamma radiation (as well as neutrons and electrons).
- It allows detailed treatment of geometry, including source, shield and surrounding structures.
- It allows detailed treatment of particle interactions with materials, including scattering.
- It includes options for variance reduction, i.e. numerical methods for faster convergence.

MCNP is developed and maintained by the US Government through Los Alamos National Laboratory. It is maintained under a formal software quality assurance system. The main data files are available as standard input files.

MCNP is a widely-used code. For example, it is referenced in about 17,000 articles according to Google Scholar. It has extensive verification and validation, some of which is documented through the MCNP home website, and some of which is demonstrated through the many applications of the code documented in the literature.

Slide #141 shows an example of a test of MCNP for backscattering calculations. In this case, the code results are compared with measurements of backscattering from various materials including plastic, aluminum and steel (Loat et al. 2010). The results are in good agreement.

MCNP was used in the DGR Preliminary Safety Report for the estimate of the importance of wall scattering in an underground emplacement room. The geometry is as shown in slide #142. The assessment was bounding in that it considered a higher dose rate ILW emplacement room, and that it considered a full room of packages (99 rows x 3 waste packages per row). Calculations were conducted only with Co-60 for computational efficiency; this radionuclide accounts for 92% of the dose based on MicroShield calculations. A relative error target of less than 5% was used.

The calculations were done with two models, one with air surrounding the room and one with rock. This allows the contribution of wall scattering to be determined. It was found to be a small contribution to the total dose rate - about 5%. Another sensitivity case tested the importance of the front row of ILW packages, and showed that these accounted for the bulk of the dose rate to the assumed worker location.

In summary, radiation dose modelling for external dose rates to workers and public was carried out as part of the assessment of the operations phase of the repository. Confidence in the model and results is provided through the following lines of evidence:

- The use of MicroShield as the primary code. This is a standard commercial code, widely used by industry including OPG, and accepted by regulators.
- This is a standard application of MicroShield, with direct dose calculations from waste packages in simple shielding geometries.
- The inputs and results were checked through independent calculations.
- The results for one relevant case were compared with MCNP, a more accurate code.
- The contribution of scattering to the doses was evaluated with commercially-available specialty codes (MicroSkyshine and MCNP). Their results showed that scattering was a small dose contribution.

Overall, these radiation dose results support the preliminary design and safety assessment of the DGR. The results are consistent with general expectations from handling such waste packages at existing OPG facilities.

4.4 Non-Human Biota Calculations

4.4.1 Methodology to Assess Doses to Non-Human Biota

This discussion of the assessment of radiological effects to non-human biota is limited to the preclosure phase of the DGR project.

The methodology adopted for this project (as indicated in slide #145) constitutes a Tier-2 assessment as defined in the Environmental Impact Statement (EIS) guidelines. This represents a semi-quantitative evaluation using site-specific data, existing site information, and very conservative assumptions. It is also generally consistent with the approach to assess ecological risk recommended in CSA N288.6-12 (CSA 2008), specifically Preliminary Quantitative Risk Assessment (PQRA) of non-human biota which is equivalent to a Tier-2 assessment.

A similar methodology has been employed in other environmental assessment work to assess radiological effects of the project to non-human biota, for example the Environmental Assessment for the Darlington New Nuclear Project.

4.4.2 Fundamental Aspects of the Model

4.4.2.1 Key Features

Non-human biota could be exposed to radiation and radioactivity via direct exposure (gamma exposure) from waste packages or through indirect exposure to radioactivity in environmental media (various pathways). Slide #146 shows the key features (equations) of the model used to assess radiological doses to non-human biota resulting from the DGR Project.

Assessment Methodology for Direct Exposure

During operation of the DGR, waste packages will be transferred from the Western Waste Management Facility to the DGR via a crossing of the railway ditches. The packages may then remain in the above-ground WPRB for a few days prior to transfer to underground emplacement rooms. During this process, non-human biota along the transfer route and in the vicinity of the WPRB may be exposed to gamma radiation. The resulting gamma dose can be calculated as follows:

Gamma dose = Dose rate × Exposure time

Where

Dose rate = Dose rate at the location where the species of concern resides (mGy/h)

Exposure time = Period during which the species of concern is exposed to the package being transferred or stored at WPRB (hours)

Assessment Methodology for Indirect Exposure

In addition to direct exposure, non-human biota undergoes indirect exposure to radioactivity in environmental media by various pathways. For this type of exposure, the method to calculate dose to non-human biota is as follows:

1. Characterization of representative species from an ecological perspective such as food and water intakes, habitat occupancy rates, etc.

2. Characterization of representative species and the environment from the radiation perspective such as environmental transfer factors, internal and external dose coefficients, etc.

3. Calculation of internal dose and external dose to representative species. The general conceptual-level equations are as follows:

   - *Total dose = internal dose + external dose*

   - *Internal dose = dose coefficient* $_{int}$ *× concentration of radionuclide in species*

     Where concentration of radionuclide in species = intake x concentration in intake x transfer factor

   - *External dose = dose coefficient* $_{ext}$ *× concentration of radionuclide in environmental media*

4.4.2.2 Considered Scenarios – Normal Operations

The evaluated direct exposure scenario considered external exposure to waste which is being transferred from WWMF. It is conservatively assumed that representative indicator species are exposed for a period of 1 hour per day at a distance of 10 m (slide #147). The dose rates at 2 m from the package are used to estimate doses external doses to non-human biota. These doses are estimated assuming an inverse square law relationship.

For the purposes of evaluating Indirect Exposure for normal operations, doses were assessed for concentrations twice the current levels at Bruce site. Calculations were conducted for maximum observed concentrations in various media types. Information on other aspects of scenario for Normal Operations is provided further. This includes information on receptors, exposure pathways, transfer factors and dosimetry. For accidents scenarios, it was assumed that the radionuclides released to air as a result of an accident will reach equilibrium with other environmental media such as soil and water immediately.

4.4.2.3 Considered Scenarios – Accidents

The accident scenario is consistent with the bounding source terms and concentrations evaluated in the Preliminary Safety Report for the DGR. It involves fire at a single outdoor container with moderator resin. Again, maximum estimated air concentrations were used for the purposes of this assessment. A 24-hour exposure period was assumed, to reflect that radionuclide concentrations will reduce over time and that only a small fraction of the habitat will be impacted by maximum concentrations.

Other aspects of the accident scenario are consistent with Normal Operations.

4.4.2.4 Conceptual Exposure Pathways

An ecosystem is a natural unit consisting of biota communities and their non-living (abiotic) environment, interacting as a functional unit. Slide #149 depicts the food chain for a typical Southern Canadian deciduous forest ecosystem. Slide #150 illustrates the exposure of species to different environmental media. Note that these figures are for illustration purposes. The pathways considered for dose calculation are discussed later.

4.4.3 Confidence in Model

Confidence in the model used for dose assessment and the results of the assessment are based on the pedigree of the model and input data, and on the verification and review processes employed in performing the work. This is discussed in slides #151 and #152.

4.4.3.1 Pedigree of Methodology and Input Data

Dose Assessment Methodology

As discussed previously, the methodology used in this project to assess radiological effects to non-human biota constitutes a Tier-2 assessment as defined in the EIS guidelines and is consistent with the recently published standard for environmental risk assessment, CSA N288.6-12. It is also consistent with international practice (FASSET 2003). In addition, this methodology has been successfully used in recent EA work in Canada, e.g., (OPG 2009).

Input Data

The input parameters for the model used for dose calculation, as shown in slide #151, are grouped into the following categories:

- Environmental concentrations
- Internal and external dose coefficients

- Intakes and exposure
- Transfer factors
- Relative Biological Effectiveness (RBE)

As discussed below, the values for different input parameters are taken from reputable sources and therefore confidence in the values of various input parameters is justified.

Environmental Concentrations

The maximum radionuclide concentrations in environmental media such as air, water, soil and sediment are used to estimate dose to non-human biota for normal operations. As described earlier, these maximum current concentrations were doubled to ensure that the predicted exposure is for bounding conditions. Maximum air concentrations from the Preliminary Safety Report for the DGR are used to estimate doses to non-human biota for accidents and malfunctions.

All these data have the appropriate quality assurance pedigree. Specifically, they include measured concentration data from the Environmental Assessment for the WWMF Refurbishment Waste Storage (RWS) Project (OPG 2005) and Bruce Power’s Radiological Environmental Monitoring Program (REMP) (BRUCE POWER 2009). Bruce Power’s REMP has been carried out at the Bruce nuclear site for more than ten years. It is operated under a stringent quality assurance/ quality control program, compliant with the requirements of CSA N288.4-90 (CSA 1990), the Canadian standard for environmental monitoring at Class I nuclear facilities.

For the accident scenario, the primary source of data (airborne emission) is the DGR Preliminary Safety Report. Concentrations of radionuclides in other environmental media such as water and soil were derived from the air concentrations based on site specific parameters documented in CSA N288.1-08 (CSA 2008).

Internal and External Dose Coefficients

Internal and external dose coefficients used in this work are based on the Framework for Assessment of Environmental Impact (FASSET) project (FASSET 2003).

The FASSET project was launched in November 2000 under the EC 5th Framework Program, to develop a framework for the assessment of environmental impact of ionising radiation in European ecosystems. It involved 15 organizations in seven European countries, and set out to organize radio-ecological and radio-biological data into a logic structure that would facilitate the assessment of effects on non-human biota resulting from known or postulated presence of radionuclides in the environment. The FASSET Project has been completed and the final report was issued in 2004. It is extensively used in ecological risk assessments with about 14,000 references in Google Scholar.

Intakes and Exposure (Occupation Time)

The primary source for food and water intake is US EPA’s Wildlife Exposure Factors Handbook (US EPA 1993). The soil/sediment consumption rates were based on Survey of Soil Ingestion by Wildlife published in Journal of Wildlife Management (Beyer et al. 1994). For the fraction of time the species of concern spends in the study areas, it was conservatively assumed 0.5 for migrating species such as birds and 1 for species such as deer, fox and vole.

Transfer Factors

Feed-to-animal transfer factors were used to estimate radionuclide concentrations in species of interest based on concentrations in its food intake. The values were taken from CSA N288.1-08 (CSA 2008) for some species such as deer. If the values were not available for certain species, such as Mallard, the transfer factor of 1 was assumed. Similarly, air-to-mammal transfer factors were used to estimate radionuclide concentration in species of interest via inhalation based on concentration in air. The values reported in CSA N288.1-08 were used in this work.

Relative Biological Effectiveness (RBE)

Radiation effects on biota depend not only on the absorbed dose, but also on the relative biological effectiveness (RBE) of the particular radiation. For example, some studies show that the biological effects of tritium were 1.8 to 2.3 larger than the effects of X-rays or gamma radiation, for the same absorbed dose. FASSET (2003) suggested the use of an RBE of 3 for low energy beta radiation energies < 10 keV (tritium for example) and 1 for both beta radiation with energies greater than 10 keV and for gamma radiation in order to illustrate the effect of RBE on internally-deposited radionuclides.

In this work, an RBE of 3 has been assumed for internally-deposited tritium. This may result in an overestimate of the dose accruing to an organism from internally-deposited tritium.

4.4.3.2 Assessment

The outputs of the dose assessment were independently verified for correctness/accuracy and reviewed for reasonableness and for meeting project objectives. These activities were carried out in compliance with the requirements specified by the AMEC NSS Quality Management System (QMS).

As summarized on slide #152, AMEC NSS QMS defines the processes used to ensure work meets client expectations and accepted and approved quality standards. The QMS complies with the requirements of the following standards:

- ISO 9001:2008, Quality Management Systems;
- CSA N286-05, management system requirements for Nuclear Power Plants specifically those portions relevant to procurement and design;
- CSA N286.1-00, Procurement Quality Assurance for Nuclear Power Plants;
- CSA N286.2-00, Design Quality Assurance for Nuclear Power Plants;
- CSA N286.7-99, Quality Assurance of Analytical, Scientific and Design Programs for Nuclear Power Plants;
- CAN3- Z299.1-85 (R2006) Quality Assurance Program –Category 1;
- ASME Section III – NCA-4000 2007 Edition; and
- ASME NQA-1 1994 and NQA-1 2008 and NQA-1a-2009 Editions.

AMEC NSS has been ISO 9001 certified since November 2005.

4.4.4 Calibration, Validation and Verification

Transfer factors were not calibrated with site specific concentrations; however whenever possible, model source term inputs were based on available measured site specific concentrations in various environmental media and non-human biota.

Non-human biota dosimetry model and transfer factors used in the assessment were validated through several international studies and intercomparison exercises, such as EMRAS Biota Working Group (EMRAS 2012). It was found that doses to terrestrial species were more closely correlated with predictions than aquatic and that individual pathway exposures did not always agree to full extent; however discrepancies were cancelled out for total dose agreement.

The accuracy of model implementation was verified using AMEC NSS QA system, described in slide #153.

4.4.5 Uncertainty Analysis

4.4.5.1 Sources of Uncertainty

The uncertainty associated with the assessment of radiological effects to non-human biota can be grouped into three categories, including concept-based, input-data based, and criteria-based. Significant sources of potential uncertainty are listed in slide #154:

1. Input-data based
    - Selection and characterization of indicators
    - Characterization of contaminants (radionuclides of concern, concentration data)
2. Concept-based
    - Environmental pathways (species specific)
3. Criteria-based
    - Selected dose criteria

Further discussion of each source of uncertainty and justification of the selected approach is provided in slide #155 through slide #160.

4.4.5.2 Uncertainty Analysis

<u>Selection of Valued Ecosystem Components and Indicators</u>

The species selected as indicators of the VECs for the assessment of radiological effects for the normal operations and malfunctions and accident conditions are listed in slide #155. They are representative of the species of non-human biota present in the study areas. In accordance with the ICRP (International Commission on Radiological Protection) concept of using Reference Animals and Plants, it is not the intention to represent key links in food chains or key links in ecosystem functioning. The objective is to consider ‘typical’ organisms representative of different environments. In summary, the selection of valued ecosystem components and indicators is consistent with best practice in Canada and is in compliance with the principle of

ICRP 108 (ICRP 2008). Therefore, the uncertainty related to identification of VEC and selection of indictors is minimized.

Characterization of Indicators

From the dose calculation perspective, characteristics of concern for indicators include food intake, water intake, soil and sediment intake, and exposure period. As discussed above, the values for food and water intake were taken from US EPA’s Wildlife Exposure Factors Handbook (US EPA 1993) and soil/sediment consumption rates were based on published survey data (Beyer et al. 1994). For the fraction of time the species of concern spends in the study areas, it was conservatively assumed 0.5 for migrating species such as birds and 1 for species such as deer, fox and shrew.

Pathways

Exposure pathways are species specific. In this work, the following pathways have been considered:

- Exposure to soil/sediment
- Food/water ingestion
- Soil/sediment intake
- Immersion in water (external)
- Direct radionuclide uptake (from water, for fish)
- Inhalation

A quantitative assessment of dermal exposure was not taken into account as exposure from this pathway is limited due to blockage by fur and feathers. This is consistent with the approach used in recent Environmental Assessments.

Since all significant pathways through which indicators are exposed to radiation have been considered, uncertainty associated with this factor is negligible.

Characterization of Contaminants

Uncertainty in characterization of contaminants is also related to uncertainty in estimates of predicted environmental concentrations.

The following bounding assumptions were made:

- For normal operations it was assumed that Project concentrations would be double the maximum-detected values in different environmental media (water, soil, sediment, air, etc). This is a bounding assumption because predicted DGR releases are significantly below current emissions from the Bruce nuclear site.
- For accidents, air concentrations were derived from maximum estimates in the Preliminary Safety Report. Concentrations for other media were derived using site specific parameters, consistent with CSA N288.1-08. This conservatively assumes instantaneous equilibrium.

In both cases, the use of maximum concentrations is conservative because it does not take into account that the population of indicator species is spread across its habitat area.

Dose Criteria

Guidelines to protect population of non-human biota are under development. Different dose criteria have been considered by Canadian and international agencies to assess radiological effects to non-human biota (Environment Canada and Health Canada 2003, UNSCEAR 1996, Garisto 2005, Garnier-Laplace 2006). Selected Estimated No Effects Values are provided in slide #160.

These values are:

- Consistent with the low values in various studies,
- Consistent with dose criteria for post-closure phase as accepted by CNSC (2009).

The use of ENEV for Tier-2 assessment is conservative. According to CSA N288.6-12, less conservative Lowest Observed Adverse Effect Level (LOAEL) could be used as benchmark value for Tier-2 assessment.

4.4.6 Assessment Results

Based on the assessment results documented in relevant Technical Support Documents, there were no adverse effects to non-human biota resulting from the DGR project. Therefore, a Tier-3 assessment, which includes field surveys, use of less conservative assumptions and more detailed modeling, was not required.

4.4.7 Summary

The methodology for assessing radiological effects to non-human biota is discussed, focusing on fundamental aspects of the model, confidence in the model and the uncertainty. The following conclusions can be drawn based on the assessment.

- The assessment methods are consistent with Canadian and international guidance.
- The scenarios assessed represent the bounding cases.
- The dose criteria used for assessment are very conservative.
- The estimated doses to non-human biota are below the screening criteria.
- There is uncertainty in the selection of input parameters, and in the selection of the assessment criteria.
- High confidence that the results do not underestimate the doses due to conservatism in the assessment.

5.0 ENVIRONMENTAL MONITORING

5.1 AERMOD

The air concentrations of both indicator (air quality), and non-indicator (i.e., for health) compounds associated with the activities at the DGR Project were determined using AERMOD (version 09292). The AERMOD dispersion model is a public-domain model, developed jointly by the United States Environmental Protection Agency (U.S. EPA) and the American Meteorological Society (AMS). The AERMOD model is the default regulatory dispersion model in the United States and Ontario for most applications. The model is also accepted in many other jurisdictions across Canada and internationally.

5.1.1 AERMOD – Background

The AERMOD model was developed with the objective of incorporating state-of-the-art dispersion modelling concepts in a model that would replace the Industrial Source Complex (ISC) model as the regulatory default model in the United States. The AERMIC (American Meteorological Society (AMS)/United States Environmental Protection Agency (EPA) Regulatory Model Improvement Committee) developed AERMOD in seven steps:

- initial model formulation:
- developmental evaluation:
- internal peer review and beta testing;
- revised model formulation;
- performance evaluation and sensitivity testing;
- external peer review; and
- submission to the EPA for consideration as a regulatory model.

In 2000, the EPA proposed that AERMOD be adopted as the EPA's preferred regulatory model for both simple and complex terrain. In 2005, AERMOD was adopted by the EPA and promulgated as their preferred regulatory model, effective as of December 2005. The model has been adopted as the default regulatory model in Ontario, the required use of which is being phased in by industry.

The AERMOD atmospheric dispersion modelling system is an integrated system comprised of three separate modules (slide #167).

- The AERMET meteorological data pre-processor is used to convert available hourly meteorological observations into the necessary model inputs that characterize the surface layer as well as the vertical profile of the lower boundary layer (slide #168).
- The AERMAP terrain pre-processor is used to manage the terrain and receptor inputs, and is of greatest importance at locations with significant topography (slide #169).
- The AERMOD dispersion module, which is used to calculate concentrations and deposition rates.

5.1.2 AERMOD – Fundamental Aspects

The AERMOD model is a steady-state dispersion model, meaning the model assumes that meteorological conditions remain constant across the entire modelling domain for each hour modelled. The AERMOD model is applicable to rural and urban areas, flat and complex terrain, surface and elevated releases and multiple sources (including point, area and volume sources). It is a steady-state plume model.

The basic dispersion parameters within the model vary depending on the atmospheric stability. During stable conditions, both the horizontal and vertical dispersion follows a Gaussian distribution. During unstable conditions, the horizontal dispersion is assumed to be Gaussian while the vertical dispersion is assumed to occur with a bi-Gaussian distribution.

The AERMAP pre-processor facilitates the evaluation of dispersion in and around complex terrain, something that was not required when assessing the DGR Project. AERMOD also includes PRIME (Plume Rise Model Enhancements), which is an algorithm for modeling the effects of downwash created by the pollution plume flowing over nearby buildings.

AERMOD dispersion module uses the hourly meteorological inputs, along with the terrain and source information to calculate hourly concentrations at each of the receptors, for each of the hours of meteorological input. These hourly concentrations can then be averaged within the model to yield longer-term concentrations (e.g., daily or annual). Because of the nature of the model, emissions are dispersed outward from the source and the model predictions are not bounded.

5.1.3 AERMOD – Calibration

The process of development and adoption of AERMOD as a regulatory model took about 15 years. During that period, the model was extensively tested and calibrated against monitoring data, both by the developers and by third-parties as part of the adoption process. To aid the process, numerous data sets suitable for use in model calibration have been made freely available by the U.S. EPA.

5.1.4 AERMOD – Verification

Prior to proposing AERMOD as a regulatory model, the AERMIC working group spent nearly nine years developing the code and verifying the model. After its proposal in 2000, the verification process included third-party reviewers who scrutinized the code to ensure its validity. This process led to a number of upgrades prior to the official adoption of AERMOD in 2006 (e.g., the inclusion of the PRIME downwash algorithms).

The verification process for AERMOD has continued since 2006, with periodic updates to address issues and enhance the model.

5.1.5 AERMOD – Uncertainty Analysis

While the AERMOD model has been thoroughly reviewed and its accuracy verified, there is the potential for uncertainties associated with the inputs to the model. To reduce these uncertainties, and to ensure the modelling does not underestimate the potential effects of the DGR Project, the following tenets were kept in mind when selecting model inputs:

- select the best available local data sources;
- select the best available data sources in situation where suitable local data are not available;
- select conservative inputs; and
- run multiple simulations.

An example of the application of this approach can be seen with the selection of meteorological data used as inputs to the dispersion modelling (slide #175). The primary source of hourly wind and temperature data used in the modelling came from the 50 m tower located on the Bruce nuclear site. In fact, this tower is located adjacent to the DGR Project. For meteorological parameters that were not available from on-site, data were taken from the corresponding hours at the station operated by the Meteorological Services of Canada at Wiarton Airport. Data collected at this station is of the highest quality and meets the World Meteorological Organization (WMO) requirements. In the case of the twice-daily upper air soundings, data were not available either on-site or from Wiarton. Twice daily soundings were obtained from Gaylord, Michigan, which also meets WMO requirements. Wind observations were available at two levels on the 50 m tower, at 10 m above the ground and at 50 m. It was determined that winds from the 10 m height would be most appropriate for use as those winds showed the influence of local phenomena such as lake breezes. Phenomena like the lake breezes would be important in characterizing how the emissions from the DGR Project are dispersed. By selecting a full, five-year meteorological data set (2005 through 2009) as an input to the modelling, the modelling should simulate the full range of conditions likely to be experienced at the site.

The uncertainty related to the emissions inventory was managed by evaluating the scenario with the highest overall emissions (slide #177). Stage 1 of the site preparation and construction phase had the highest overall emissions and was selected as conservatively representing the conditions that would occur during that phase of the project.

In Ontario, and many other jurisdictions, regulatory guidance allows that the highest predictions from the modelling can be discarded. For example, regulatory guidance in Ontario allows for the eight highest hourly predictions in each year modelled to be discarded. Effectively, the 99.9th percentile of the modelling results would be used. In assessing the air quality effects for the DGR Project, the highest predicted hourly concentrations were used, and no data were excluded. In the case of hourly NO_2, the absolute highest off-site prediction was nearly 28% higher than the highest prediction when the eight highest hours in each year modelled were excluded (slide #178).

In a similar manner, Ontario guidance allows for the exclusion of the highest daily prediction from each of the years modelled. In assessing the air quality effects for the DGR Project, the highest predicted daily concentrations were used, and no days were excluded. In the case of daily $PM_{2.5}$, the absolute highest off-site prediction was nearly 29% higher than the highest prediction when the highest day in each year modelled was excluded (slide #179).

5.1.6 AERMOD – Summary of Confidence

The air quality modelling for the DGR Project was done using AERMOD, a widely accepted model internationally, which is also a regulatory model in Ontario. The model has been extensively tested, the codes verified and the results validated. The model continues to undergo regulatory and third-party scrutiny, and is updated to address issues and enhance the capabilities. The best local meteorological data were used, where available, and the best data from other sources used when suitable local data were not available. Generally, conservative choices were used in selecting emission inputs, as well as presenting the modelling results. Overall, there is a high level of confidence that the air modelling completed for the assessment of the DGR Project does not underestimate the potential air quality effects.

5.2 Cadna/A

5.2.1 Noise Modelling – Fundamental Aspects

Noise modelling for the DGR Project was carried out in accordance with accepted practices in the Province of Ontario. Two aspects that have been specifically identified within the Atmospheric Environment Technical Support Document are:

- use of Cadna/A (Computer Aided Noise Abatement) software (version 3.72.131); and
- predictions based on ISO 9613-2.

In addition, the noise assessment focussed on the human response to noise. This included noise predictions at the two (2) closest dwellings and Inverhuron Provincial Park. Specifically, noise levels were presented as "A-weighted" decibels (dBA) using a 1-hour energy equivalent sound level (L_{eq}) (slide #183).

Noise predictions were also provided to the terrestrial wildlife and human health disciplines for assessment.

5.2.1.1 Key Aspects of Noise Assessment

Logarithmic Scale

Noise levels are typically expressed on a logarithmic scale, in units called decibels (dB). Since the scale is logarithmic, a sound that is twice the sound pressure level as another will be three decibels (3 dB) higher (e.g., 50 dB + 50 dB = 53 dB).

Weighting

Noise data and analysis are typically given in terms of frequency distribution. The levels are grouped into octave bands. The centre frequencies for each octave band are 31.5, 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hertz (Hz). The human ear responds to the pressure variations in the atmosphere that reach the ear drum. These pressure variations are composed of different frequencies that give each heard sound its unique character.

It is common practice to sum sound levels over the entire audible spectrum (i.e., 20 Hz to 20 kHz) to give an overall sound level. However, to approximate the hearing response of humans, each octave band measured has a weighting applied to it. The resulting "A-weighted" sound level is often used as a criterion to indicate a maximum allowable sound level. In general, low frequencies are weighted higher, as human hearing is less sensitive to low frequency sound.

Environmental noise levels vary over time, and are described using an overall sound level known as the L_{eq}, or energy averaged sound level. The L_{eq} is the equivalent continuous sound level, which in a stated time, and at a stated location, has the same energy as the time varying noise level. It is common practice to measure L_{eq} sound levels in order to obtain a representative average sound level.

Existing Noise Levels

The existing noise levels for the DGR project were measured at three locations (i.e., two closest dwelling and Inverhuron Provincial Park). The measured data summarizes the existing noise levels in the absence of the project and provides information on daily trends.

Project Noise Levels

The project noise levels represent the predicted noise emissions from the project sources/activities at the three off-site receptor locations and do not included the existing noise levels.

Ambient Noise Levels

Ambient noise levels combine the existing noise levels and the project noise levels to establish the project effects.

5.2.1.2 Cadna/A Software

Cadna/A software is a tool used for implementing the ISO 9613-2 prediction algorithms and others as required. This modelling software allows for the development of large- and small-scale 3-dimensional models (similar to CAD drawings) that accurately represent existing or proposed facilities and identify receiver locations in the vicinity that may experience noise effects. As a result, noise can be considered in the early stages of design to reduce off-site noise effects at sensitive receiver locations.

Cadna/A is in use in more than 60 countries around the globe and has implemented more than 30 noise prediction standards (slide #185) including:

- ISO 9613, including VBUI and meteorology according to CONCAWE (International, EC-Interim);
- VDI 2714, VDI 2720 (Germany);
- DIN 18005 (Germany);
- ÖAL Richtlinie Nr. 28 (Austria);
- BS 5228 (United Kingdom);
- General Prediction Method (Scandinavia);
- Ljud från vindkraftverk (Sweden); and
- Harmonoise, P2P calculation model, preliminary version (International).

5.2.1.3 ISO 9613 Model

ISO 9613 Acoustics – Attenuation of sound during propagation outdoors includes two parts:

- Part 1 (1993): Calculation of the absorption of sound by the atmosphere; and
- Part 2 (1996): General method of calculation.

ISO 9613-2 specifies an engineering method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of environmental noise at a distance from a variety of sources. The method predicts the equivalent continuous A-weighted sound pressure level or Leq under meteorological conditions favourable to propagation from sources of known sound emission. The L_{eq} is the equivalent continuous sound level, which in a stated time, and at a stated location, has the same energy as the time varying noise level.

The Ontario Ministry of the Environment (MOE) has adopted ISO 9613-2 as the prediction algorithm to be used in noise assessments requiring an Environmental Compliance Approval (Air & Noise) [formerly Certificate of Approval (Air & Noise)] or a Renewable Energy Approval (including wind farms).

Noise Modelling Assumptions

The following assumptions were made as part of the noise modelling of the DGR project:

- Predicted A-weighted, 1-hour Leq's at off-site receptors;
    - Two closest dwellings; and
    - Inverhuron Provincial Park.

In addition, the following factors, listed in slide #189, were considered in the noise predictions:

- All receptors down-wind;
- Wind speeds were less than 18 km/hr;
- All sources operating simultaneously;
- Sources modelled appropriately as points, areas or lines;
- Used proposed site layout plan, buildings and equipment list for predicting off-site noise levels; and
- Topographic data and existing ground conditions incorporated into noise model.

Noise predictions were also provided for other disciplines as follows:

- Terrestrial wildlife
    - Seven on-site ecological locations;
    - Predicted linear (i.e., non-weighted), equivalent hourly noise levels (dBLin); and
    - Assessment of noise effects in the Terrestrial Environment TSD.
- Human Health
    - Predictions at two closest dwellings and Inverhuron Provincial Park;
    - Predicted percent highly annoyed (%HA) and specific impact or impulse noise (HCII); and
    - Assessment of health effects in Appendix C of the EIS.

Ray Tracing

Ray tracing noise models assume that sound mimics rays of light, which are used to find receivers and intervening objects and then predict the sound pressure level (SPL) at a specified location. SPLs can be predicted in the community or close to the source, at isolated receivers or as contours.

The advantages of ray-tracing software include the ability to manage very large projects, screening by multiple barriers and finite-sized sources, and multiple reflections by screens and objects. Line and area sources can be defined by ray-tracing software, which can be used to model buildings. The software partitions finite-sized sources into many point sources automatically. These advantages can lead to more precise modelling of sources and propagation paths, and result in more accurate predictions.

Attenuation Factors

ISO 9613-2 incorporates the calculation procedure summarized in ISO 9613-1 and consists of octave-band algorithms (with mid-band frequencies ranging from 63 Hz to 8,000 Hz) for calculating the attenuation of sound that originates from a point source, or an assembly of point sources. The source (or sources) may be moving or stationary. The following physical effects are included in the algorithms:

- geometrical divergence (i.e., spherical spreading);
- atmospheric absorption (based on ISO 9613-1);
- ground effect or ground impedance;
- reflection from surfaces; and
- screening by obstacles (e.g., barrier or buildings).

Geometrical Divergence

Geometric divergence accounts for spherical spreading in the free field from a point source. Therefore, for each doubling of distance, there is a reduction in sound level of 6 dB. For sources that do not behave as points (e.g., roads), the attenuation will be based on cylindrical spreading in the free field from the line source. In this circumstance, for each doubling of distance, there is a reduction in sound level of only 3 dB.

Atmospheric Absorption

The atmospheric attenuation coefficient depends strongly on the frequency of the sound, the ambient temperature and relative humidity of the air, but only weakly on the ambient pressure. As identified in Table 1, low frequency noise (i.e., less than 250 Hz) will attenuate very little due to the atmosphere; however, mid and high frequency noise will experience much greater levels of attenuation.

Table 1: Atmospheric Attenuation Coefficients

Temperature °C	Relative Humidity %	Atmospheric Attenuation Coefficient α (dB / km)							
		Nominal Mid-Band Frequency (Hz)							
		63	125	250	500	1,000	2,000	4,000	8,000
10	70	0.1	0.4	1.0	1.9	3.7	9.7	32.8	117
20	70	0.1	0.3	1.1	2.9	5.0	9.0	22.9	76.6
30	70	0.1	0.3	1.0	3.1	7.4	12.7	23.1	59.3
15	20	0.3	0.6	1.2	2.7	8.2	28.2	88.8	202
15	50	0.1	0.5	1.2	2.2	4.2	10.8	36.2	129
15	80	0.1	0.3	1.1	2.4	4.1	8.3	23.7	82.8

In Ontario, the MOE requires that atmospheric absorption be based on 10°C and 70% relative humidity.

Ground Effect or Ground Impedance

Ground attenuation is primarily the result of sound reflected by the ground surface interfering with the sound propagating directly from a source to a receiver. The downward-curving propagation path (i.e., downwind or ground based temperature inversion) ensures that this attenuation is determined primarily by the ground surfaces near the source and near the receiver. Three distinct regions for ground attenuation are specified in ISO 9613-2 (i.e., source, middle and receiver) and are defined as follows:

- G (source) – an area defined by 30 times the source height;
- G (middle) – the area between G (source) and G (receiver) provided these areas do not overlap; and
- G (receiver) – an area defined by 30 times the receiver height.

Within ISO 9613-2 three categories of reflecting surface are specified as follows:

- Hard ground, which includes paving, water, ice, concrete and all other ground surfaces having a low porosity. Tamped ground, for example, as often occurs around industrial sites, can be considered hard. For hard ground G = 0.
- Porous ground, which includes ground covered by grass, trees or other vegetation, and all other ground surfaces suitable for the growth of vegetation, such as farming land. For porous ground G = 1.
- Mixed ground: if the surface consists of both hard and porous ground, then G takes on values ranging from 0 to 1, the value being the fraction of the region that is porous.

Reflections

Reflections may be from outdoor rooftops, and vertical surfaces, such as the facades of buildings, which can increase the SPLs at receiver locations. The contribution of the reflections to the overall SPL at a receiver location is dependent on the absorptive/reflective properties of the reflecting surface. Ground reflections are not included as they enter into the calculation of ground effect.

Screening (Barriers)

An object is considered to be a barrier if it meets the following requirements:

- the object breaks the line-of-sight between the source and receiver;
- the surface density is at least 10 kg/m² (in Ontario the MOE requires this to be 20 kg/m²), which minimizes the transmission of sound through the barrier;
- the object has a closed surface without large cracks or gaps; and

the horizontal dimension of the object normal to the source-receiver line is larger than the acoustic wavelength (λ) at the nominal mid-band frequency for the octave band of interest (as a result of large wavelengths, barriers are less effective at mitigating low frequency noise).

5.2.2 ISO 9613-2 Calibration

As the model is empirically based, the algorithms are derived from measurements. Also, since its publication in 1996, numerous studies have been carried out comparing predicted results to measured levels. It has generally been observed that the Standard meets the published accuracy within the stated assumptions.

In addition to comparing predicted results to measured data, other studies have sought to compare ISO 9613-2 to other recognized standards including:

- Harmonoise; and
- NORD 2000.

These studies have found that for unscreened sources, the predictions are within 1 to 2 dB of the other standards. However, for sources that are screened, ISO 9613-2 may predict significantly higher noise levels at receiver locations. Therefore, ISO 9613-2 will predict similar noise levels to other standards for simple geometries and may over predict noise levels in situations where barriers are present.

5.2.2.1 Site-specific Calibration

Previous work has allowed for the measurement of specific on-site noise sources (e.g., back-up generators), measurements at specific locations within the site to capture emissions from large areas, and spot measurements (i.e., short term) and monitoring (i.e., long term) at off-site receiver locations (slide #188). Using this measured data, models were generated and calibrated to the on-site and off-site measured noise levels.

In order to calibrate the models, attenuation factors, as identified in Section 2.3.3 were adjusted to achieve the measured results. Specifically, ground effect, reflections and screening were adjusted. These model set-ups were used for the DGR Project.

5.2.3 Verification of ISO 9613-2 (slide #190)

The verification of ISO 9613-2 has been carried out through the following:

- International Standards Organization (ISO) has one of the most rigorous verification protocols prior to adoption of any standard;
- ISO 9613-2 model was part of the Canadian Standards Association (CSA) standard Z107.10 (currently adopted by the Canadian Acoustical Association)
- Currently undergoing consideration for acceptance by the American National Standards Institute (ANSI); and
- 2005: Golder verified the implementation of ISO 9613-2 algorithms in Cadna/A Independent Verification of ISO 9613-2 in Cadna/A.

5.2.4 Sources of Uncertainty

Uncertainty in the predicted noise levels is derived from the following sources listed in slide #191:

- Noise emissions;
    - The amount of noise energy emitted;
    - Timing of noise emissions;

- Factors affecting noise propagation;
    - Screening (presence of foliage);

    - Directivity of sources;
    - Ground effect;
- Model accuracy;
    - Predictions are ± 3 dB within 1 km.

5.2.4.1 Managing Uncertainty in Emissions

The noise emissions data used for the DGR Project were taken from Golder’s database of similar sources. The list of sources was provided to Golder by OPG and the source noise emissions were matched. All of the data within Golder’s database has been acquired using type 1 analyzers having an accuracy of ± 1 dB. In order to manage this uncertainty, the noise data used typically represents worst-case emissions of the sources (e.g., loader with a full bucket loading a truck vs. loader idling). Also, all the sources were assumed to operate simultaneously for a full hour period and included the back-up generator.

5.2.4.2 Managing Uncertainty in Propagation (slide #193)

The prediction models did not include screening provided by trees and directivity was only included for the vent exhausts. Ground effect was based on site-specific conditions. In addition, all receptors were assumed down-wind from all sources at the same time. Therefore, no reduction in noise level was considered for receptors that were considered up-wind.

5.2.4.3 Managing Uncertainty in Predictions (slide #194)

Six stages of construction were modelled in order to identify the worst-case predictions during this phase of the DGR Project. In addition, source locations were selected, within the project site footprint, to result in higher predicted noise levels at receiver locations. These predicted levels were compared to the quietest existing hourly level at each receptor.

5.2.5 Summary of Confidence

Slides #198 and #199 outline the factors that contribute to the conclusion that noise effects at all receptors will be lower than predicted by Cadna/A in the analysis performed for the DGR project.

6.0 REFERENCES

AECOM and ITASCA CANADA. 2011. Regional Geology – Southern Ontario. AECOM Canada Ltd and Itasca Consulting Canada Inc. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-15 R000. Toronto, Canada.
(available at www.nwmo.ca/dgrgeoscientificsitecharacterization)

AMEC GEOMATRIX. 2011. Seismic Hazard Assessment. AMEC Geomatrix, Inc. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-20 R000. Toronto, Canada. (available at www.nwmo.ca/dgrgeoscientificsitecharacterization)

Armstrong, D.K. and T.R. Carter. 2006. An updated guide to the subsurface Paleozoic stratigraphy of southern Ontario. Ontario Geological Survey, Open File Report 6191.

Armstrong D.K. and T.R. Carter. 2010. The subsurface Paleozoic stratigraphy of Southern Ontario. Ontario Geological Survey, Special Volume 7.

Beyer, W.N., E. Connor, and S. Gerould. 1994. Journal of Wildlife Management 58, 375-382.

Bruce Power. 2009. Annual Summary and Assessment of Environmental Radiological Data for 2008. Bruce Power report B-REP-03419-00009-R00.

CNSC. 2009. Letter from K. Klassen to F. King. DGR Project for OPG’s LILW - Proposed Acceptance Criteria for Postclosure Safety Assessment of Radiological Impacts on Non-Human Biota and for Non-Radiological Impacts on Humans and Non-Human Biota, August 17, 2009.

CSA. 1990 (reaffirmed 2008). Guidelines for Radiological Monitoring of the Environment. Canadian Standards Association, Standard N288.4- M90.

CSA. 2008. Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operation of Nuclear Facilities. Canadian Standards Association, Standard N288.1-08.

EMRAS. 2012. Modelling Radiation Exposure and Radionuclide Transfer for Non-human Species. Report of the Biota Working Group of EMRAS Theme 3, Environmental Modelling for Radiation Safety (EMRAS) Programme
(available at http://www-ns.iaea.org/downloads/rw/projects/emras/final-reports/biota-final.pdf Extracted September 10, 2012)

ENVIRONMENT CANADA and HEALTH CANADA. 2003. Priority Substance List Assessment Report – Releases of Radionuclides from Nuclear Facilities (Impact on Non-Human Biota). Canadian Environmental Protection Act.

FASSET. 2003. Deliverable 3. Dosimetric Models and Data for Assessing Radiation Exposures to Biota. Framework for Assessment of Environmental Impact report. EC 5th Framework Programme.

Garisto, N.C. 2005. Nominal radioecological benchmarks for the ecological risk assessment of radioactive waste management facilities. Proceedings of CNS Waste Management Conference, Ottawa, Canada.

Garnier-Laplace, J., C. Della-Vedoca, R. Gilbin, D. Copplestone, K. Kingston and P. Ciffroy. 2006. First derivation of predicted no effect values for freshwater and terrestrial ecosystems exposed to radioactive substances. Environmental Science and Technology Journal. 40, No. 20, 6498-6505.

GEOFIRMA. 2011. Postclosure Safety Assessment: Groundwater Modelling. Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization DGR-TR-2011-20 R000. Toronto, Ontario. (available at http://www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

GEOFIRMA and QUINTESSA. 2011. Postclosure Safety Assessment: Gas Modelling. Geofirma Engineering Ltd. and Quintessa Ltd. report for the Nuclear Waste Management

Organization NWMO DGR-TR-2011-31 R000. Toronto, Canada.
(available at http://www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

ICRP. 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. International Commission on Radiological Protection Publication 108. Annals of the ICRP, 38 (4-6).

INTERA. 2011. Descriptive Geosphere Site Model. Intera Engineering Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-24- R000. Toronto, Canada. (CEAA Registry Doc# 300)

ITASCA CANADA and AECOM. 2011. Three-Dimensional Geological Framework Model. Itasca Consulting Canada, Inc. and AECOM Canada Ltd. Report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-42 R000. Toronto, Canada.
(available at www.nwmo.ca/dgrgeoscientificsitecharacterization)

Loat, B.V., N. Hung and H. Phuong. 2010. Monte Carlo simulation by code of MCNP and experimental check for measuring thickness of materials for the specializing system of MYIO-101. VNU Journal of Science, Mathematics – Physics 26, 43-49.

Maul P.R. and P.C. Robinson. 2002. Exploration of Important Issues for the Safety of SFR 1 using Performance Assessment Calculations. Swedish Nuclear Power Inspectorate (SKI) report 02:62. Stockholm, Sweden.

Maul, P., P. Robinson, R. Broed and R. Avila. 2004. Further AMBER and Ecolego Intercomparisons. Swedish Nuclear Power Inspectorate (SKI) report 2004:05. Stockholm Sweden.

NWMO. 2011. Geosynthesis. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-11 R000. Toronto, Canada. (CEAA Registry Doc# 300)

OPG. 2005. Ecological Risk Assessment Technical Support Document for WWMF RWS Project.

OPG. 2009. Ecological Risk Assessment and Assessment of Effects on Nonhuman Biota Technical Support Document New Nuclear – Darlington. Ontario Power Generation report NK054-REP-07730-00022 Rev 000. Toronto, Canada.

Peltier, W.R. 2011. Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-14 R000. Toronto, Canada.
(available at www.nwmo.ca/dgrgeoscientificsitecharacterization)

QUINTESSA. 2011. Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario. Quintessa Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-26 R000. Toronto, Canada.
(available at http://www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

QUINTESSA and GEOFIRMA. 2011. T2GGM Version 2: Gas Generation and Transport Code. Quintessa Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management

Organization NWMO DGR-TR-2011-33 R000, Toronto, Canada. (available at http://www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

QUINTESSA and SENES. 2011. Postclosure Safety Assessment: Analysis of Human Intrusion and Other Disruptive Scenarios. Quintessa Ltd. and SENES Consultants Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-27 R000. Toronto, Canada. (available at http://www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

US EPA. 1993. Wildlife Exposure Factors Handbook. United States Environmental Protection Agency report EPA/600/R-93/187. Washington D.C., USA.

UNSCEAR. 1996. Effects of Radiation on the Natural Environment. United Nations Scientific Committee on the Effects of Atomic Radiation. Vol. V92-53957

ATTACHMENT 2

Attachment to OPG letter, Albert Sweetnam to Dr. Stella Swanson, “Deep Geologic Repository Project for Low and Intermediate Level Waste – Submission for the October 11, 2012 JRP Technical Information Session #2”

October 3, 2012

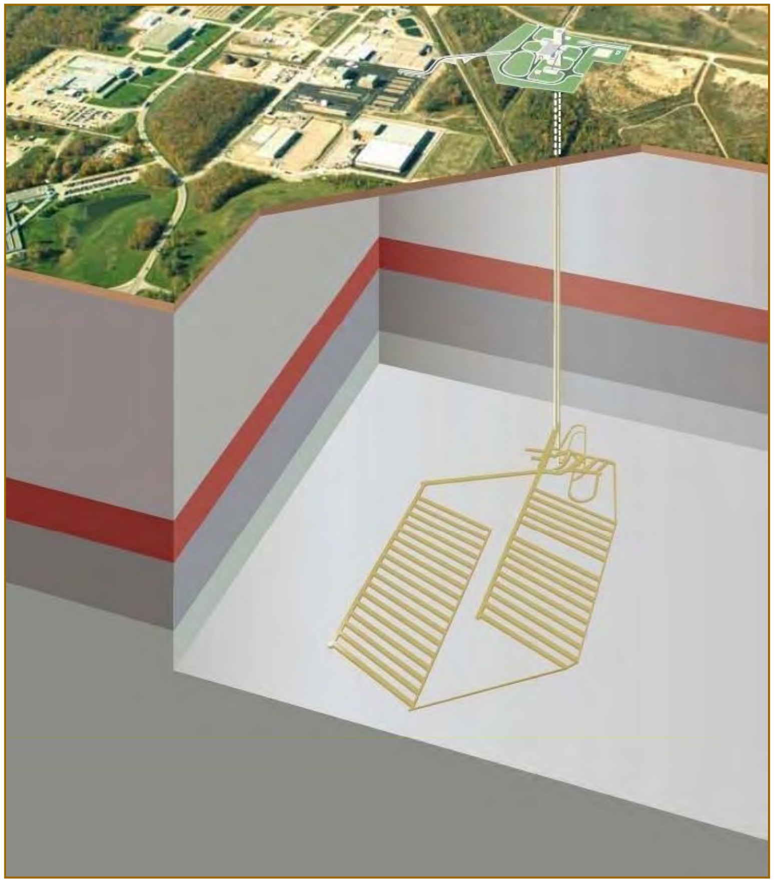
CD#: 00216-CORR-00531-00142

OPG’s Presentation for JRP’s Technical Information Session #2 on October 11, 2012

Presentation to Joint Review Panel

Technical Information Session #2

Ottawa, Ontario



ONTARIO POWER GENERATION

Outline of Presentation

Part One - Geoscience Modelling

- **3-DGFM**
- FRAC3DVS-OPG
- TOUGH2-MP
- MIN3P

Part Two - Repository Evolution Modelling

- FLAC3D
- FRAC3DVS-OPG
- T2GGM
- AMBER

Part Three - Radiation Dose Modelling

- MicroShield, MicroSkyshine, MCNP
- Non-Human Biota

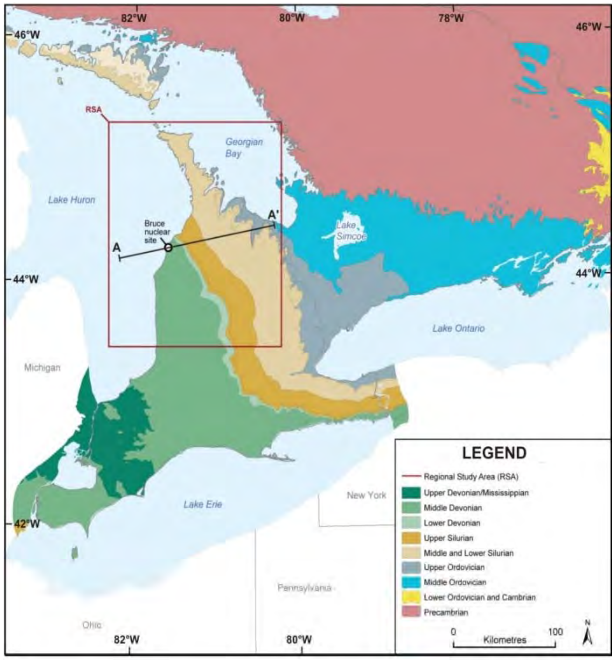
Part Four – Environmental Modelling

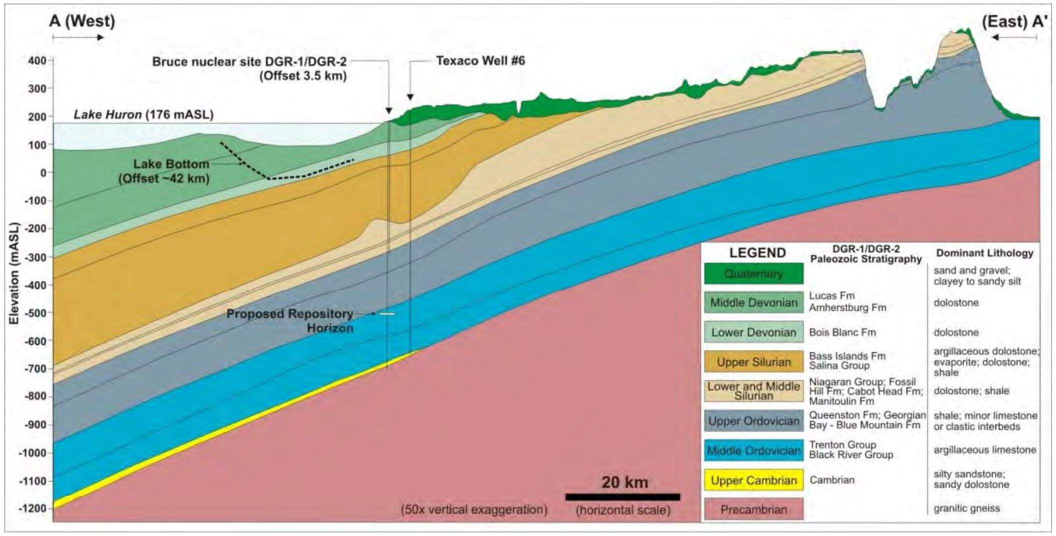
- AERMOD
- Cadna/A

Geoscience Modelling: 3-DGFM

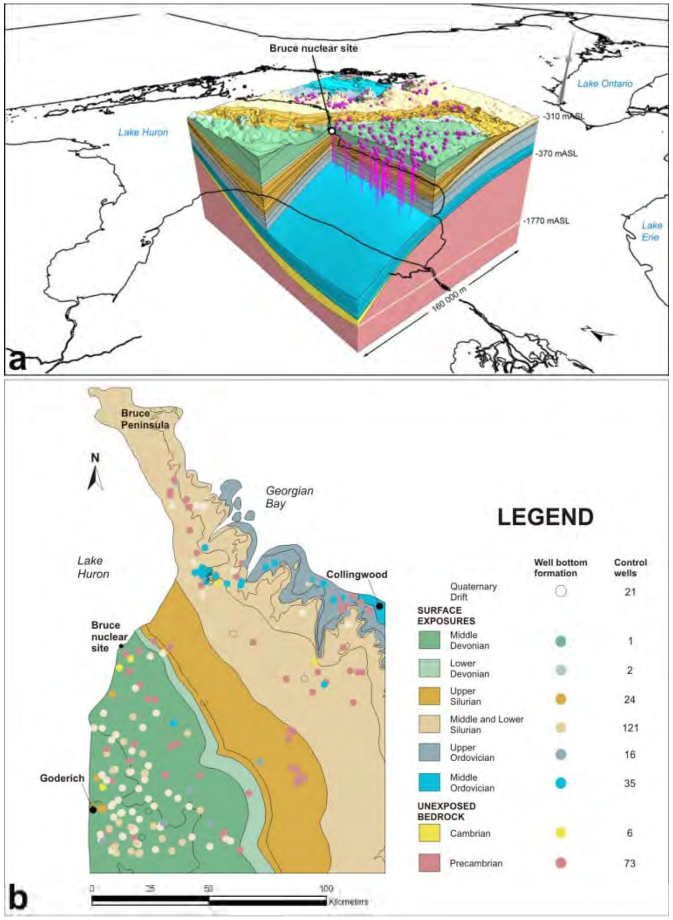
Purpose:

To develop a 3-dimensional geologic framework model (3-DGFM) that describes sedimentary bedrock stratigraphy and geometric continuity within the 35,000 km^2 DGR regional scale domain.





3-DGFM – Topographic/Geologic Data

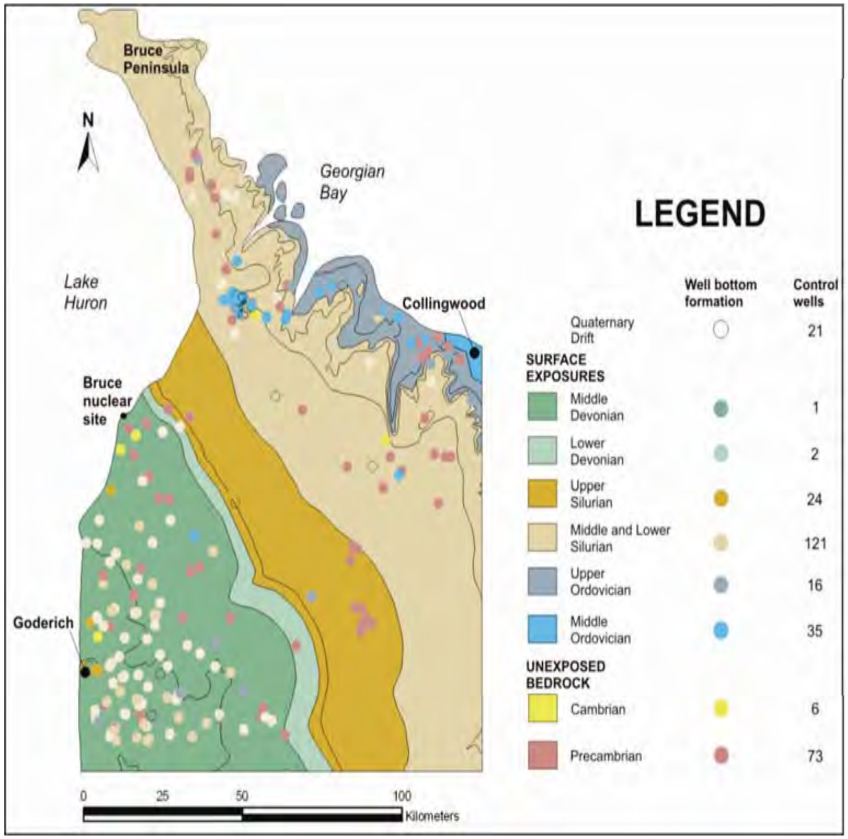


i. Ontario Oil, Gas and Salt Resources Library (OGSRL) Petroleum Wells Subsurface Database (Borehole records 1930-present);
ii. Ontario Geologic Survey Digital Bedrock Geology of Ontario Seamless Coverage ERLIS Data Set 6 (Scale 1:50,000);
iii. Historic borehole geophysical survey logs from selected wells within the RSA (OGSRL);
iv. OGS Open File Report 6191, "An updated guide to the Paleozoic stratigraphy of southern Ontario" (Armstrong and Carter 2006);
v. Michigan Department of Natural Resources and Environment, Petroleum Well Database;
vi. OGS Digital Bedrock topography and overburden thickness mapping, Southern Ontario – Miscellaneous Data Release no. 207; and
vii. National Oceanic and Atmospheric Administration (NOAA) digital bathymetry mapping of Lake Huron and Georgian Bay (Great Lakes Bathymetry Gridding Project 2007).

3-DGFM – Data Verification

Historic Drilling Records – Data Screening:

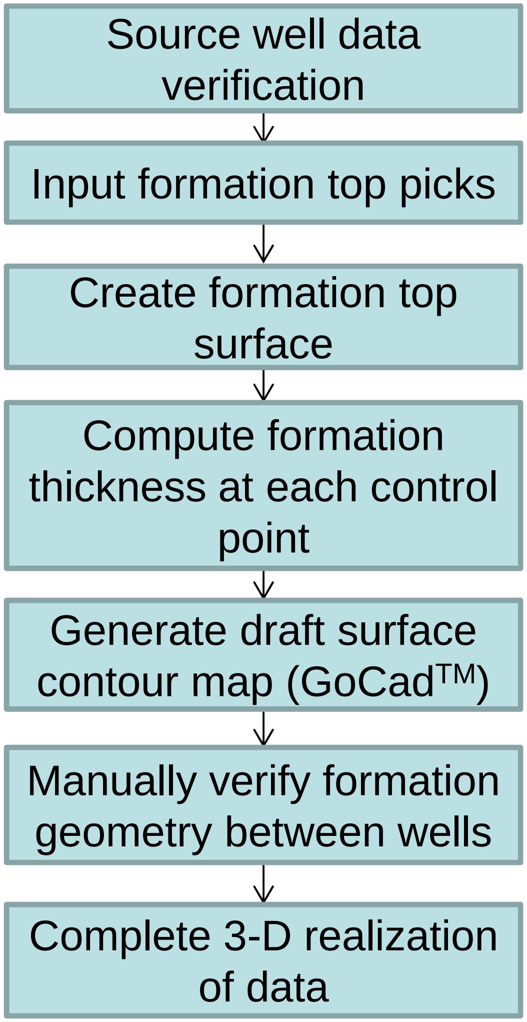
- Detect historic well log errors (e.g., no data; incorrect stratigraphic contact elevation, incorrect collar ground surface elevation);
- Determination if correct stratigraphic relationships are recorded correctly in the well log by comparison to adjacent well record(s); and
- Check geophysical well logs (when available) against current established Petroleum Well reference geophysics (Armstrong and Carter, 2006).



Result:

- 299 of the 341 well records were included in final 3-DGFM (all decisions documented in Appendix C of report)

3-DGFM – Modelling Approach



Source well data verification

Input formation top picks

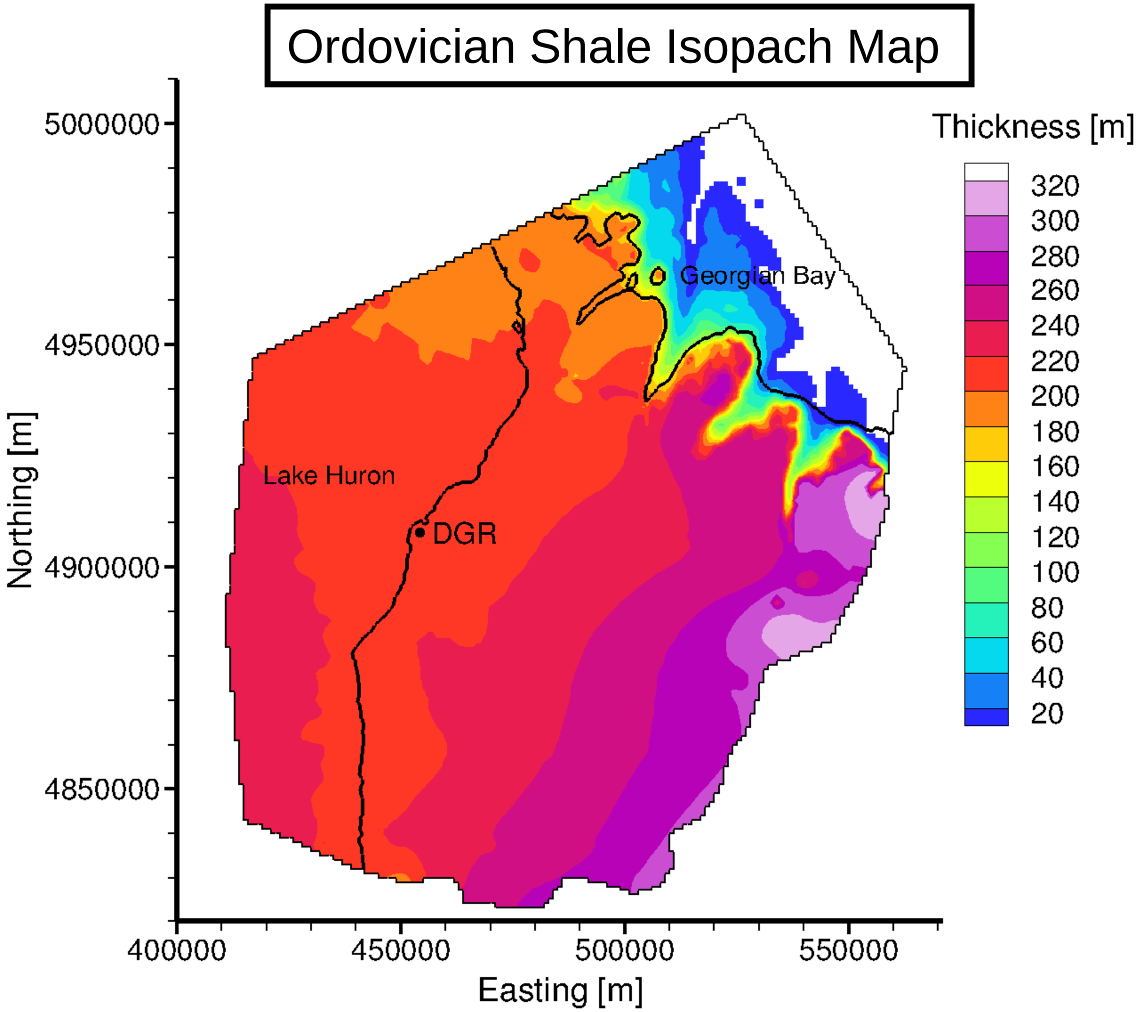
Create formation top surface

Compute formation thickness at each control point

Generate draft surface contour map (GoCad™)

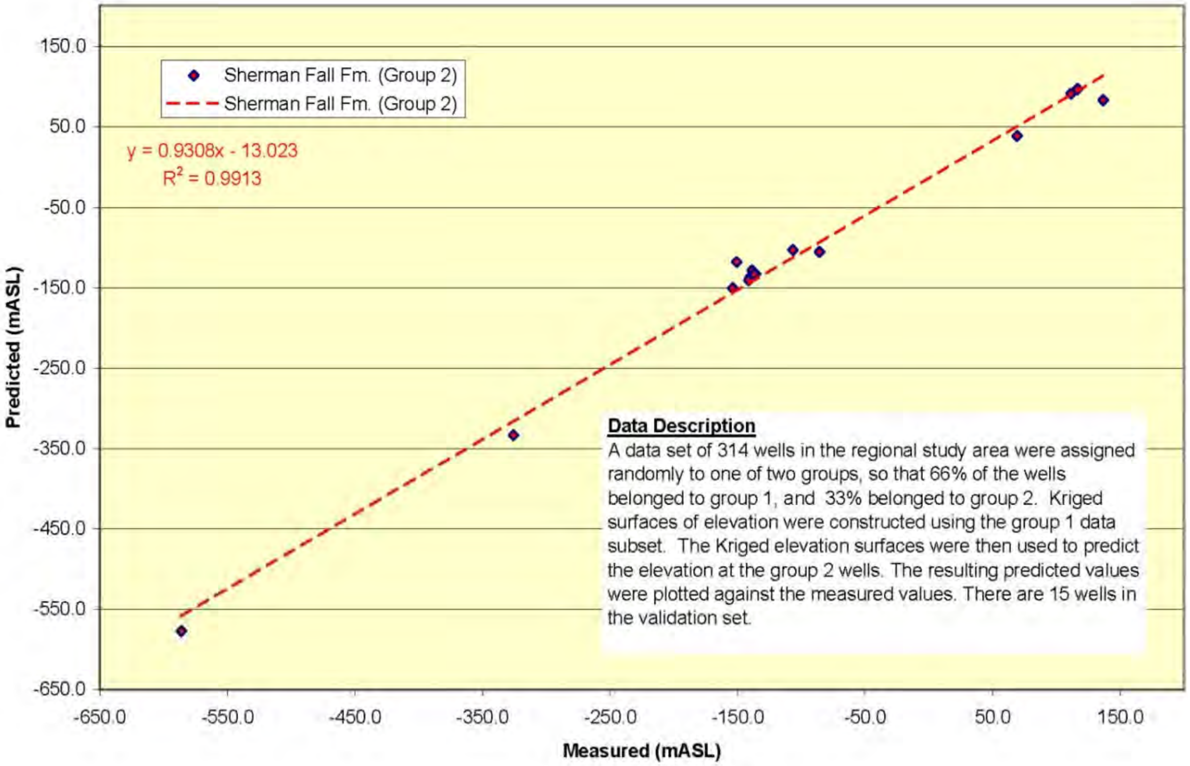
Manually verify formation geometry between wells

Complete 3-D realization of data



Ordovician Shale Isopach Map

3-DGFM – Model Testing (Regional Scale)



Data Description

A data set of 314 wells in the regional study area were assigned randomly to one of two groups, so that 66% of the wells belonged to group 1, and 33% belonged to group 2. Kriged surfaces of elevation were constructed using the group 1 data subset. The Kriged elevation surfaces were then used to predict the elevation at the group 2 wells. The resulting predicted values were plotted against the measured values. There are 15 wells in the validation set.

A formation top surface was generated using 67 % of wells intersecting the Sherman Fall Formation, while the other 33 % of the wells were compared for their actual and predicted depths.

3-DGFM – Model Testing (Site Scale)

Formation	3-DGF - Depth of Formation (mBGS)	DGR-4 - Depth of Formation (mBGS)	Absolute Error – 3-DGF vs DGR-4 (m)
Detroit River Gp	1.1	7.5	6.5
Bois Blanc Fm	86.0	76.2	9.8
Bass Islands Fm	124.1	126.0	1.9
Salina G Unit	171.7	170.1	1.6
Salina F Unit	180.3	177.4	2.9
Salina E Unit	220.4	221.0	0.6
Salina D Unit	244.4	245.5	1.0
Salina B and C Units	246.5	247.3	0.8
Salina B Anhydrite Salt	285.2	290.8	5.6
Salina A2 Carbonate	293.4	292.5	0.9
Salina A2 Anhydrite Salt	319.4	320.9	1.5
Salina A1 Carbonate	326.8	325.1	1.7
Salina A1 Evaporite	364.6	366.8	2.2
Niagaran	369.0	375.6	6.6
Reynales Fossil Hill Fm	409.7	410.0	0.3
Cabot Head Fm	414.4	411.5	2.9
Manitoulin Fm	434.9	435.7	0.8
Queenston Fm	451.1	446.3	4.8
Georgian Bay/Blue Mtn Fm	521.9	519.3	2.6
Cobourg Fm	656.5	653.1	3.4
Sherman Fall Fm	689.0	689.0	0.0
Kirkfield Fm	733.3	717.3	16.0
Coboconk Fm	764.1	763.0	1.1
Gull River Fm	781.3	786.8	5.5
Shadow Lake Fm	838.4	839.0	0.6
Cambrian	845.9	844.1	1.8

Blind depth test

Prediction of formation top depths in DGR-4 based on model surface projections

Large error is a result of modification of top pick criteria for the Kirkfield Formation

3-DGFM – Confidence Assessment

Confidence that the 3-DGFM reflects a reasoned understanding of bedrock stratigraphy across the regional model domain is based on the following factors:

- Data Screening: Historic OGSRL well logs vetted
- Model Verification: 3-dimensional visualization
  - Well Log data checked against published well reference data
  - Model formation surfaces reflect all reference data points/contacts
  - Model formation surfaces manually refined to reflect geologic understanding
- 3-DGFM is consistent with published bedrock geology, bedrock topography and Lake Huron bathymetric data sets
- The model passed both regional and site-scale performance tests
- Peer-review, including 4 core workshops, provided feedback on the geological framework classification scheme developed for use in the model
- The data used in the model is publicly available for independent model development and verification (Appendix C of NWMO DGR-TR-2011-42)

3-DGFM – Relative Contribution to Confidence

Line of Evidence	**Relative Contribution** **Regional Scale**	 **Site Scale**
Data Verification • Screening of historical data	++	N/A
• Core workshop consensus	N/A	+++
Data Calibration • Nearest neighbour borehole correlations	+	+++
Data Certainty	++	+++
Model Confidence (Overall)	++	+++
• Lateral stratigraphic traceability	+++	+++
• Estimated Thicknesses	++	+++
• Structural Framework	+	+++

<u>Note</u>: + Lower; ++ Medium; +++ Higher; N/A Not applicable

Outline of Presentation

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- AERMOD
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Geoscience Modelling – FRAC3DVS-OPG

Purpose:

To conduct numerical hydrogeologic analyses at basin, regional and site-specific scales to develop and test the understanding of long-term shallow, intermediate and deep groundwater system properties and behaviour relevant to DGR safety.

Objective:

Issue-based analyses conducted to explore and examine groundwater system evolution, system property uncertainty, long-term stability and behaviour as constrained by observation data sets. Specific simulations included:

- Regional Scale (18,000 km^2) saturated density-dependent
- Site-specific (400 km^2) saturated density-dependent
- Site-specific two-phase gas/water
- Paleohydrogeology – glacial perturbations

FRAC3DVS-OPG – Fundamental Aspects

Model Development:

- The FRAC3DVS model was developed by Therrien (1992)
- The FRAC3DVS model was officially released in 1995
- Numerous journal papers have been published on the attributes of the model
- User base in academia, consulting and government
- OPG supported the development of FRAC3DVS beginning in 2001
- The OPG version of FRAC3DVS has a comprehensive user manual; QA/QC has 35 verification test problems

Model Attributes (partial list):

- Three-dimensional, density-dependent flow and solute transport in variably saturated porous media
- Transport by advection, mechanical dispersion and diffusion
- Radionuclide parent-daughter in-growth
- One-dimensional mechanical loading
- Estimation of water mean life expectancy and solute transit time probabilities

FRAC3DVS-OPG – Modelling Approach (1)

Modelling Process: Issue Based

Do the physics simulated by the model adequately describe the processes occurring?

A numerical model based on the physics requires:

- Specification of geometry or spatial extent
- Estimation of parameters and constitutive laws
- Specification of boundary conditions and initial conditions for transient problems
- Appropriate discretization of the spatial domain and time scale

FRAC3DVS-OPG was used for:

- Data analysis and verification
- Data synthesis (i.e., integration)
- Hypothesis testing

FRAC3DVS-OPG – Modelling Approach (2)

Uncertainty Analysis in the model study:

- ***Conceptual Model uncertainty*** is investigated through the use of two computational models:
  - FRAC3DVS-OPG with and without mechanical coupling to simulate saturated flow
  - TOUGH2-MP to simulate flow with an immiscible gas phase
- ***Parameter uncertainty*** is investigated using
  - sensitivity analyses and "what if" scenarios to explore the parameter space with the check being "Do the results adequately describe the data observed (i.e., model calibration)?"
  - alternate boundary conditions to assess their impact on the performance measures describing the DGR site

36 numerical models were developed in the study to explore the influence of groundwater system parameters, boundary conditions and physics used to describe the DGR subsurface domain.

FRAC3DVS-OPG – Study Design (1)

Structured Model Simulations/Scenarios

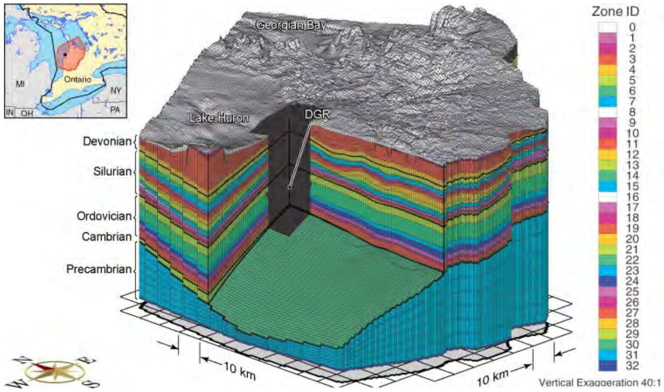
- Estimation of the vertical hydraulic conductivities of the Ordovician sediments
    - Sensitivity analysis developed with the model results being compared to the pressure profile observed in the DGR boreholes
- Investigate the depth of penetration into the geosphere of glacial melt water
    - 10 different paleohydrogeologic scenarios developed to explore the parameter space and model physics
- Investigate the cause of the measured under-pressures in the Ordovician sediments and over-pressures in the Cambrian sandstone
    - Use two different models (FRAC3DVS-OPG and TOUGH2-MP) to investigate flow in the Ordovician sediments (if it is occurring) and different hypotheses of the cause of the under-pressures
- Investigate issues such as the impact on groundwater flow of Precambrian rock with enhanced hydraulic conductivity
    - Design numerical experiments to investigate the impact on performance measures such as mean life expectance (MLE)

FRAC3DVS-OPG – Study Design (2)

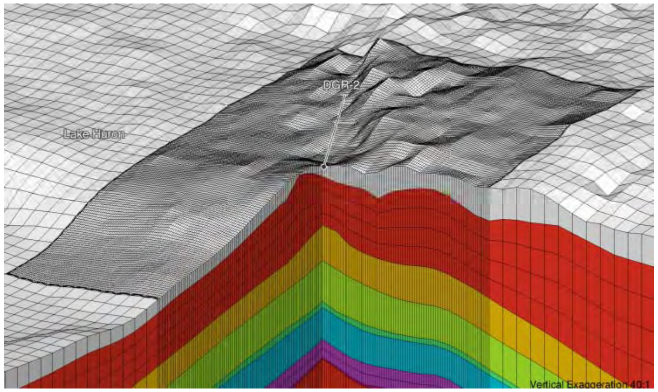
- Investigate the impact of the boundary conditions on the study performance measures such as MLE
  - Analyze flow in two different conceptual models (regional scale and Michigan Basin cross-section)
  - Investigate alternate boundary conditions for the top of the domain (recharge boundary condition and specified depth to water table)
  - Undertake sensitivity analyses with alternate lateral boundary conditions for the regional-scale model and the paleohydrologic model
  - Use either embedment or nested models for the site-scale analyses; that is, the lateral boundaries for the site-scale model are derived from the solution of the regional-scale model
- Investigate the hypothesis that vertical fractures connecting the Cambrian sandstone and the Niagaran occur proximal to the DGR site
  - Site-scale sensitivity analyses undertaken; the degree to which the model results describe the DGR site data and the site performance measures was assessed
- Parameter sensitivity analyses were undertaken throughout the study to provide confidence in the results

FRAC3DVS-OPG – Spatial Scales

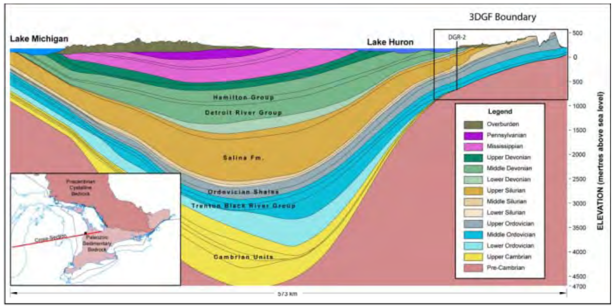
Application at four spatial scales



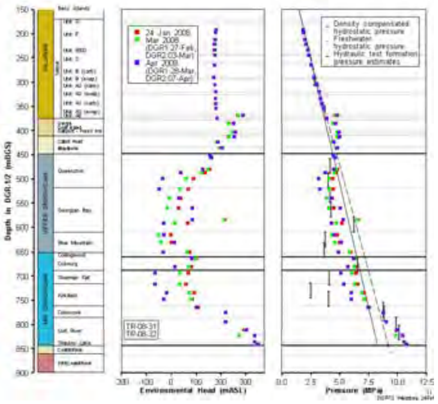
Regional-scale



Site-scale



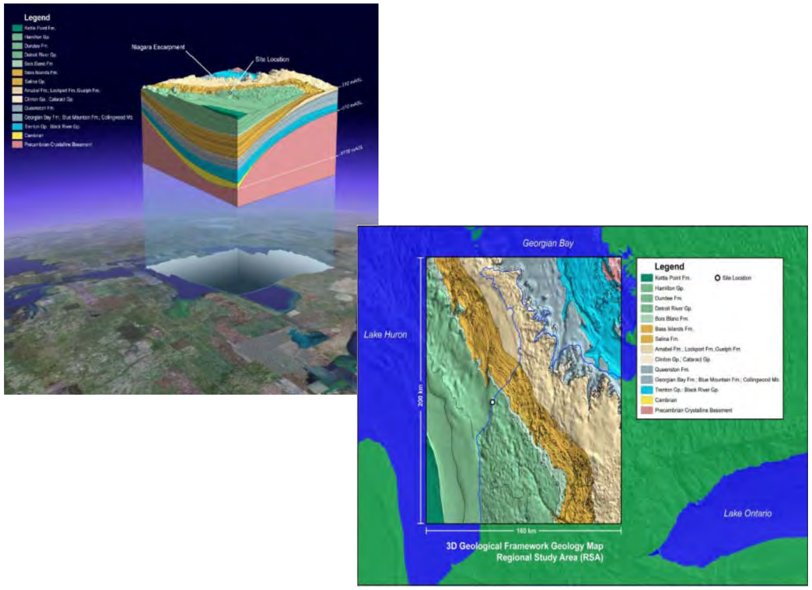
Cross-section

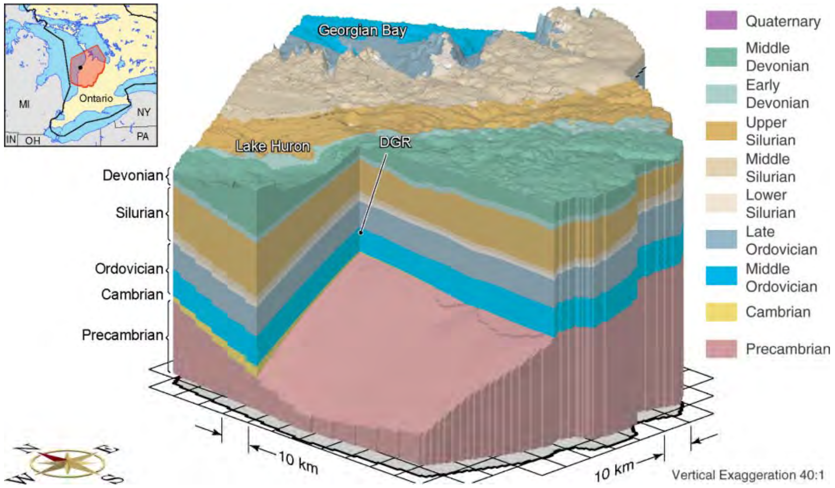


One-dimensional column

FRAC3DVS-OPG – Model Layout

The layers of the numerical model represent the bedrock stratigraphy identified in the DGR boreholes and the layers identified in the three-dimensional geologic framework model.

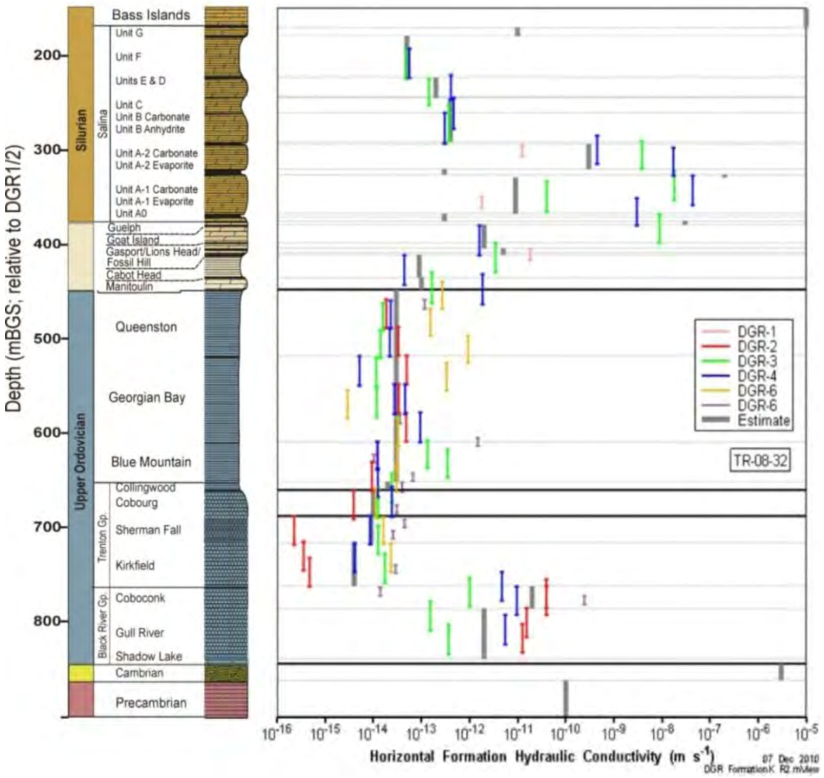




Uncertainty Assessment – Parameter (1)

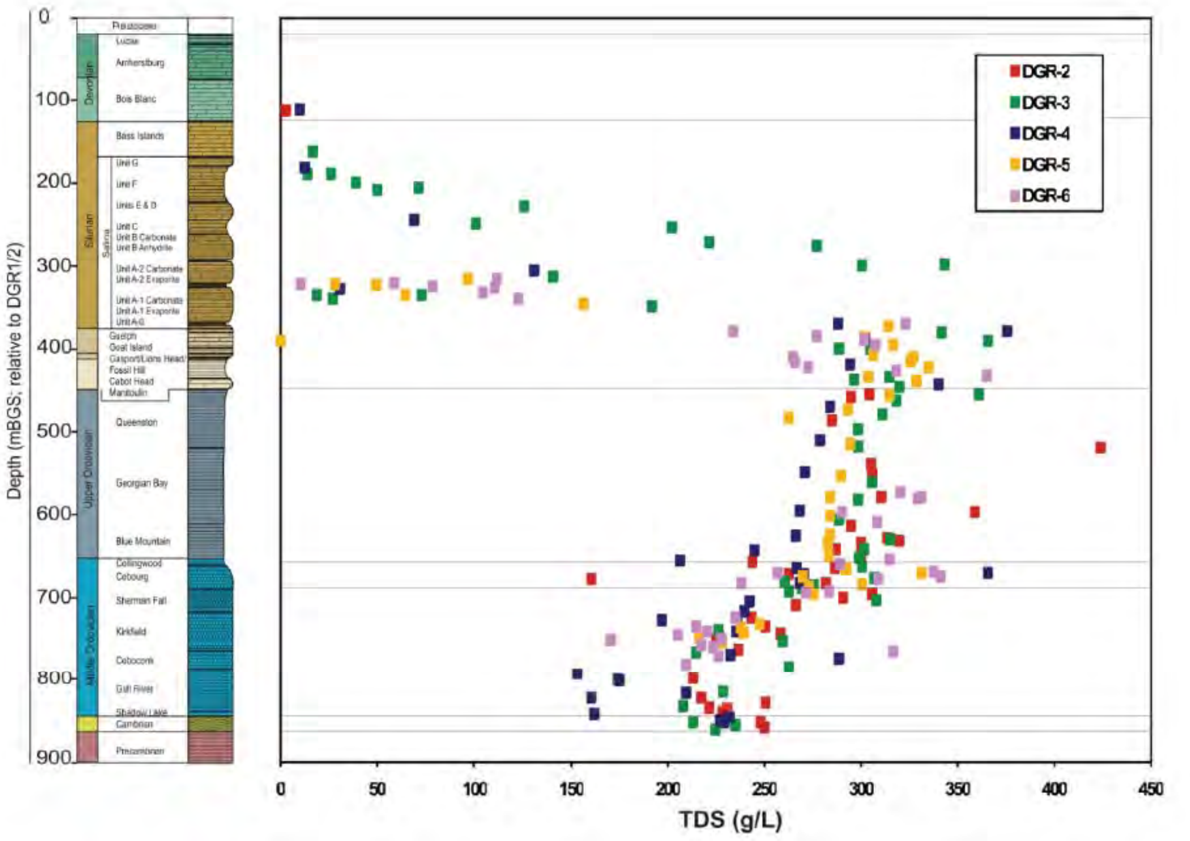
The base-case numerical simulations use:

- the rock mass hydraulic conductivities estimated from in-situ straddle packer tests in the DGR boreholes (Descriptive Geosphere Site Model).
- Uncertainty is investigated using a parameter sampling approach



Uncertainty Assessment – Parameter (2)

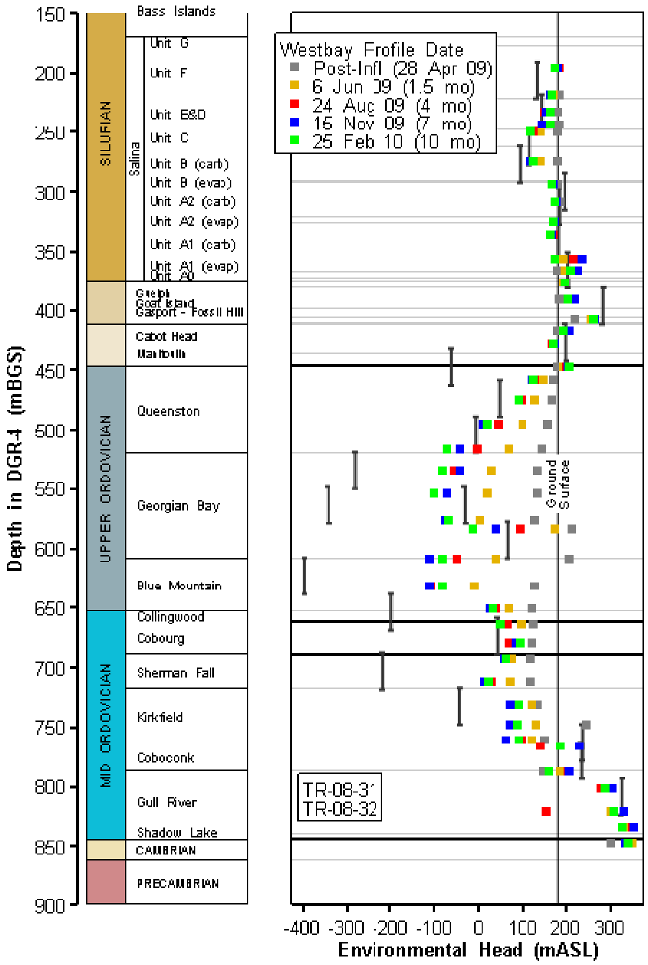
Reference groundwater/pore fluid densities were linked to: i) observed total dissolved solids (TDS) concentrations determined from laboratory rock core analyses and opportunistic groundwater sampling; and ii) regional hydrogeochemical trends within the sedimentary sequence.



Uncertainty Assessment – Parameter (3)

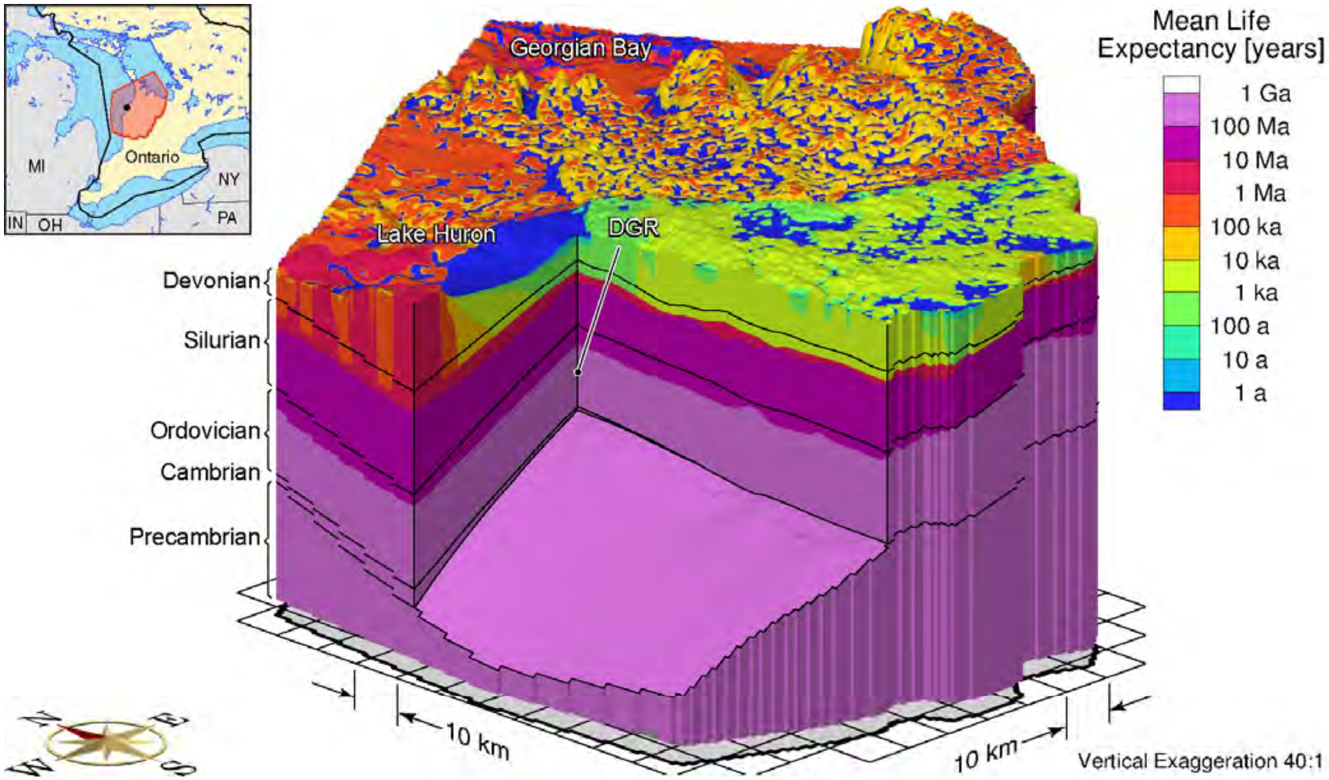
DGR field and laboratory data:

- Geomechanical properties derived from laboratory geomechanical tests, for example, Young's moduli and Poisson's ratios, were used to estimate and justify specific storage coefficients and one-dimensional loading efficiencies necessary for Hydro-Mechanical Paleohydrogeologic simulations.
- Effective diffusion coefficients necessary for simulation of mass transport derived from UNB laboratory data sets.
- Observed formation hydraulic pressures measured in the Westbay-instrumented DGR boreholes were used to assess reliability of numerical simulations performed to estimate vertical rock mass hydraulic conductivities.



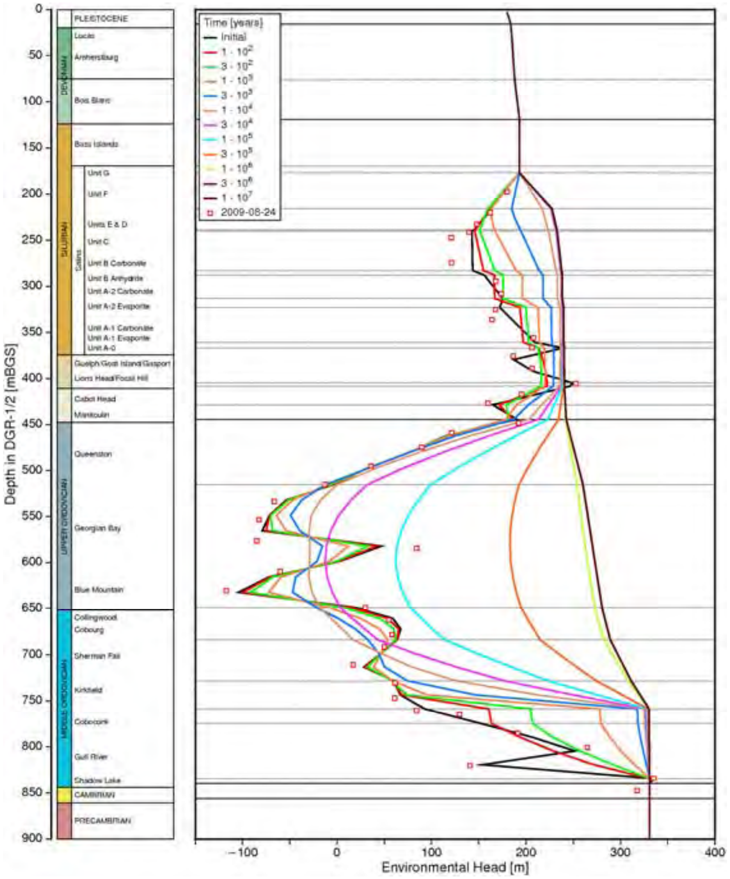
FRAC3DVS-OPG – Solute Transport

The mean life expectancy (MLE), which is a measure of the time that it will take a solute to migrate to a point of groundwater discharge, is estimated to be greater than 100 million years.



Calibration – Site-specific Analogue (1)

Site-specific analogue supports case that the vertical hydraulic conductivities of the Ordovician formations are on the order of 1×10^{-14} m/s or less based on comparison to observed hydraulic head data sets.



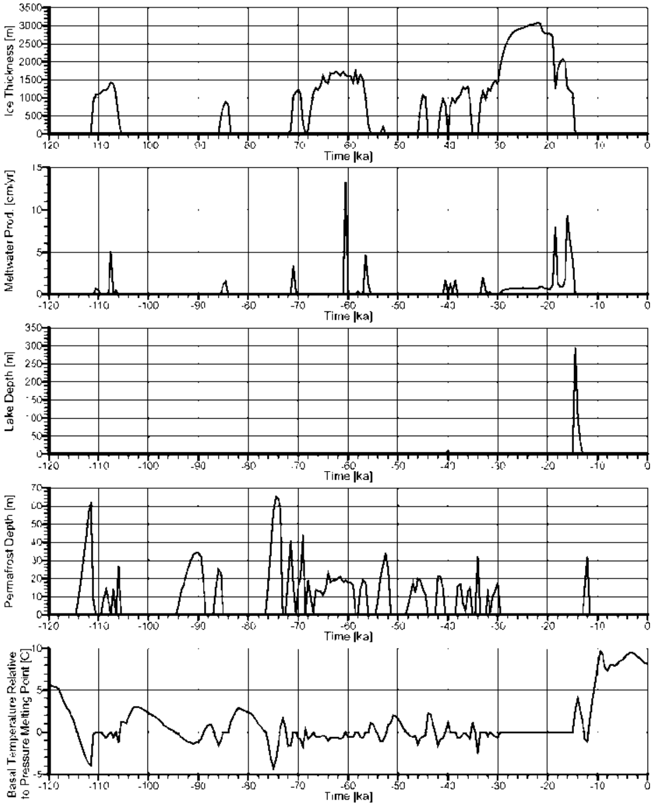
The observed upward vertical gradient in the Shadow Lake, Gull River and Coboconk cannot be maintained if K_v is greater than 1×10^{-14} m/s

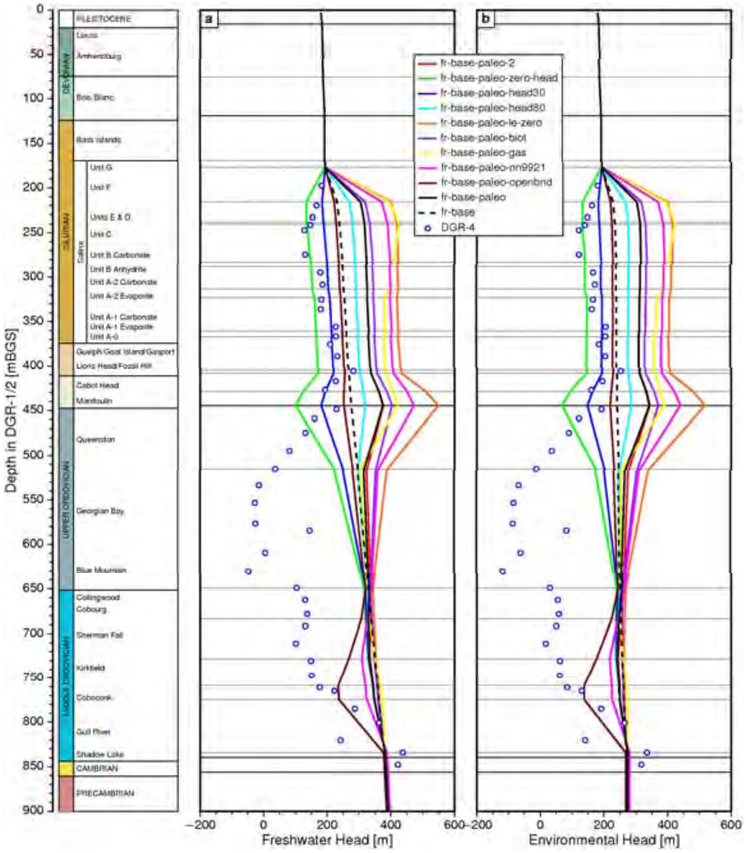
The occurrence of under-pressures requires a low formation scale K_v

A result of the low K_v is diffusion dominant transport

Calibration – Site-specific Analogue (2)

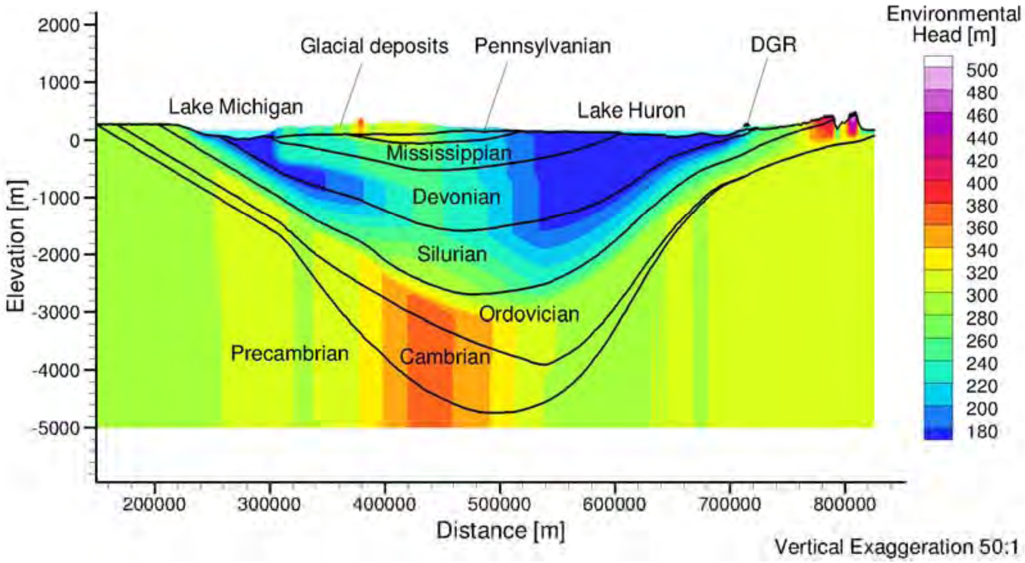
The observed strong under-pressures in the Ordovician sediments could not be uniquely described by paleohydrogeologic scenarios; the results from the 10 sensitivity analyses provide bounding estimates that support this conclusion.

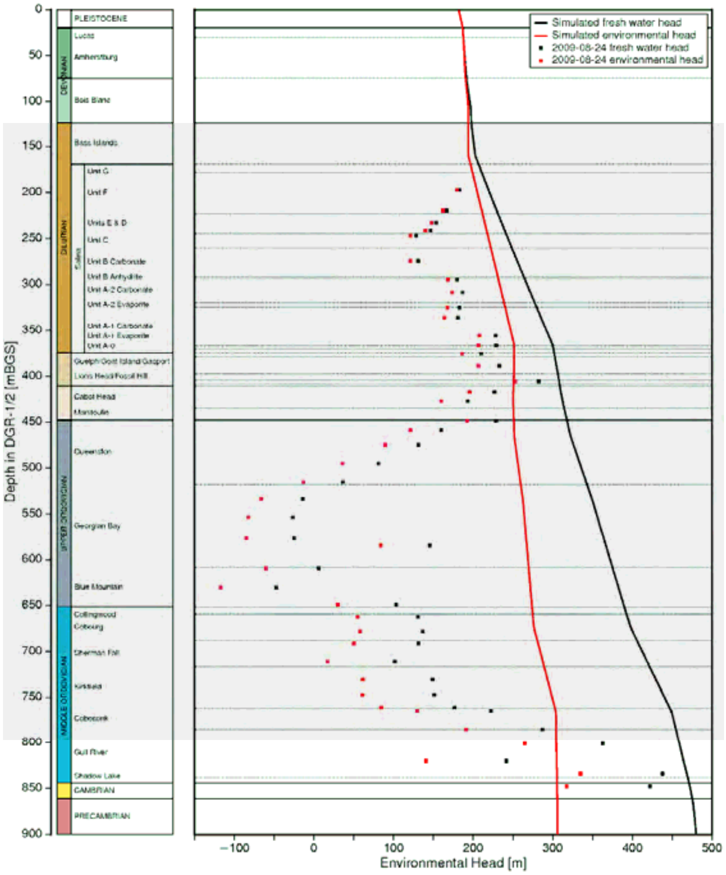




Calibration – Site-specific Analogue (3)

The over-pressures in the permeable Cambrian sandstone observed beneath the Bruce nuclear site appear related to the combined results of basin topography, hydrostratigraphic geometry and the fluid density variation at basin scale.



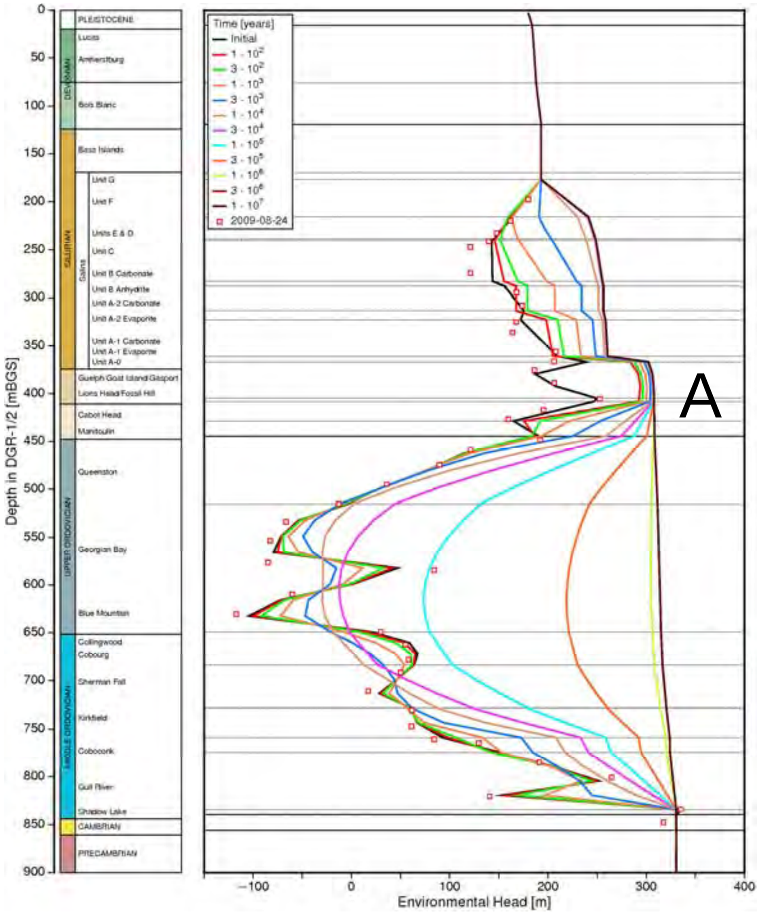


A

B

Calibration – Hypothetical Vertical Fractures

Vertical fractures proximal to the location of the proposed DGR that connect the Cambrian and Guelph formations are inconsistent with the observed pressures in the DGR boreholes.



Note that the heads in the Niagaran are not preserved

Confidence Assessment

The hydrogeologic modelling study was designed to investigate ***model uncertainty***

- Two different computational models were used: FRAC3DVS-OPG and TOUGH2-MP
- Variants of FRAC3DVS-OPG were used: with and without mechanical coupling

The study design explored ***parameter uncertainty*** by sampling the parameter space and by the use of alternate conceptual models and alternate descriptions of the model boundary conditions.

The study design addressed hypotheses and issues using “what if” scenarios.

The model results from the 36 scenarios of the study design were compared to the data for the DGR site in ***model calibration*** to build confidence in the results and conclusions.

Confidence in the results was also achieved using mutliple lines-of-evidence:

- The numerical modelling results are consistent with the geochemical, geomechanical and geologic models of the DGR site

FRAC3DVS-OPG – Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Widely used and reviewed code	+++
Verification of the model to other codes	+++
Verification that model results are consistent with the conceptual model	+++
Calibration of parameters using input data from the DGR site when available (e.g., pressures)	+++
Sensitivity analysis used to confirm that solute transport in the Ordovician sediments is diffusion dominant and insensitive to the description of the boundary conditions	+++
Sensitivity analysis used to confirm that solute transport in the Ordovician sediments is diffusion dominant and insensitive to glaciation	+++
Sensitivity analysis used to confirm that solute transport in the Ordovician sediments is diffusion dominant and insensitive to uncertainties in the hydraulic parameters	+++
Sensitivity analysis used to confirm that solute transport in the Ordovician sediments is diffusion dominant and insensitive to the mechanisms causing the under-pressures in the sediments	+++
Glacial meltwater does not penetrate into the Ordovician units	+++
Over-pressures in the Cambrian sandstone are the result of the geometry of the layers in the Michigan Basin and variations in the density of water in the basin	+++
The under-pressures in the Ordovician sediments are the result of glaciation	+
Overall Confidence	**+++**

Note: *+ Lower; ++ Medium; +++ Higher*

Outline of Presentation

Part One - Geoscience Modelling

- 3-DGFM
- FRAC3DVS-OPG
- **TOUGH2-MP**
- MIN3P

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- FLAC3D
- FRAC3DVS-OPG
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- AERMOD
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Geoscience Modelling – TOUGH2-MP

Purpose:

To conduct illustrative numerical simulations to examine and test the hypothesis that the observed formation under-pressures in the Ordovician sediments, which includes the Cobourg host rock for the DGR, are associated with the presence of an immiscible gas phase in the low-permeability sedimentary rocks.

Objective:

To perform uncertainty analyses that provide a reasoned basis to constrain an understanding of the phenomena and system attributes necessary to generate and preserve the formation under-pressures observed in the Ordovician sediments.

TOUGH2-MP – Fundamental Aspects

TOUGH2-MP is a general-purpose numerical simulation program for multi-dimensional fluid and heat flows of multiphase, multi-component fluid mixtures in porous and fractured media.

The TOUGH2-MP model requires a fluid property or equation-of-state module. The DGR Hydrogeologic Modelling study used the module EOS3. The module is used for the simulation of immiscible air and water phases. The module does not include brine.

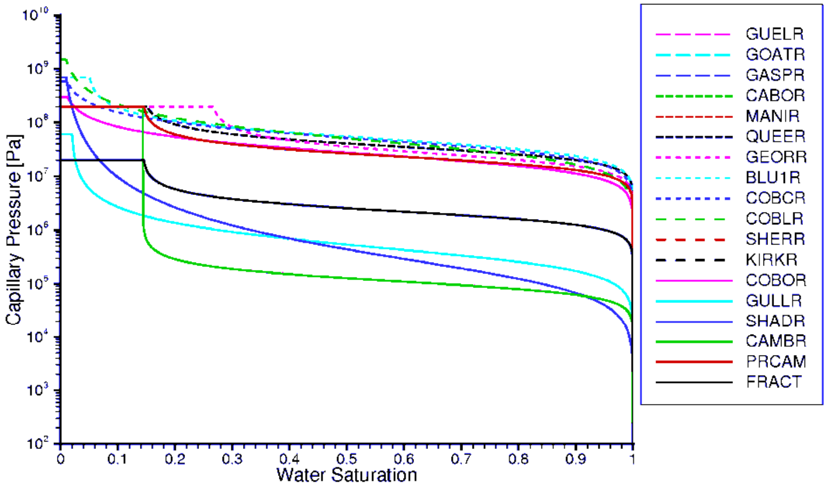
Development of the Model:

- The original TOUGH2 code was released in 1991 by Lawrence Berkeley Laboratory (LBL) (Pruess, 1991)
- TOUGH2-MP is a parallelized version of the code
- The model is used world-wide
- It is the model of choice for nuclear waste isolation studies that include an immiscible gas phase
- LBL continues to support the model

TOUGH2-MP – Modelling Approach

The impact of parameter uncertainty is minimized by using the DGR lab and field data:

- One-dimensional column representative of the stratigraphy at DGR-2
- Simulate transient flow and transport vertically between the Cambrian sandstone and the Niagaran
- Rock mass permeabilities are estimated with: i) DGR borehole straddle packer hydraulic conductivities; and ii) fluid densities estimated with laboratory derived pore fluid total dissolved solids concentrations in the Ordovician/Silurian rock
- Capillary pressure versus saturation relationships are developed from the petro-physics tests of the DGR cores:



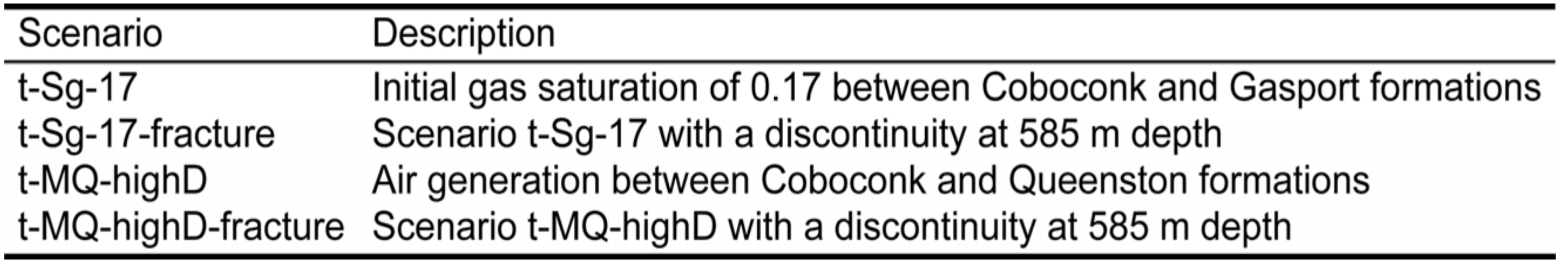
- The UNB data are used to determine the rock dependent diffusion coefficients and tortuosities

TOUGH2-MP – Hypotheses Testing (1)

It is hypothesized that the under-pressures in the Ordovician sediments are the result of the presence of an immiscible gas phase in the low-permeability, low-porosity rock matrix

Uncertainty analysis:

Four scenarios were devised to explore and test the hypothesis

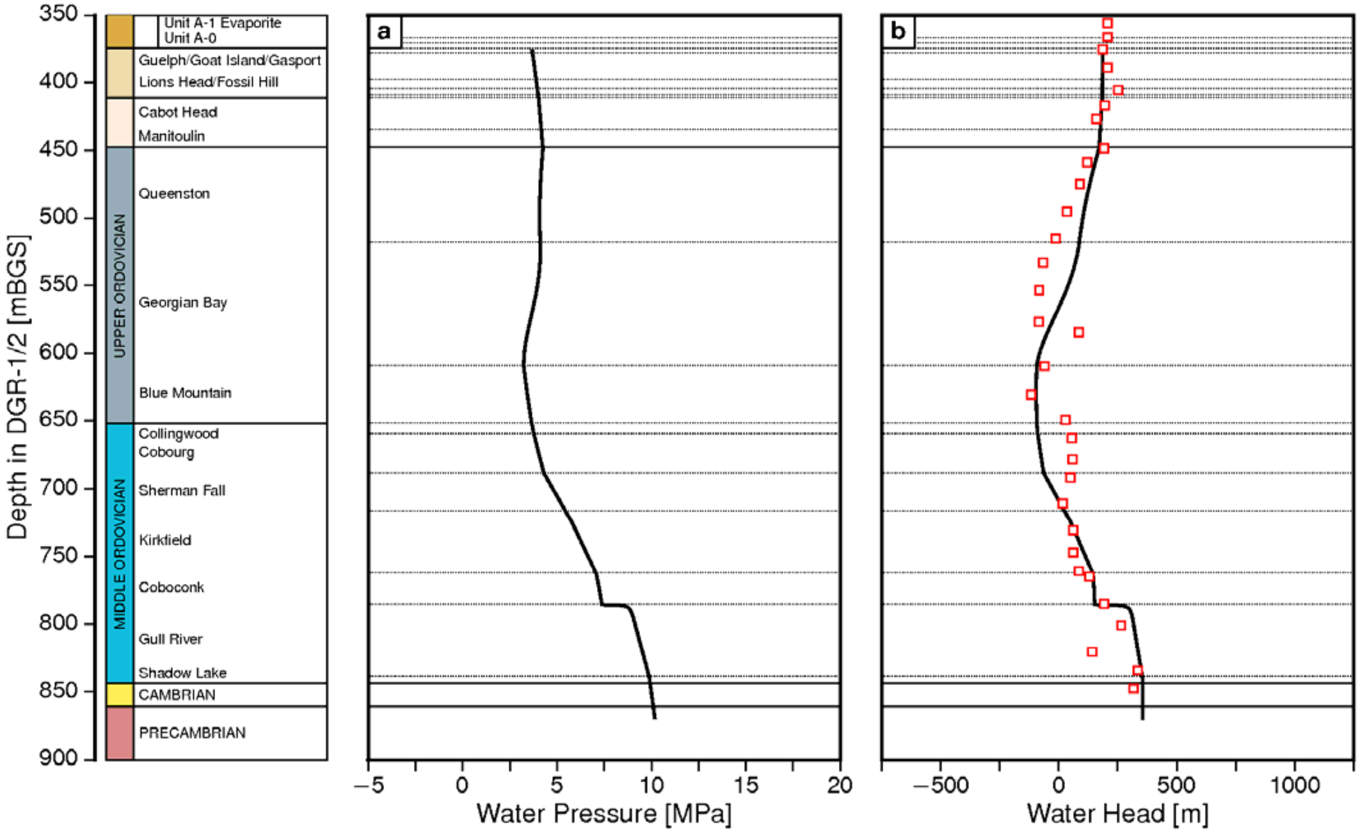


Scenario	Description
t-Sg-17	Initial gas saturation of 0.17 between Coboconk and Gasport formations
t-Sg-17-fracture	Scenario t-Sg-17 with a discontinuity at 585 m depth
t-MQ-highD	Air generation between Coboconk and Queenston formations
t-MQ-highD-fracture	Scenario t-MQ-highD with a discontinuity at 585 m depth

TOUGH2-MP – Hypothesis Testing (2)

Model Calibration: Comparison of simulated heads with observed values

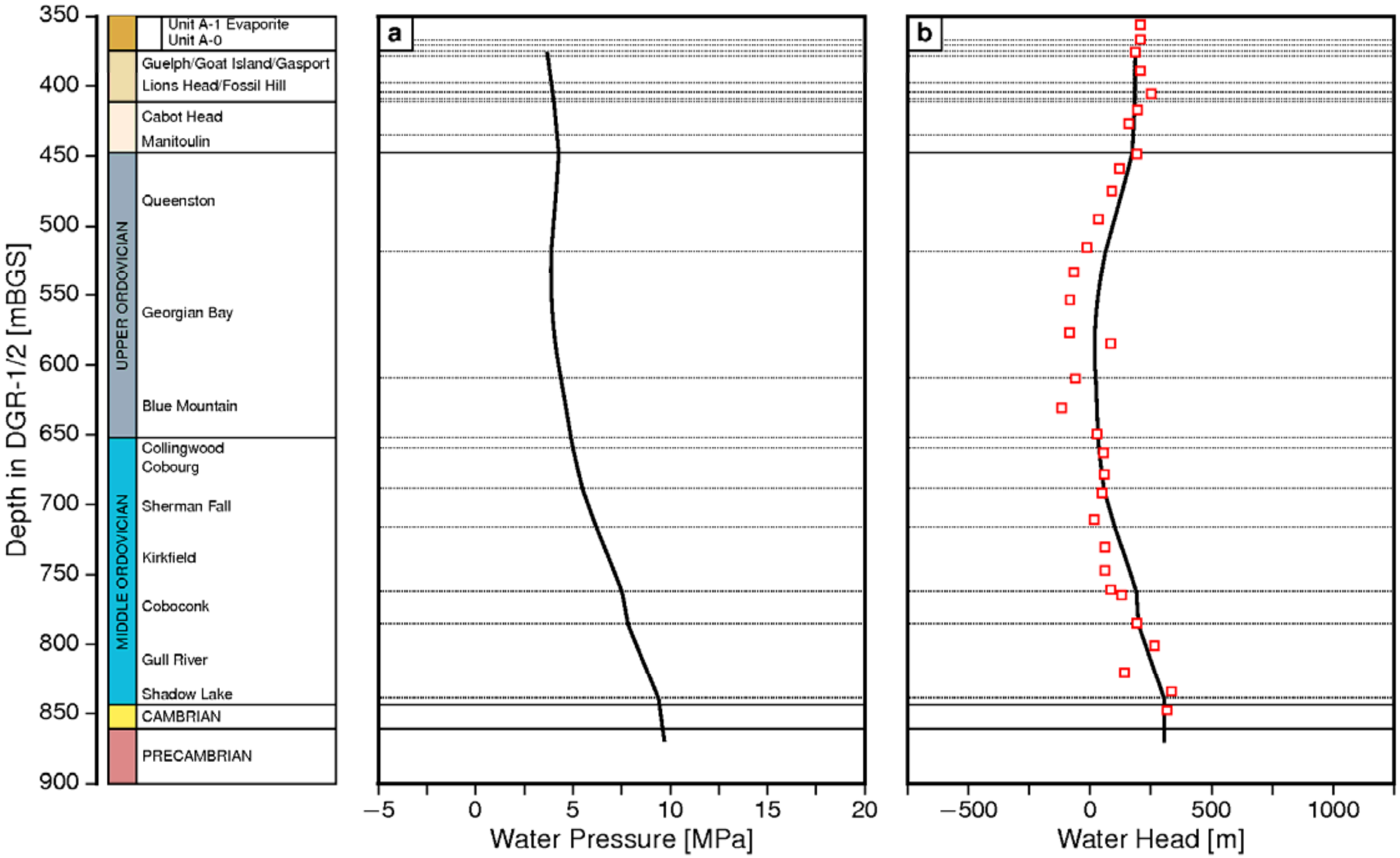
Scenario: The under-pressures in the Ordovician sediments may be explained by the slow dissipation in geologic time of an initial gas saturation (assumed for the analysis to be 17%).



TOUGH2-MP – Hypothesis Testing (3)

Model Calibration: Comparison of simulated heads with observed values

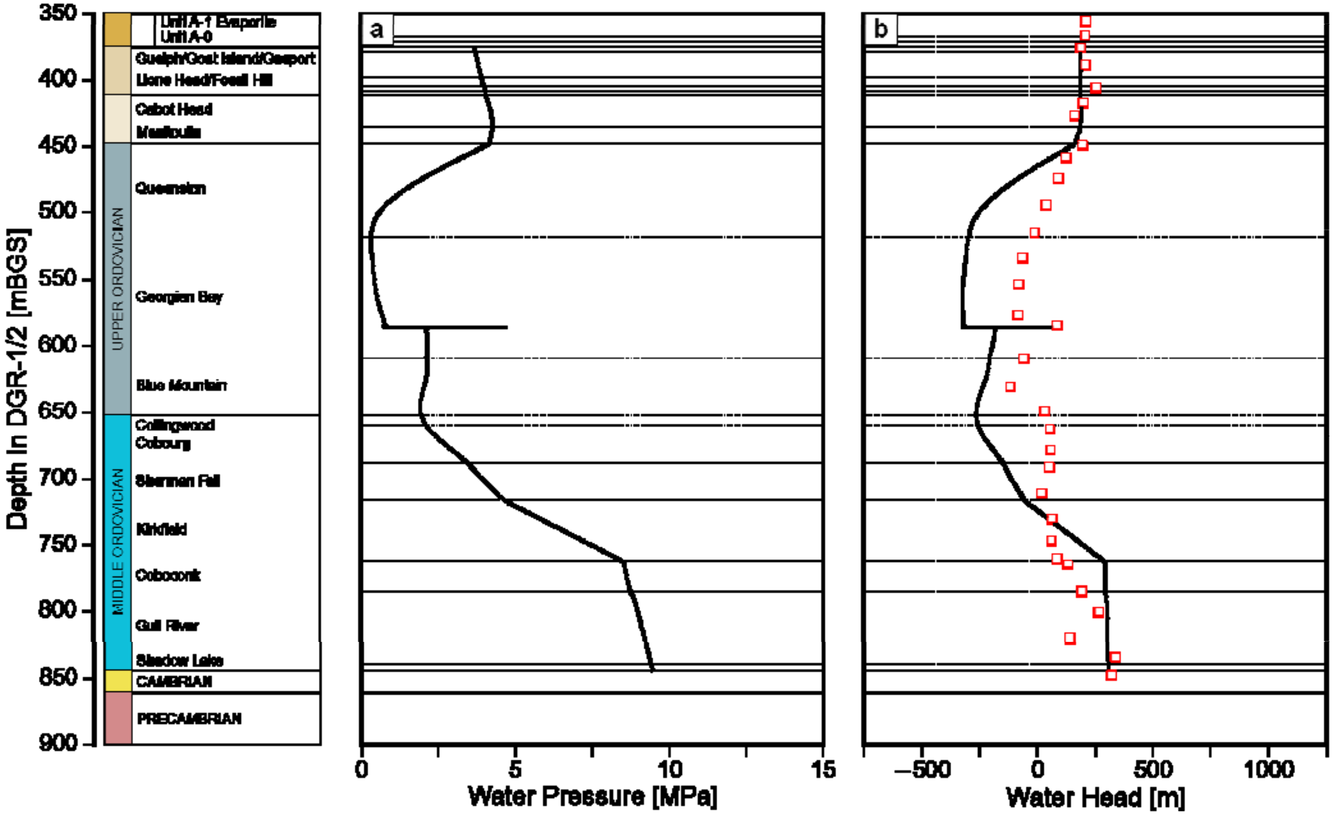
Scenario: Gas (air) generation in the one-dimensional column will result in the development of under-pressures in the Ordovician rock.



TOUGH2-MP – Hypothesis Testing (4)

Model Calibration: Comparison of simulated heads with observed values

<u>Scenario:</u> Discontinuities in the pressure profile observed in the DGR boreholes are the result of the impact of discontinuities in the rock capillary pressure versus saturation relationships on gas and water flow



TOUGH2-MP – Confidence Assessment

Confidence is provided by the study design and by model calibration where the model results are compared to the measured pressures in the DGR boreholes.

- Four different scenarios representing two conceptual model were analysed to test the hypothesis that formation under-pressures within the Ordovician sediments could be described by the presence of a immiscible gas phase. The analyses lead to the acceptance of this hypothesis.
- Based on the paleohydrogeologic analyses using FRAC3DVS-OPG, a gas phase with a few percent saturation is sufficient to preclude a glaciation explanation of the under-pressures.
- Uncertainty analysis is provided by the study design and the investigation of alternate scenarios.

TOUGH2-MP - Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Widely used and reviewed code	+++
Verification of the model to other codes	+++
Verification that model results are consistent with the conceptual model	+++
Calibration to observed formation under-pressures	+++
Sensitivity analysis of alternative conceptual models for gas phase occurrence in Ordovician sediments	++
Presence of a discontinuous gas phase in Ordovician sediments	++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

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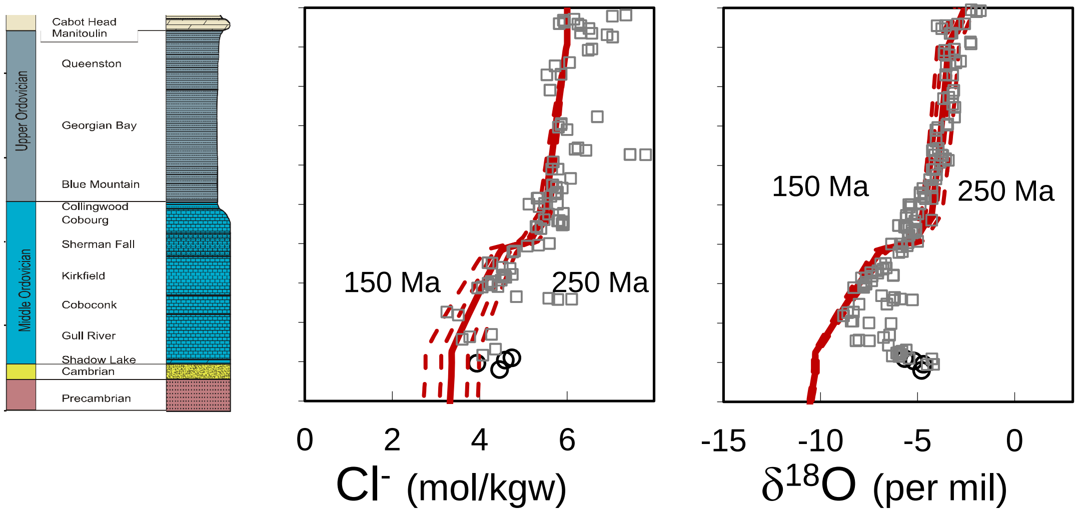
Geoscience Modelling – MIN3P

Purpose:

To provide a reasoned quantitative test that the spatial distribution of environmental tracers can be explained by diffusive processes occurring on a geologic time scale.

Objective:

To conduct numerical simulations of mass transport that provide insight and constraints on the time scale of diffusive process.



MIN3P – Fundamental Aspects (1)

- **Model Origin:**
  - Dr. K. Ulrich Mayer, Earth and Ocean Sciences, UBC
  - Numerical, finite volume – 1,2 or 3D
  - First journal publication in 2000
  - Continuous development – current version MIN3P v. NWMO

Physical

Aqueous Phase:
- pressure/density advection
- saturated/unsaturated
- diffusion

DGR Application

Gas Phase:
- ebullition (escape of bubbles)
- diffusion

Aqueous, Solid, Gas Phases:
- loading and consolidation (1D)
- heat transport

MIN3P
Capabilities:
Reactive Transport

Chemical

Activity Correction:
- Debye-Huckel (low ionic strength)
- Pitzer (high ionic strength)

Equilibrium Reactions:
- precipitation/dissolution
- aqueous complexation
- surface complexation
- ion exchange
- redox
- solute partitioning between aqueous & gas

Kinetic Reactions:
- precipitation/dissolution
- redox
- radioactive decay

MIN3P – Fundamental Aspects (2)

- **Publications:**
  - > 50 journal papers
  - > 20 peer-reviewed conference papers (many more abstracts)
  - > 10 Special publications and graduate theses

- **Research groups using MIN3P:**
  - > 20 worldwide (8 in Canada, 7 in US, 7 in Europe, 2 in Australia, 1 in South America)
  - Examples include:
    - Stanford University, USA
    - University of California at Berkeley, USA
    - University of Tuebingen, Germany
    - Helmholtz Institute, UFZ Leipizig Halle, Germany
    - University of Waterloo, Canada
    - Laval University, Canada

MIN3P – Model Verification (1)

- **Model development and verification strategy:**
  - Comparison of model results to standard set of verification examples targeted to test geochemical calculations, flow and reactive transport simulations
  - Standard verification examples are based on comparison to published results in literature, or direct comparison with analytical models or established codes (PHREEQC, PHAST, GIMRT, FLOTRAN)
  - For each code enhancement, new verification examples are added (e.g., addition of Pitzer equations for activity calculations tested using new verification example)
  - Verification for ALL examples is repeated during and after each code enhancement using automated script that executes all examples to confirm comparisons
  - Recently: Model development controlled by VisualSVN, allowing improved revision and version control

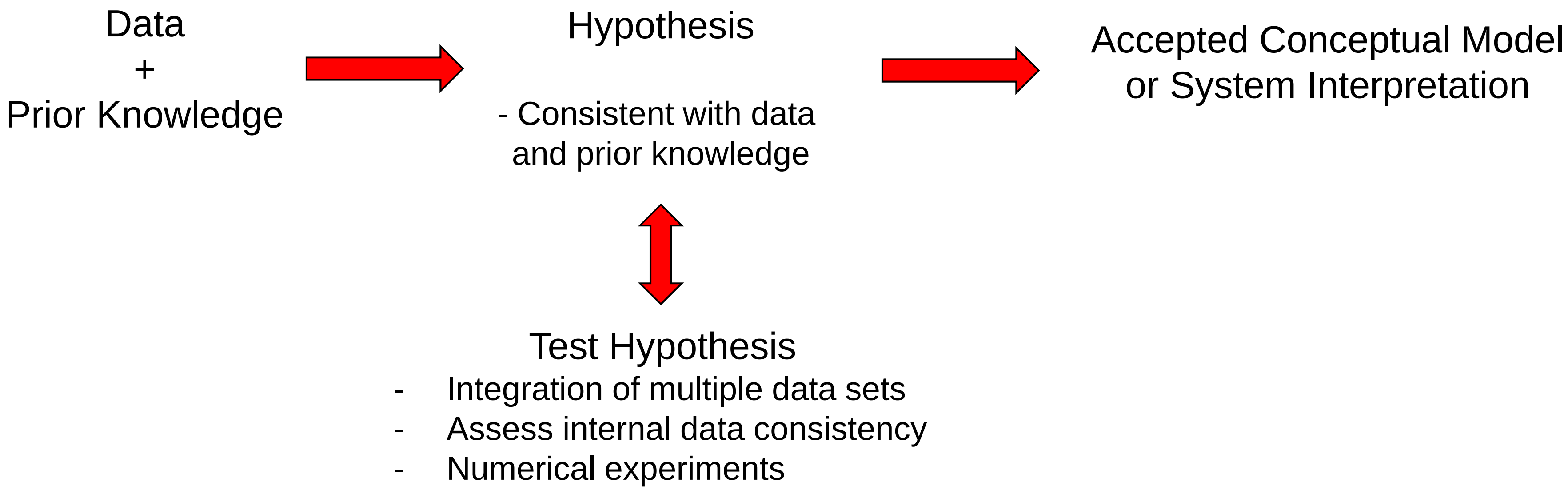
MIN3P – Model Verification (2)

Participation in international benchmarking exercises:

- 1997: Reactive transport modelling workshop at Pacific Northwest National Labs
  - Inter-comparisons with GIMRT (C. Steefel) and FLOTRAN (P. Lichtner)
- 2008: MoMaS Reactive transport modelling workshop in Strasbourg, France
  - Inter-comparison with several other modelling groups using benchmark exercises
  - **MIN3P was the only model to successfully complete the exercises**
  - Results published in special issue of Computational Geosciences (2010)
- 2012: will participate in Subsurface Environmental Simulation Benchmarking Workshop II (SSBench II), Taiwan
  - The intent is to develop and publish a set of well-described benchmark problems that can be used to demonstrate simulator conformance with norms established by the subsurface science and engineering community
  - International leaders will participate (US National Laboratories, etc.)

MIN3P – Modelling Approach

MIN3P is used for testing conceptual models, it is not used for prediction.



Data
+
Prior Knowledge

Hypothesis

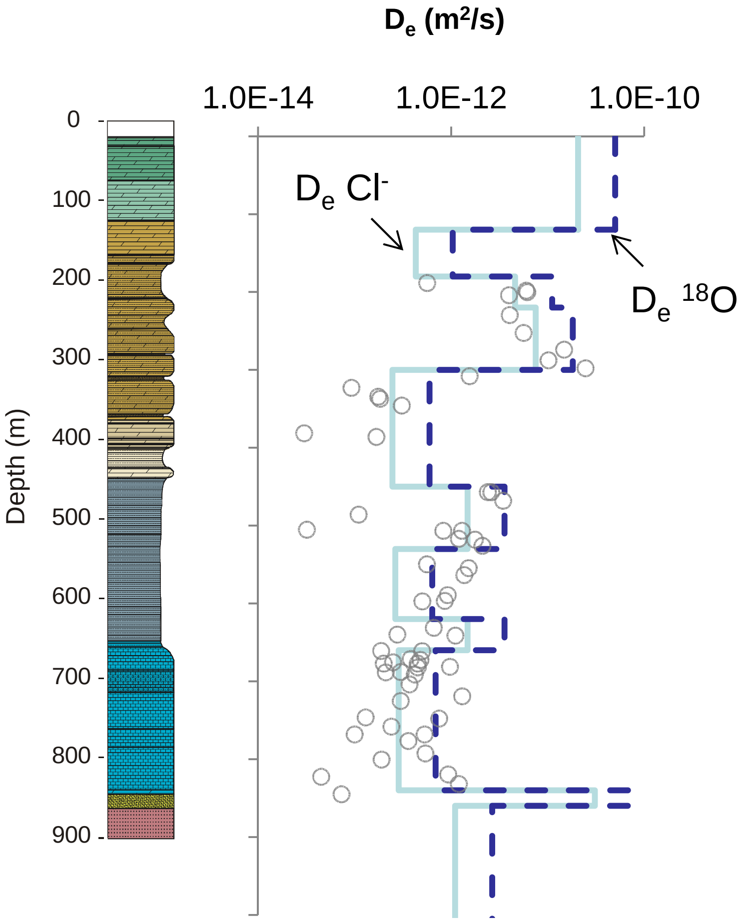
- Consistent with data and prior knowledge

Accepted Conceptual Model or System Interpretation

Test Hypothesis

- Integration of multiple data sets
- Assess internal data consistency
- Numerical experiments

MIN3P – Modelling Approach: Grid and Parameters

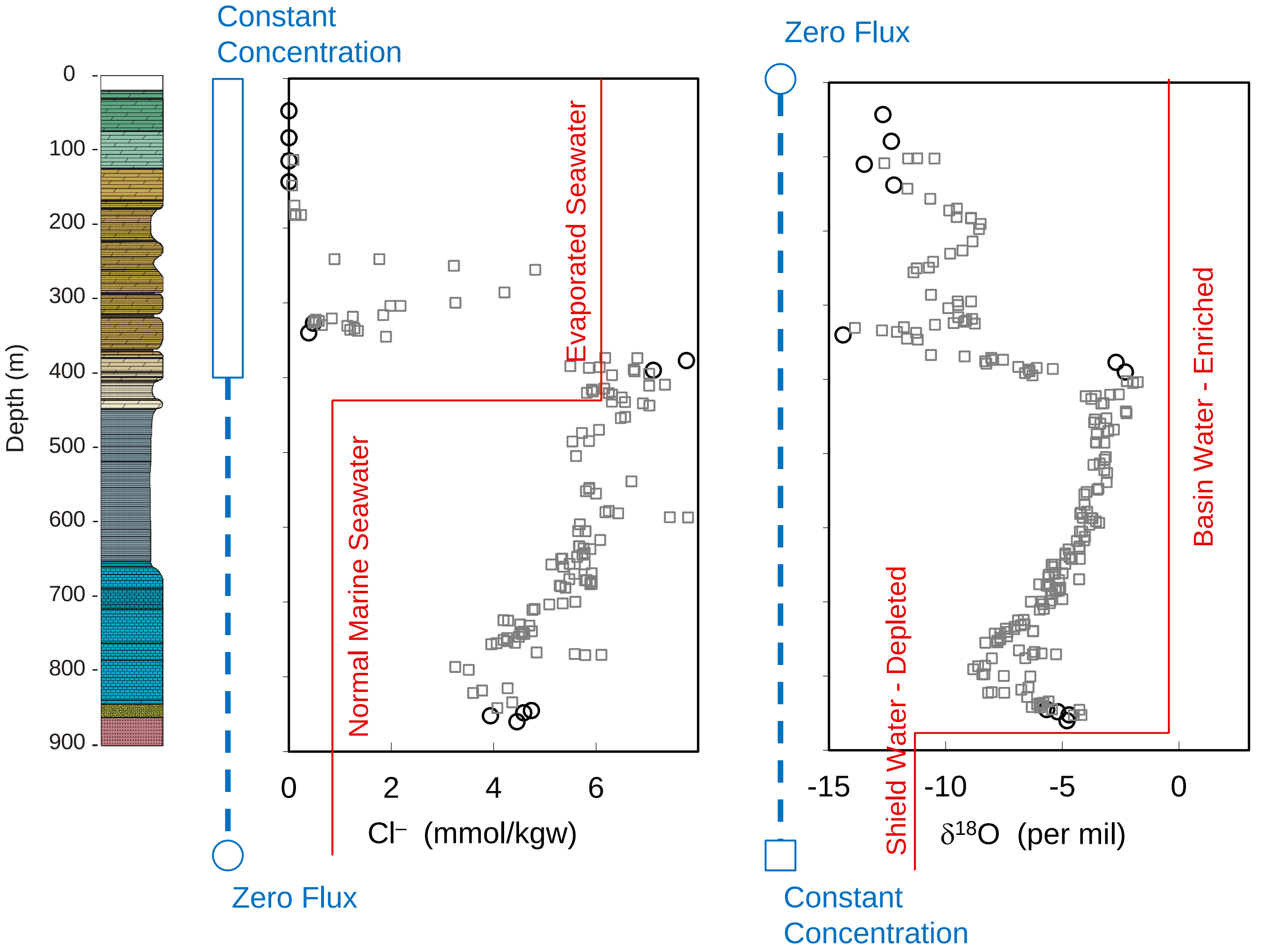


D_e – Effective Diffusion Coefficient

- Approach:
  - 1-D diffusion
    - Lateral continuity in near-horizontally layered sedimentary systems
    - Large distance from lateral boundaries
  - Grid spacing (5 m) chosen to be fine relative to formation thicknesses
  - Parameterized with laboratory measured D_e values – conservative
    - Confining pressure effects not included
    - Discrete measurements that can't capture all stratigraphic variability - other lines of evidence suggest that D_e values may be too high

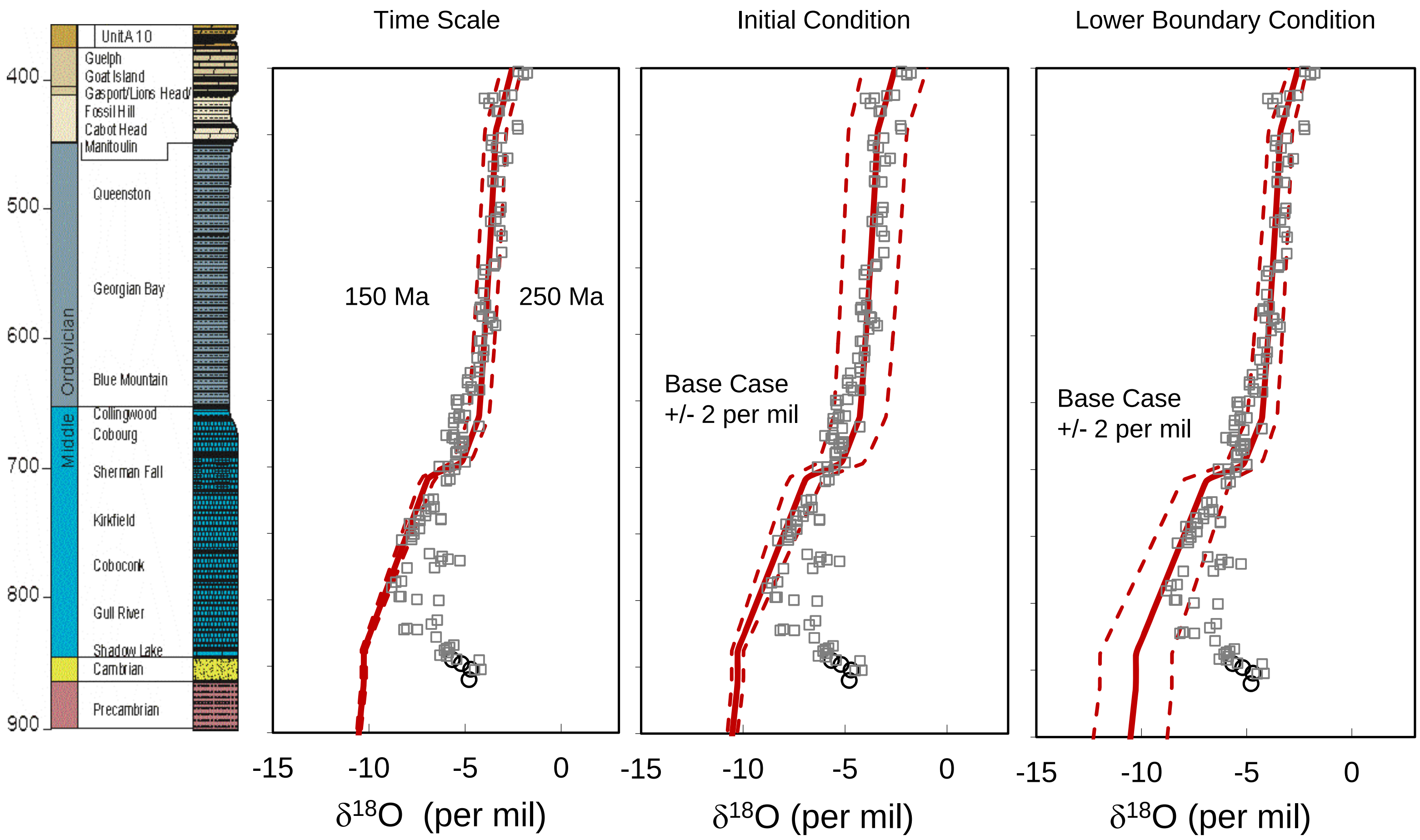
MIN3P – Modelling Approach: Boundary & Initial Conditions

Examples for Cl$^-$ and δ^{18}O



MIN3P – Assessment of Uncertainty

Sensitivity analyses constrain range of values: example for $\delta^{18}O$



MIN3P – Relative Contribution to Confidence

Line of Evidence	**Contribution to Confidence in the MIN3P Numerical Model**	**Contribution to Confidence in the System Interpretation**
Model use and reputation	+++	
Non-reactive diffusion is not a complex application of model	+++	
Boundary conditions	++	
Initial conditions	+	
Diffusion coefficients	++	
Model verification	+++	
Sensitivity analysis to define critical parameters	+++	
Prior scientific knowledge		++
Hydraulic head and conductivity data		+++
MIN3P modelling results		++
Presence of evaporated seawater		+++
Sr and He isotope data		+++
CH_4 isotope data		+++
Halite present throughout the shale		+++

Overall
++

Overall
+++

<u>Note</u>: + Lower; ++ Medium; +++ Higher

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Repository Evolution – FLAC3D

Purpose:

Shaft Seal/EDZ analysis performed for a time frame of 1,000,000 years for perturbations such as glaciations, seismic events, gas generation from corrosion of waste packages and combinations of selected scenarios.

Objectives:

Analysis was carried out for selected critical sections that included shaft seals using FLAC3D (ITASCA 2005) to explore:

- Rock mass response (short-term and long-term)
- Specific seal behaviour
- Extent of excavation damage zone (EDZ)

FLAC3D – Fundamental Aspects

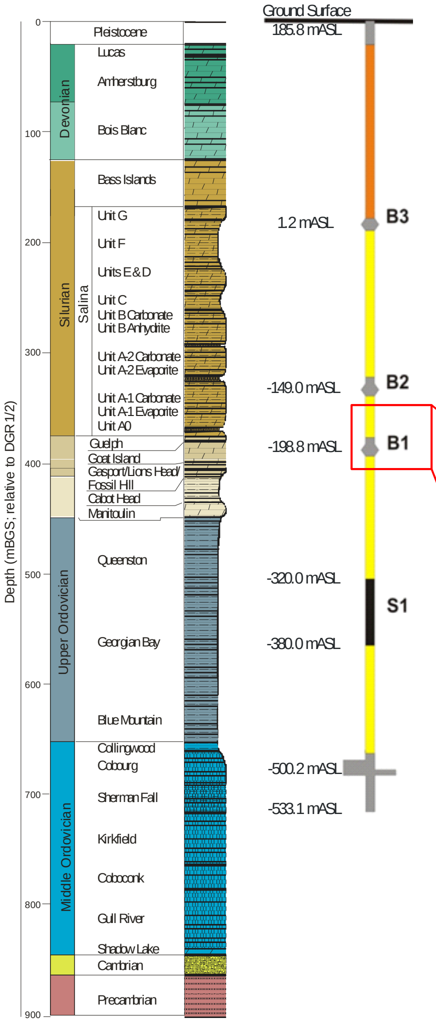
- FLAC3D V3.1 was used in the Shaft Seal and EDZ analysis
- FLAC3D is a widely used explicit finite difference three-dimensional code for advanced geotechnical analysis in geotechnical, civil, petroleum and mining engineering
- FLAC has 3687 users in 67 different countries and FLAC3D was developed and has been commercially available since 1994
- Each version of FLAC3D is verified through a standard and meticulous procedure of comparison with numerous analytical solutions
- FLAC3D V2.1 was qualified in 2002 by U.S. DOE for use on Yucca Mountain project, U.S. program for geological disposal of high-level nuclear waste
- FLAC and FLAC3D are also used in nuclear waste programs in France (ANDRA), Sweden (SKB), Finland (Posiva), Switzerland (NAGRA), Germany, and Belgium (ONDRAF/NIRAS)

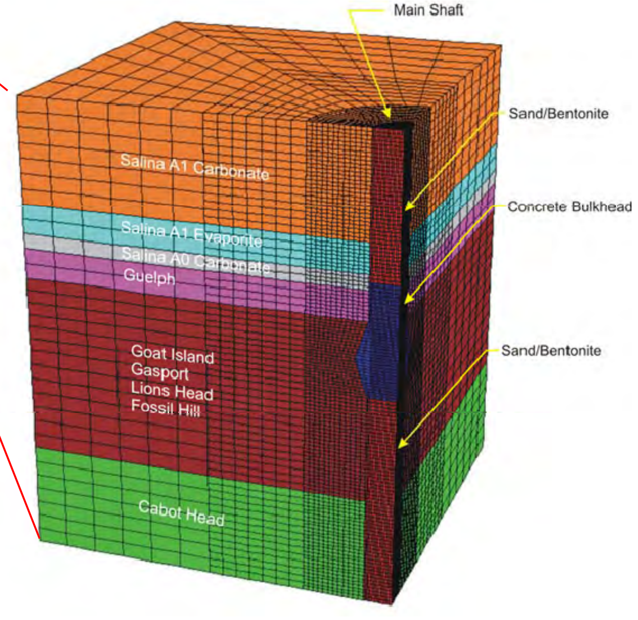
Shaft Seal/EDZ Analysis – Modelling Approach

Key horizons were selected for analysis based on the rock unit's thickness, physical properties and the in-situ stress.

The analysis used:

- Accredited laboratory data to develop rock mass parameters
- Conservative assumptions for long-term rock strength and concrete bulkhead seal degradation over a period of 100,000 years
- Conservative assumption with respect to seal degradation; stabilizing confinement due to swelling pressure from geological units and backfill materials was excluded in the analysis

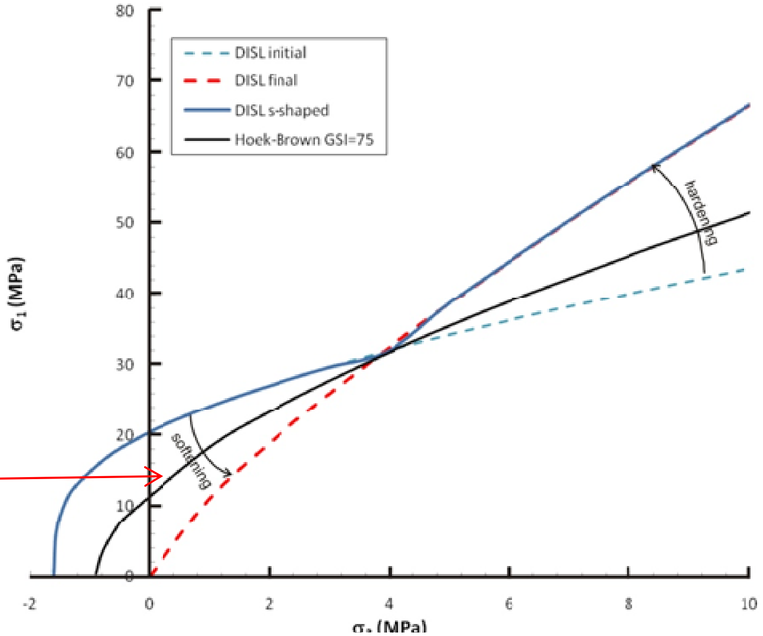




Layout of Quarter-symmetrical FLAC3D Model for B1 Seal (60m x 60m x 80m)

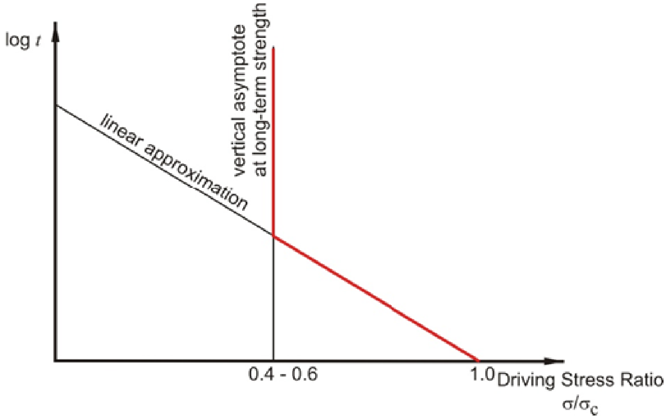
Constitutive and Time Degradation Models

- Failure envelope was developed using GSI (Geological Strength Index) approach incorporating strain weakening. In all cases the envelope was selected to give lower predicted strength than that predicted by alternative DISL (damage initiation and spalling limit) approach.



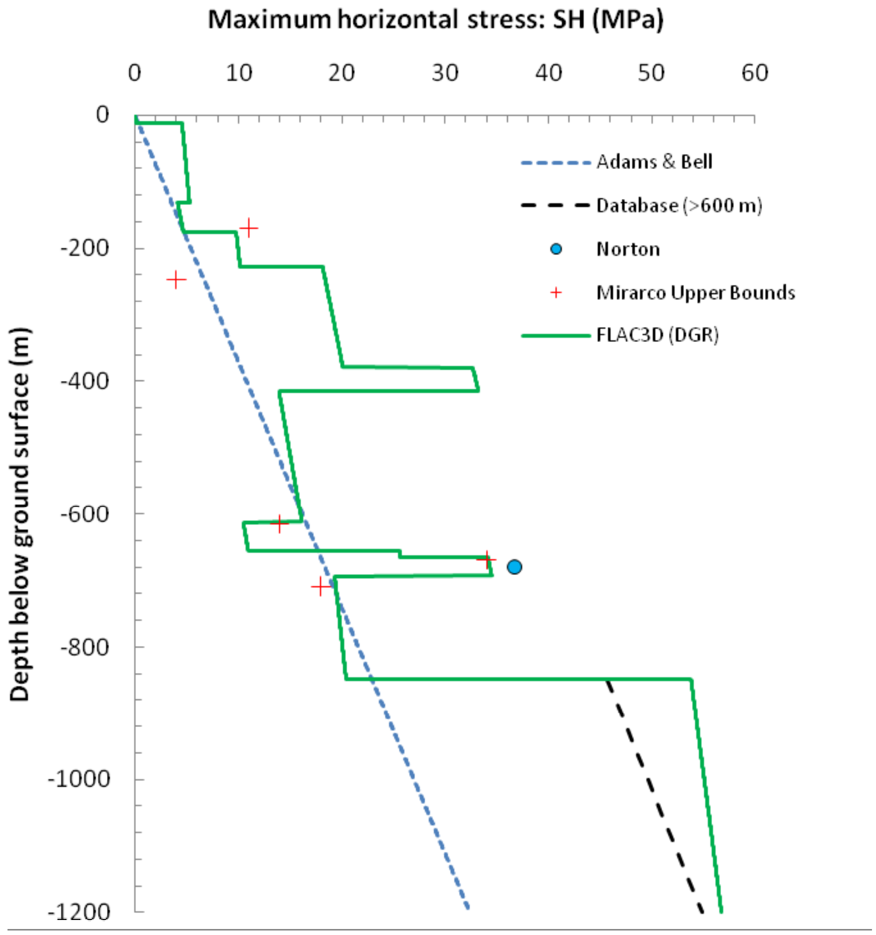
GSI strength envelope

- Long-term strength degradation model developed based on static-fatigue tests on Lac du Bonnet granite and parameters verified by long-term strength test data for Cobourg limestone.



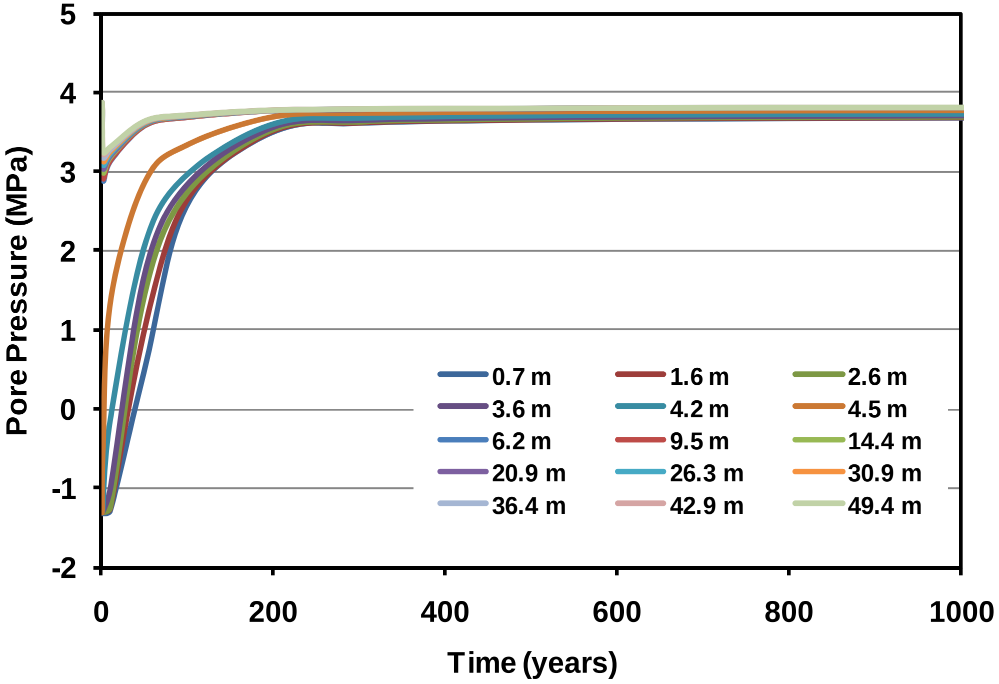
Initial Conditions – In-situ Stress

- Horizontal in-situ stress for the entire geologic profile deduced from regional depositional and tectonic modelling with conservative assumptions
- Stress magnitude calibrated with stress measurements at the Norton mine (Barberton, Ohio)
- Stress magnitudes in line with the upper bound values interpreted from borehole observations where no borehole breakout was encountered
- Approach produces maximum and conservative estimate of in situ stress based on available borehole information
- Potential for non-uniqueness in back analysis managed by incorporating most likely tectonic model for strain and loading



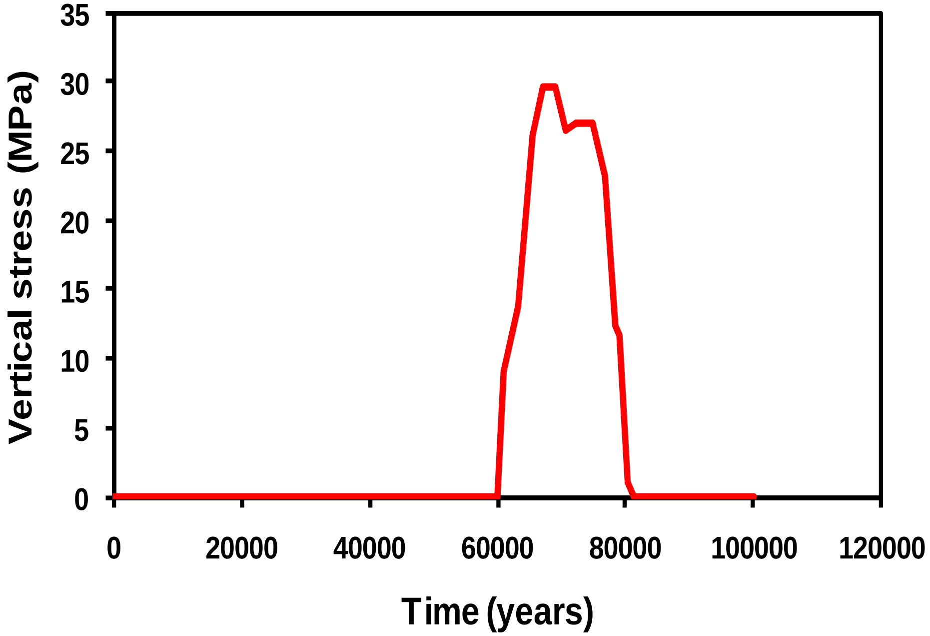
Initial Conditions – Pore Pressure Evolution

- Pore pressure build-up due to gas generation (Base Case) from waste degradation was considered
- Pore pressure data (Base Case) at various distances from the shaft center were input into FLAC3D model



Boundary Conditions – Glacial Loading

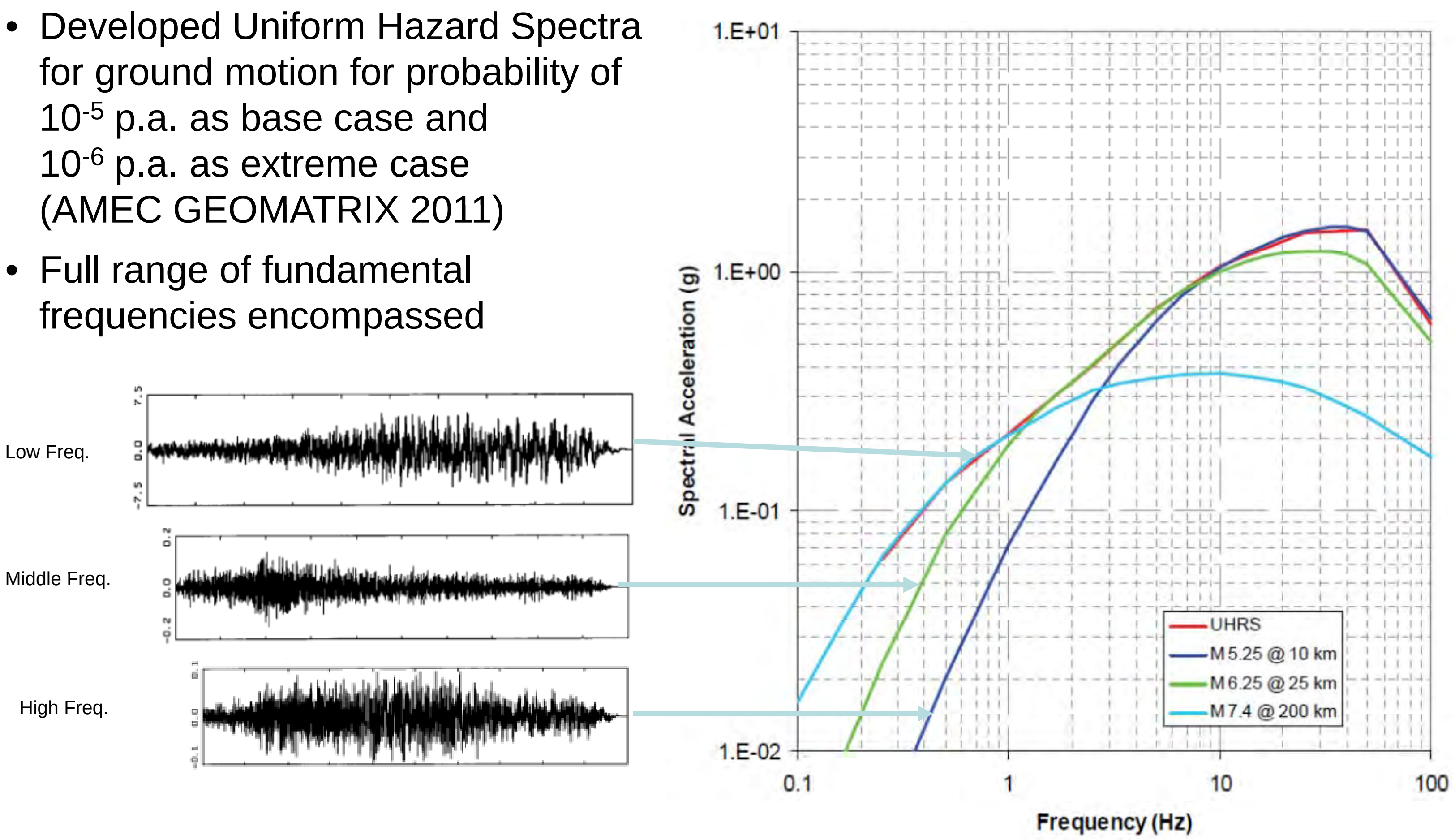
- The time history of a glacial event with maximum ice loading of 30 MPa was selected from 8 best-fit glacial ice-sheet histories generated by the Glacial Systems Model (Peltier 2011)
- This represents the conservative maximum likely loading
- Formation specific increases in horizontal stress resulting from glacial ice-sheet loading considered both Poisson's effect and crustal bending



Boundary Condition – Seismic Shaking

- Developed Uniform Hazard Spectra for ground motion for probability of 10^{-5} p.a. as base case and 10^{-6} p.a. as extreme case (AMEC GEOMATRIX 2011)
- Full range of fundamental frequencies encompassed

10^{-6} p.a Horiz. Spectra



Bounding Scenarios

Performance of shaft seals and extent of EDZ assessment for the following scenarios:

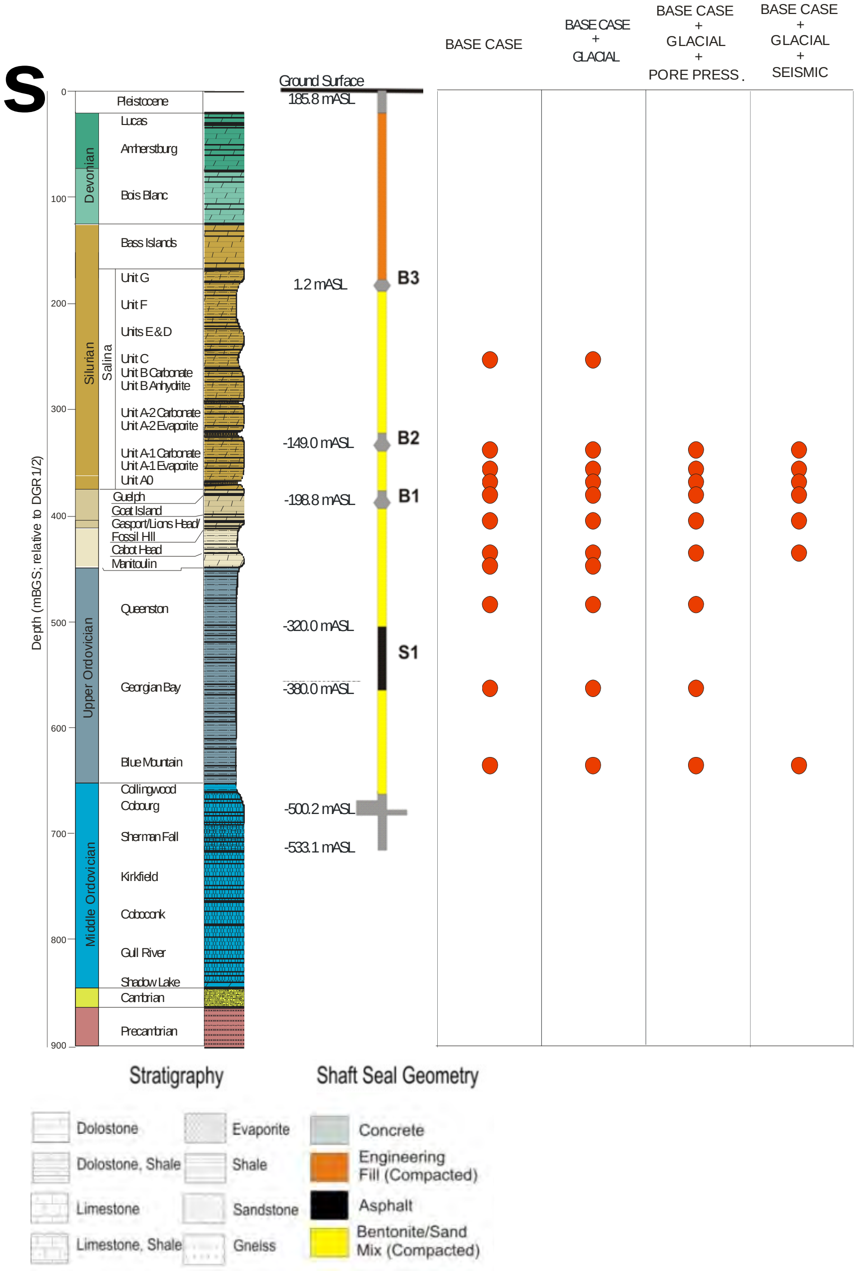
i. Time-dependent strength degradation (Base Case)

ii. Base Case + glacial loads

iii. Base Case + glacial loads + water/gas pressure

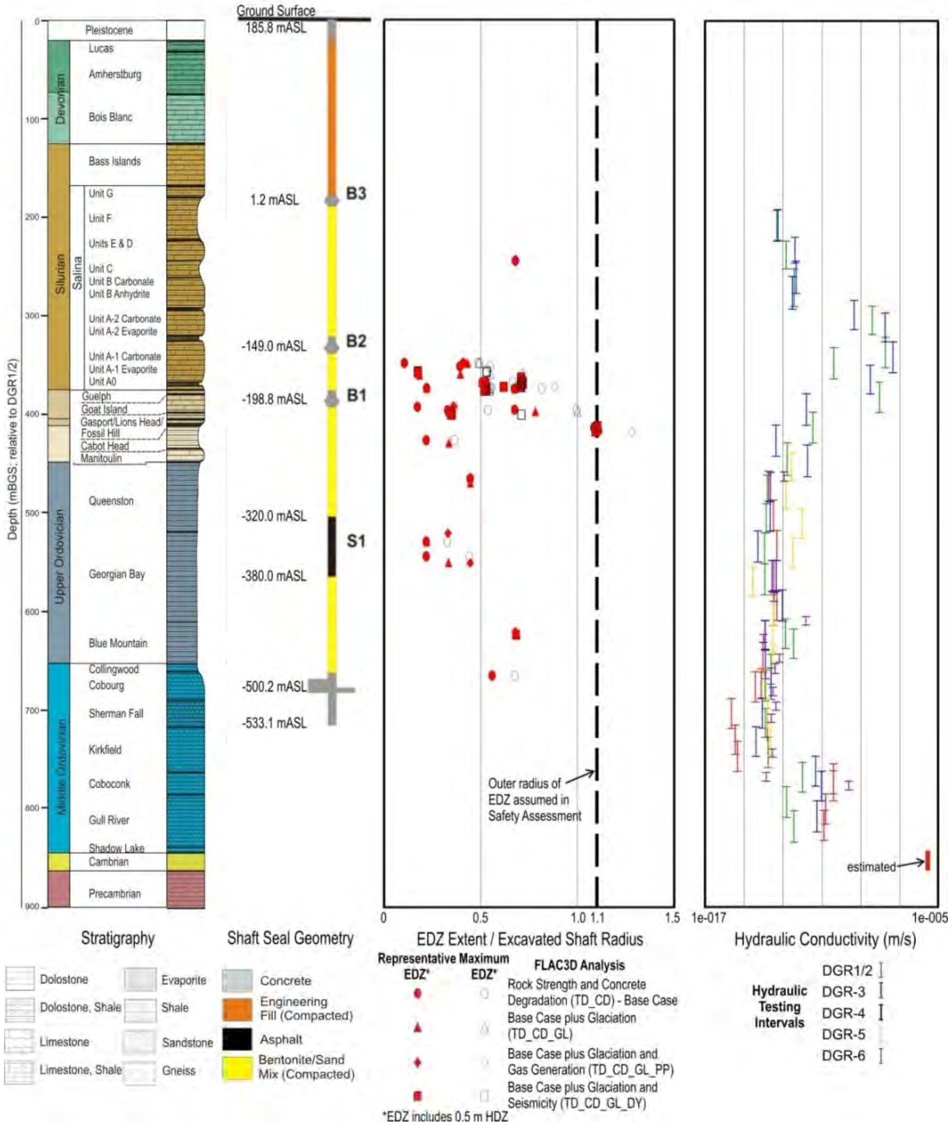
iv. Base Case + glacial loads + seismic loads

Potential for non-uniqueness (similar result from different parameter sets is not a problem for forward modelling and serve to increase confidence)



Confidence in FLAC3D DGR Modelling (1)

- Validation and Calibration (Model and Inputs)
  - In-situ stresses calibrated used observed borehole behaviour
  - High glacial and seismic loading based on historical models
  - Conservative Constitutive models and lower bound strength used based on sample test data and rockmass characterization
  - Weakening behaviour with strain and time based on literature and test data
- Verification (Correctness of Code)
  - FLAC3D has extensive verification suite linked to known solutions
  - Results verified by comparison to other codes (PHASE2)
- Reliability (Management of Uncertainty)
  - Concrete assumed to degrade over 100 ka
  - Backfill stabilization ignored
  - Combined loading cases considered
  - Stabilization due to swelling ignored
  - Linear upper bound of predicted EDZ used in Safety Assessment modelling



Confidence in FLAC3D DGR Modelling (2)

Predictive Reliability and Verification of Results

FLAC3D results compared with:

- Results of another numerical code (Phase 2)
- Results using another strength model (DISL)
- Empirical estimates of breakout depth (Martin 1999)

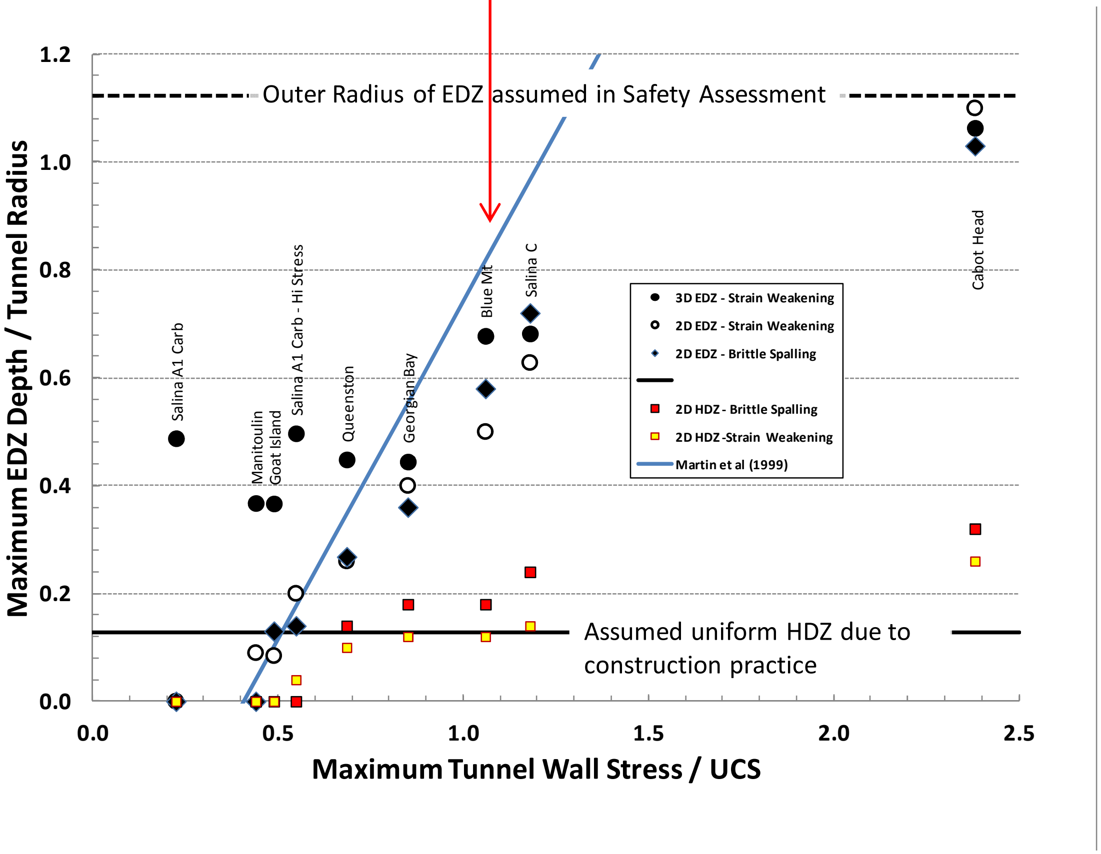
FLAC3D results for EDZ extent are in agreement or exceed predictions using other approaches

Results reviewed by expert team:

Martin, Diederichs, McCreath, and Lam

$$\frac{d_f}{a} = 1.25\frac{\sigma_{\max}}{UCS} - 0.51$$

(Martin 1999)



FLAC3D - Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Widely used and reviewed code	+++
Calibration using input data from the DGR site when available	+++
Calibration using regional data	++
Verification via confirmation that model results are consistent with the conceptual system behaviour model	+++
Verification via comparison of model results with other codes	+++
Conservative bounding conditions	+++
Sensitivity analysis used to identify critical parameters that largely determine model outcome	+
Conservative input and governing criteria used	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

Outline of Presentation

Part One - Geoscience Modelling

- 3-DGFM
- FRAC3DVS-OPG
- TOUGH2-MP
- MIN3P

Part Two - Repository Evolution Modelling

- FLAC3D
- **FRAC3DVS-OPG**
- T2GGM
- AMBER

Part Three - Radiation Dose Modelling

- MicroShield, MicroSkyshine, MCNP
- Non-Human Biota

Part Four – Environmental Modelling

- AERMOD
- Cadna/A

FRAC3DVS-OPG (v1.3)

Purpose:

- Models liquid flow and contaminant transport through geologic media
- Used to model transport of radionuclides under saturated conditions, and to cross-check T2GGM

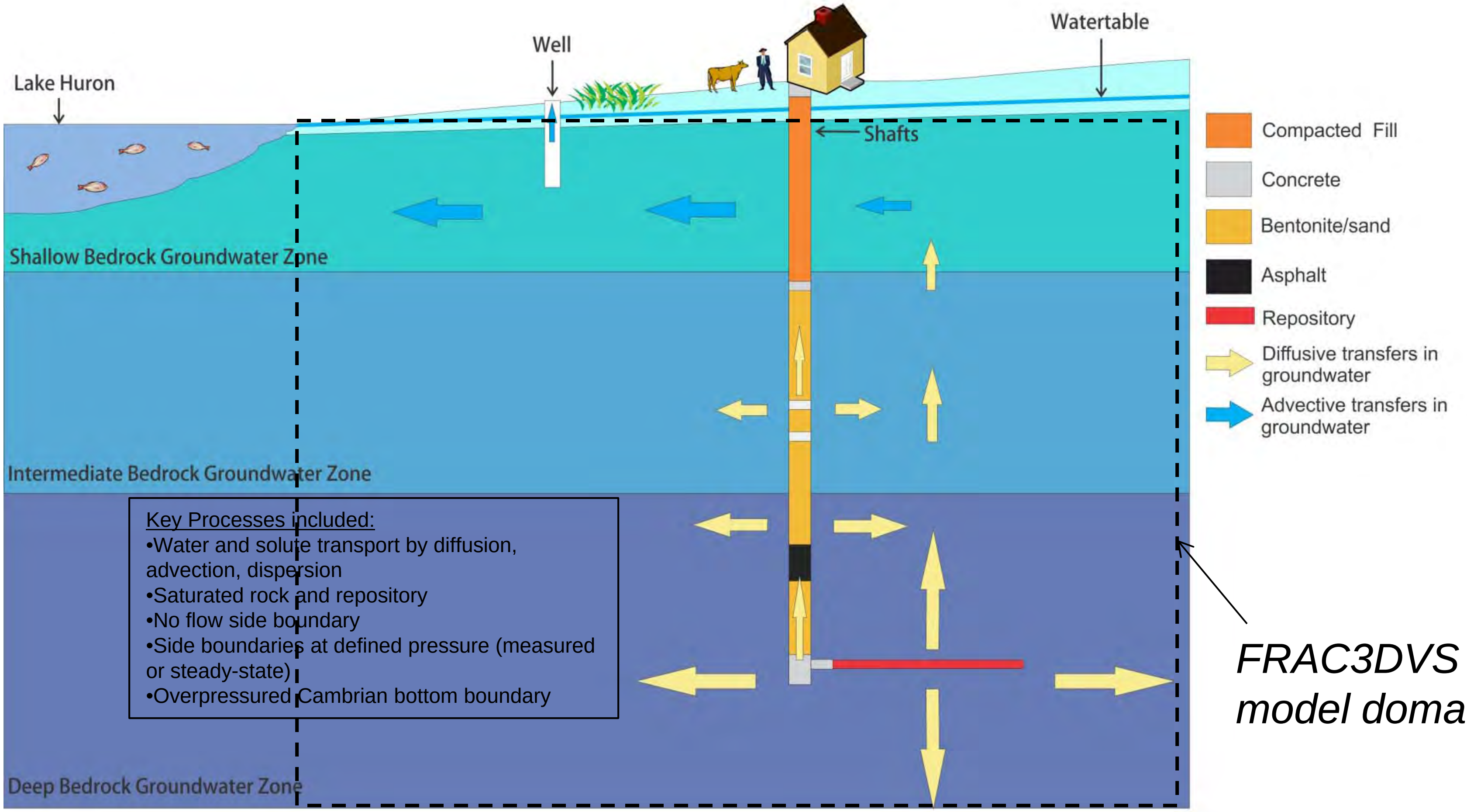
Numerical approach:

- Finite-element – triangular or brick elements
- Adaptive time stepping

Status:

- FRAC3DVS-OPG is an OPG QA-controlled version
- Details on code status presented in Geoscience Modelling presentation

FRAC3DVS-OPG – Fundamental Aspects (1)



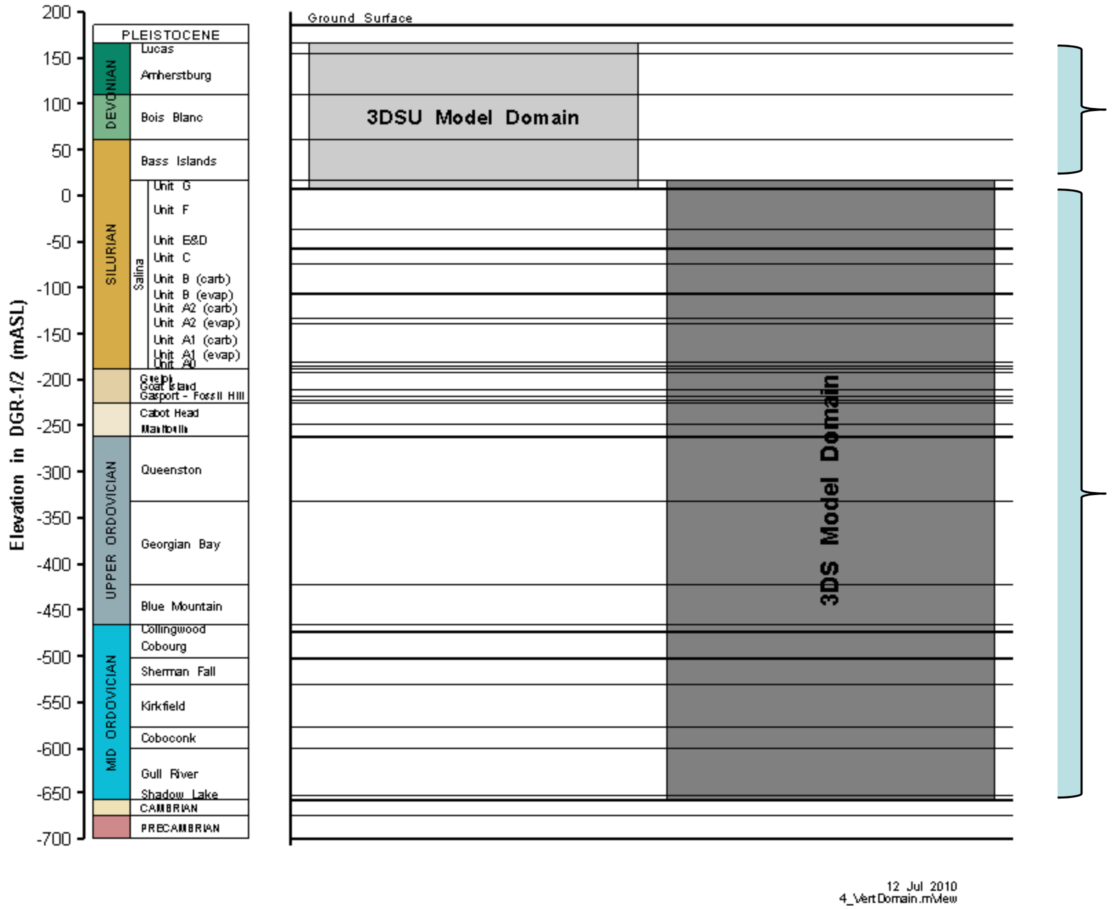
<u>Key Processes included:</u>

- Water and solute transport by diffusion, advection, dispersion
- Saturated rock and repository
- No flow side boundary
- Side boundaries at defined pressure (measured or steady-state)
- Overpressured Cambrian bottom boundary

FRAC3DVS model domain

FRAC3DVS-OPG – Fundamental Aspects (2)

Different models for different domains of rock



3D model of shallow groundwater system with advective flow and permeable formations

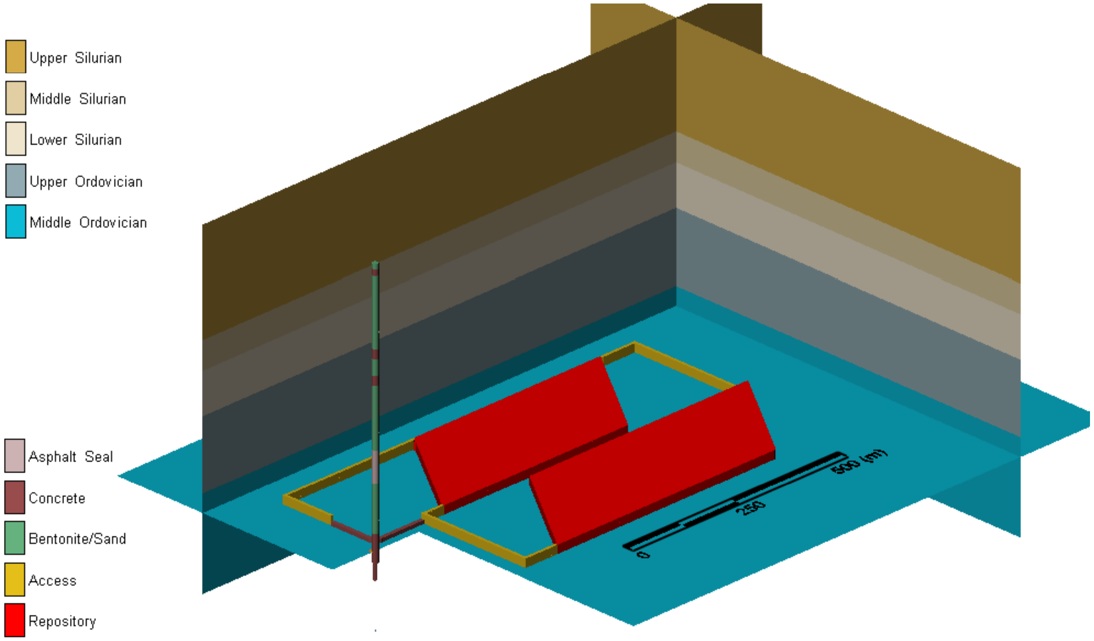
3D model of middle and deep groundwater system

All identified rock formations within each domain are explicitly modelled

FRAC3DVS-OPG – Fundamental Aspects (3)

3DD – Detailed Model

- Two shafts combined into one shaft with same area
- Emplacement rooms, tunnels, room pillars combined into porous panel with same void volume
- 10-m rockfall also included in panels and tunnels
- Some models are based on an earlier design of the service area around the shafts

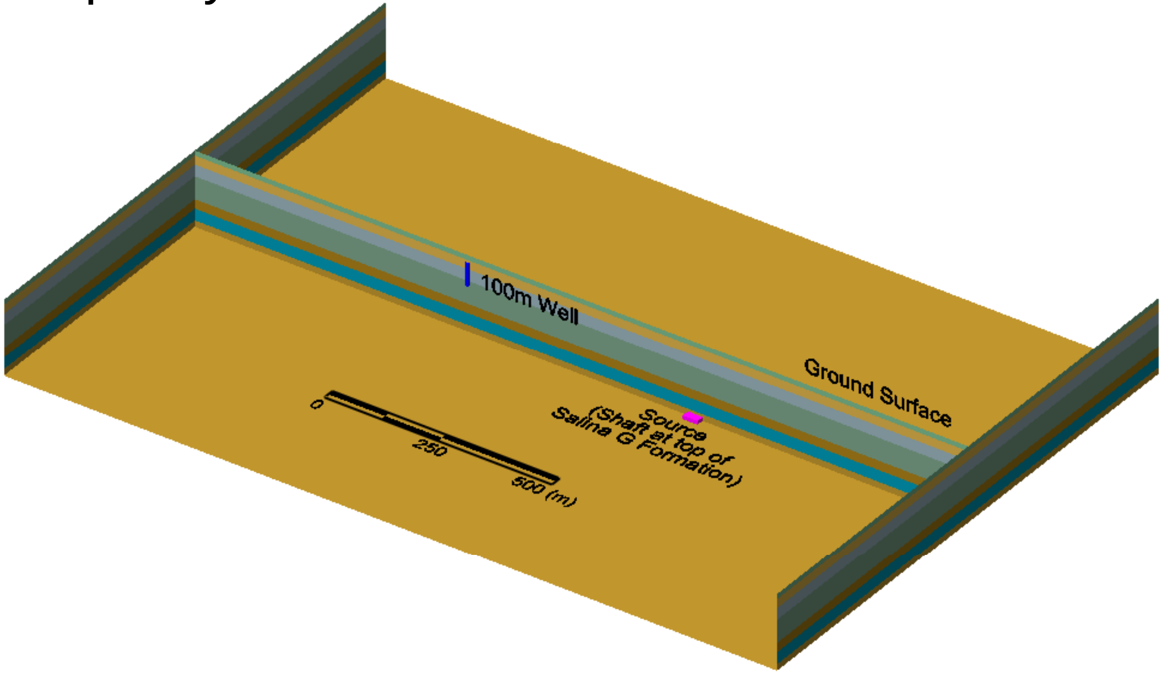


22 Aug 2012
GW_3DS_Conceptual.mView

FRAC3DVS-OPG – Fundamental Aspects (4)

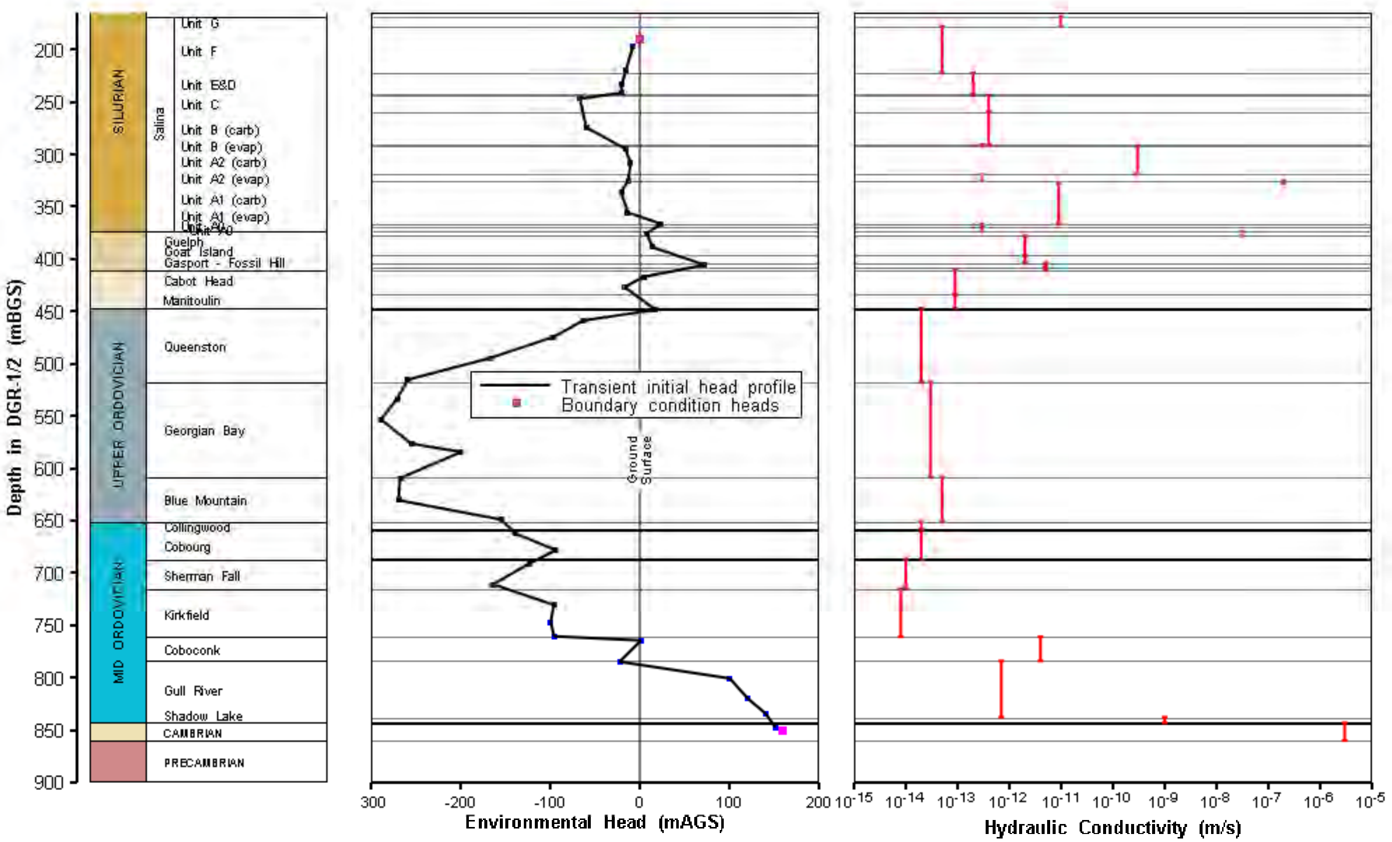
3DSU (Surface) Model

- Model covers the shallow groundwater system
- Does not include the surface till above water table
- Model includes an assumed well for water
- Upper shaft is not explicitly modelled



FRAC3DVS-OPG – Fundamental Aspects (5)

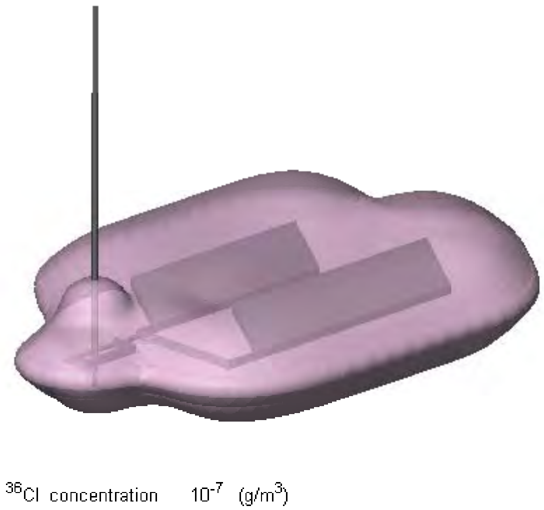
Initial Conditions: Pressure and K parameterization

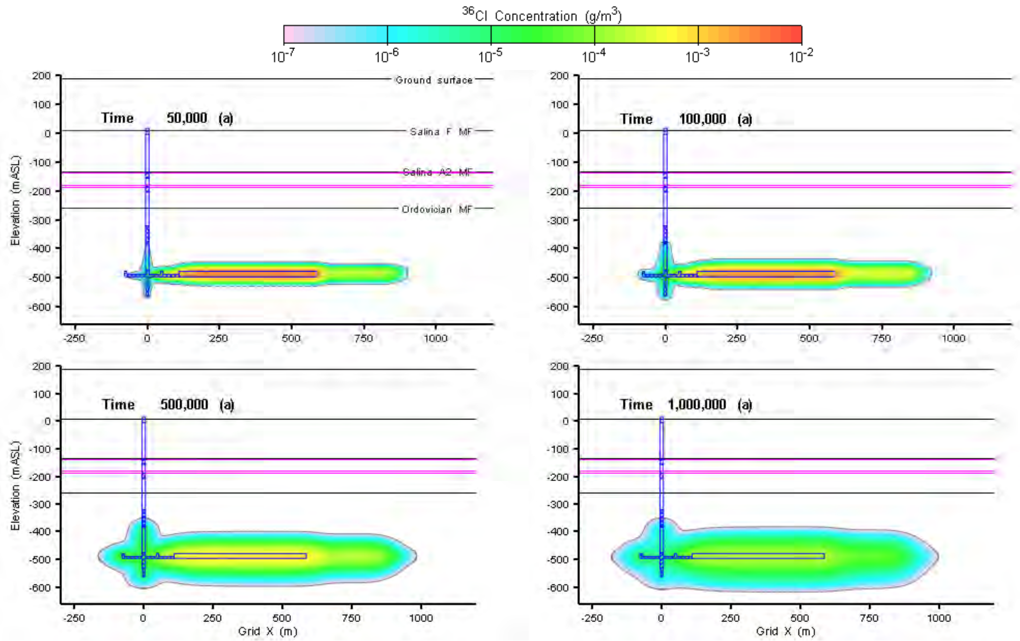


FRAC3DVS-OPG – Calibration

- Input data derived from and traceable to site characterization program:
  - Hydraulic conductivity – results from site well-test analysis
  - Porosity and diffusion coefficients – from extensive rock core testing program
  - Initial pressures – measured in-situ at site
- No free parameters have been adjusted: all parameters align with site data

FRAC3DVS-OPG – Example Results





Concentration of Cl-36 around repository as a function of time, assuming instant resaturation and instant release

FRAC3DVS-OPG – Verification (1)

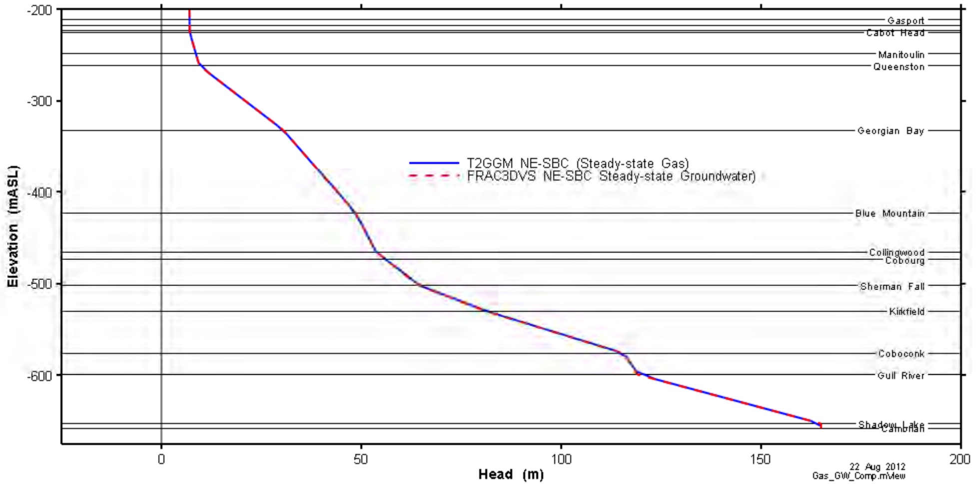
- Uses FRAC3DVS code
  - Commercial code
  - Numerically robust and well verified
- Numeric tests:
  - Simulation mass balance
  - Convergence criteria evaluated
- Data QA and Peer Review
- Comparison with simple calculations

FRAC3DVS-OPG – Verification (2)

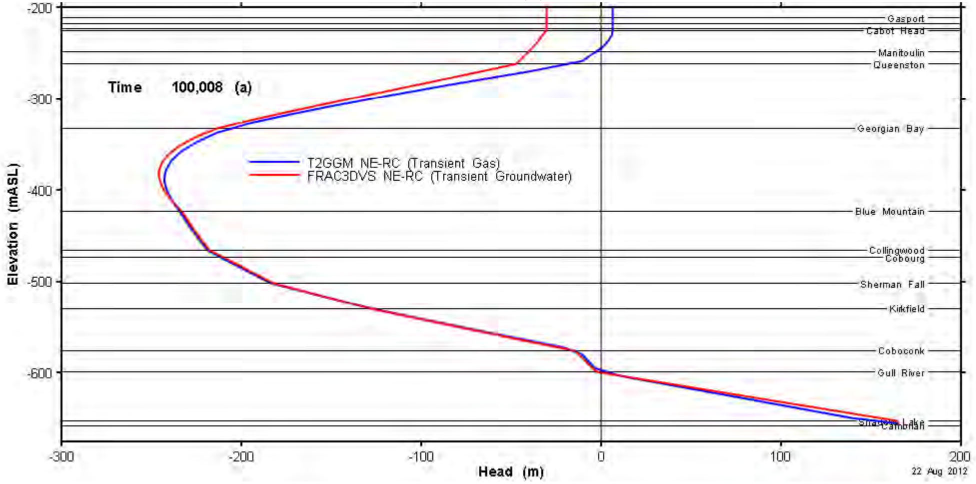
<u>Model Comparison</u>: FRAC3DVS-OPG with T2GGM

- Hydraulic head profiles

Steady-state



Transient comparison (results at 100 ka)



FRAC3DVS-OPG – Uncertainty Analysis (1)

Source of Uncertainty	How Addressed in Model

Parameters	• Sensitivity cases:
	  • Geosphere permeability (NE-AN1)
	  • EDZ permeability (NE-EDZ1)
	  • Geosphere diffusion (NE-AN2)
	  • Shaft seal construction (NE-GT5)

Repository conceptual model	• Rockfall/seismicity – assume instant formation of porous panels due to rockfall and pillar failure • Resaturation – assume instant and complete resaturation • Radionuclide source – assume instant dissolution • Gas generation – covered in T2GGM modelling

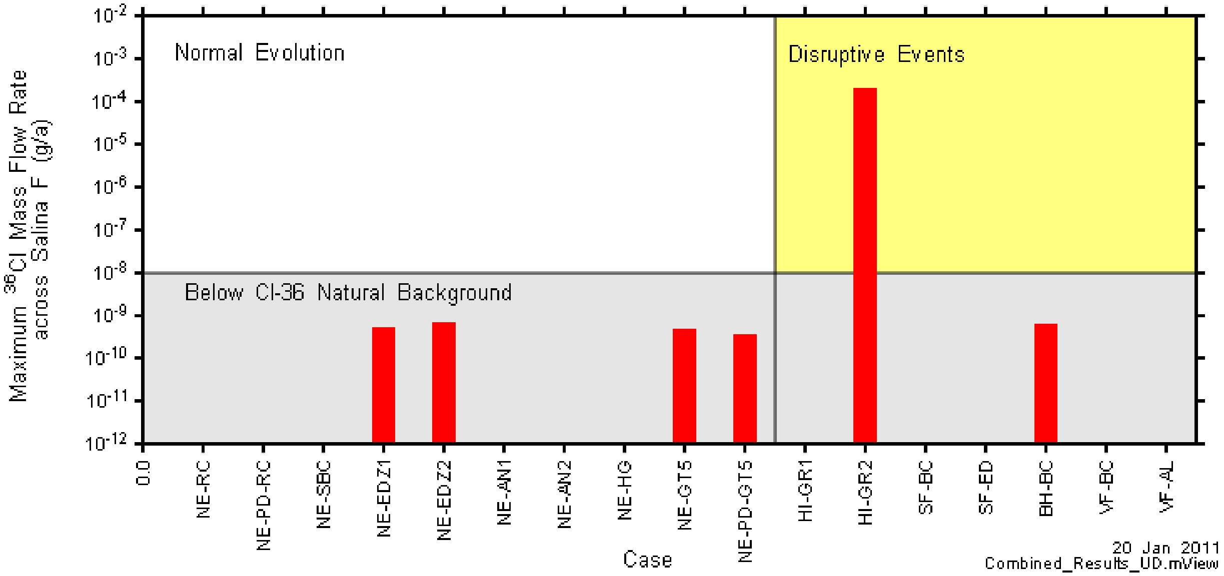
FRAC3DVS-OPG – Uncertainty Analysis (2)

Source of Uncertainty	How Addressed in Model
Geosphere conceptual model	• Ordovician under-pressures – assumed remnant pressure profile and allowed to dissipate naturally • Cambrian over-pressure – assumed constant • Gas phase in Ordovician – not included, rock assumed fully water saturated • Regional flow in Guelph and Salina Upper A1– not included in most cases, effect evaluated in NE-HG case

FRAC3DVS-OPG – Uncertainty Analysis (3)

Key Findings of Sensitivity Analysis**:**

- Transport is diffusion dominated in deep formations
- Releases to surface require enhanced path such as permeable shaft EDZ or a borehole
- Underpressured Ordovician sediments reduces mass flow to surface



Peak Cl-36 Vertical Flow across the Salina F formation

FRAC3DVS-OPG – Summary (1)

- FRAC3DVS-OPG is used in Repository Evolution to model groundwater and contaminant transport in the repository, shaft and geosphere
- It did not include gas generation or transport, and so is not a primary code for postclosure assessment, but provides support to the primary T2GGM and AMBER codes

FRAC3DVS-OPG – Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Use of FRAC3DVS code, widely used	++
Use of input data derived from site characterization	+++
Development under a QA system, with peer review at interim and final stages	+++
Comparison of model results with other codes	+
Uncertainties addressed using conservative assumptions and sensitivity analyses (~16 calculation cases)	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

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T2GGM (v2.1)

Purpose:

- Repository gas generation and reactions
- Two-phase (gas and water) movement
- Repository and shaft saturation

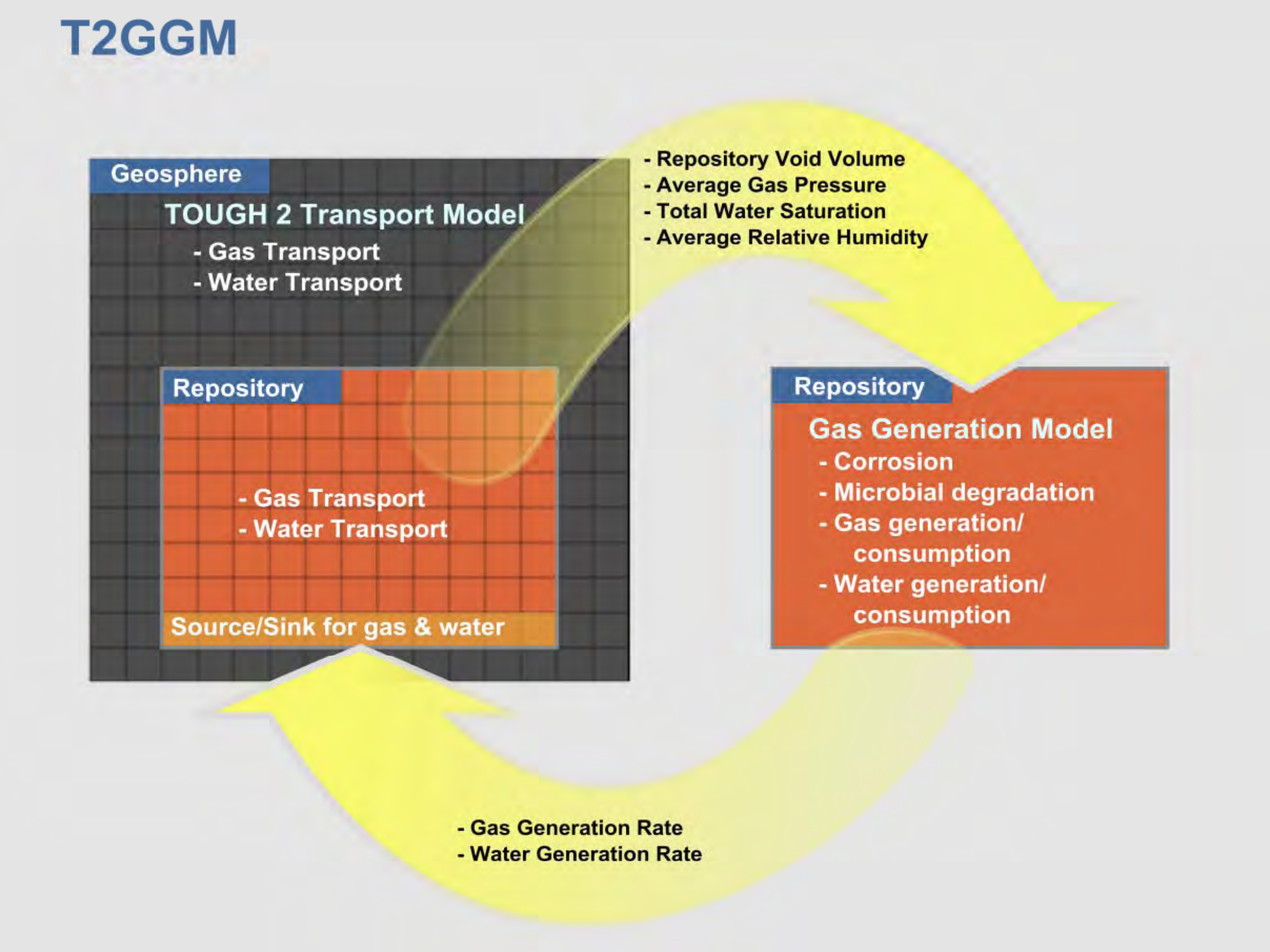
Numerical approach:

- T2GGM is integration of TOUGH2 and GGM
- Integral Finite-Difference geosphere (TOUGH2)
- Single-compartment repository model (GGM)

Status:

- TOUGH2 – widely-used commercial code,
- GGM – custom code for DGR project

T2GGM (v2.1)



T2GGM

Geosphere

TOUGH 2 Transport Model
- Gas Transport
- Water Transport

Repository

- Gas Transport
- Water Transport

Source/Sink for gas & water

- Repository Void Volume
- Average Gas Pressure
- Total Water Saturation
- Average Relative Humidity

Repository

Gas Generation Model
- Corrosion
- Microbial degradation
- Gas generation/ consumption
- Water generation/ consumption

- Gas Generation Rate
- Water Generation Rate

TOUGH2 – Fundamental Aspects

Features:

- Multiphase flow and transport code
- Advection, diffusion, isothermal or non-isothermal
- EOS3 (gas and water) equations of state
- Modified to include:
  - GGM repository model
  - Alternative gases to air (CH_4, CO_2, H_2)
  - 1-D Hydro-Mechanical capability

Key assumptions:

- Gas and liquid flow according to Darcy's Law
- Gas and liquid pressures related by capillary pressure function

GGM – Fundamental Aspects (1)

Features:

- Repository model
- Focus on microbial and corrosion processes that lead to gas generation and water consumption
- Includes biomass generation and decay
- Accounts for limitation of microbial and corrosion reactions by the availability of water
- Most reactions can occur under unsaturated conditions, with sufficient humidity
- Tracks waste material inventory for mass balance
- Accounts for gas and water flows to/from repository (into geosphere or shaft)

GGM – Fundamental Aspects (2)

- Over 30 reactions in total

Key processes:

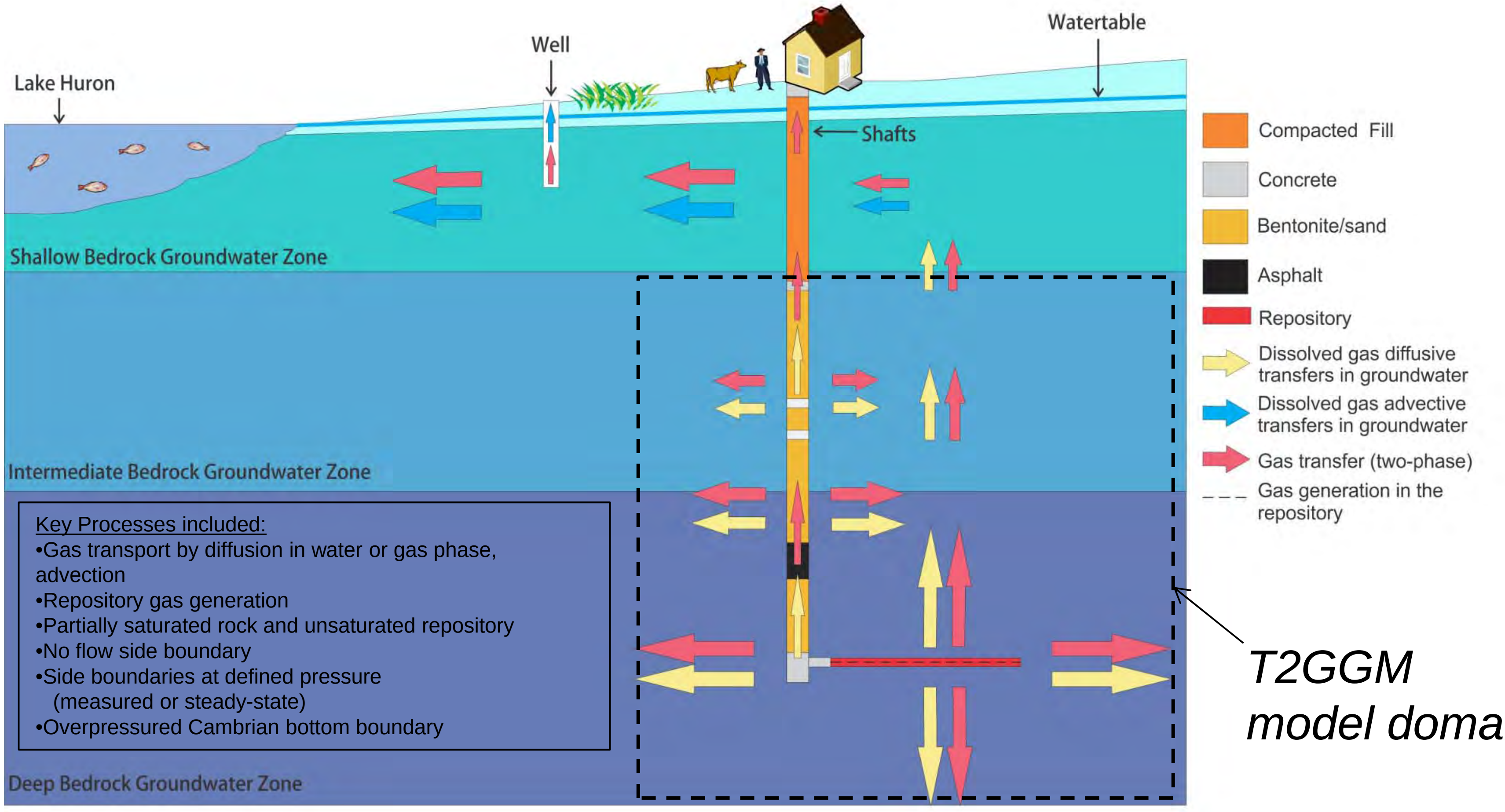
- Microbial degradation of organic wastes
  (organics + water → CH_4 and CO_2)

- Methanogenesis from hydrogen
  (H_2 + CO_2 → CH_4 and water)

- Anaerobic corrosion of metals
  (Fe or Zr + water → Fe_3O_4 or ZrO_2 and H_2)

- CO_2 enhanced corrosion of steel
  (Fe + carbonic acid → $FeCO_3$ and H_2)

T2GGM – Fundamental Aspects (1)

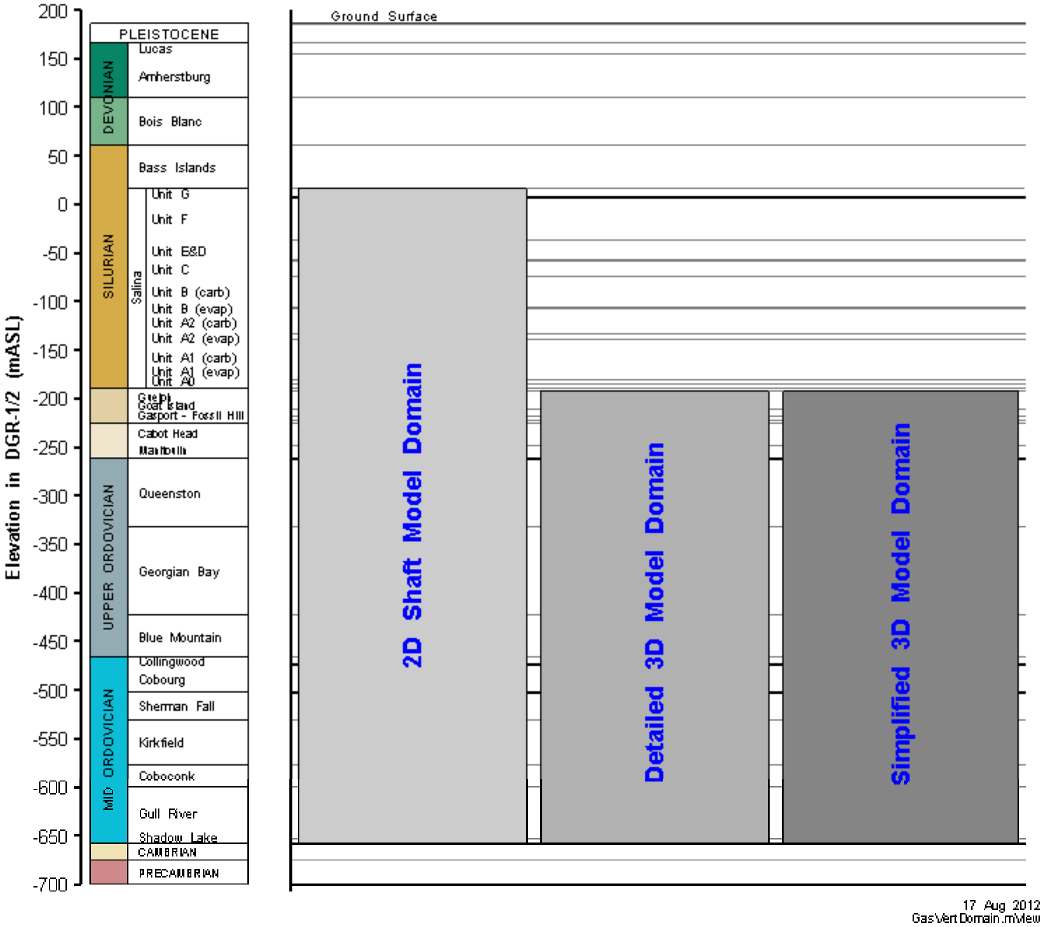


<u>Key Processes included:</u>
- Gas transport by diffusion in water or gas phase, advection
- Repository gas generation
- Partially saturated rock and unsaturated repository
- No flow side boundary
- Side boundaries at defined pressure (measured or steady-state)
- Overpressured Cambrian bottom boundary

T2GGM model domain

T2GGM – Fundamental Aspects (2)

- Different models for different domains of rock

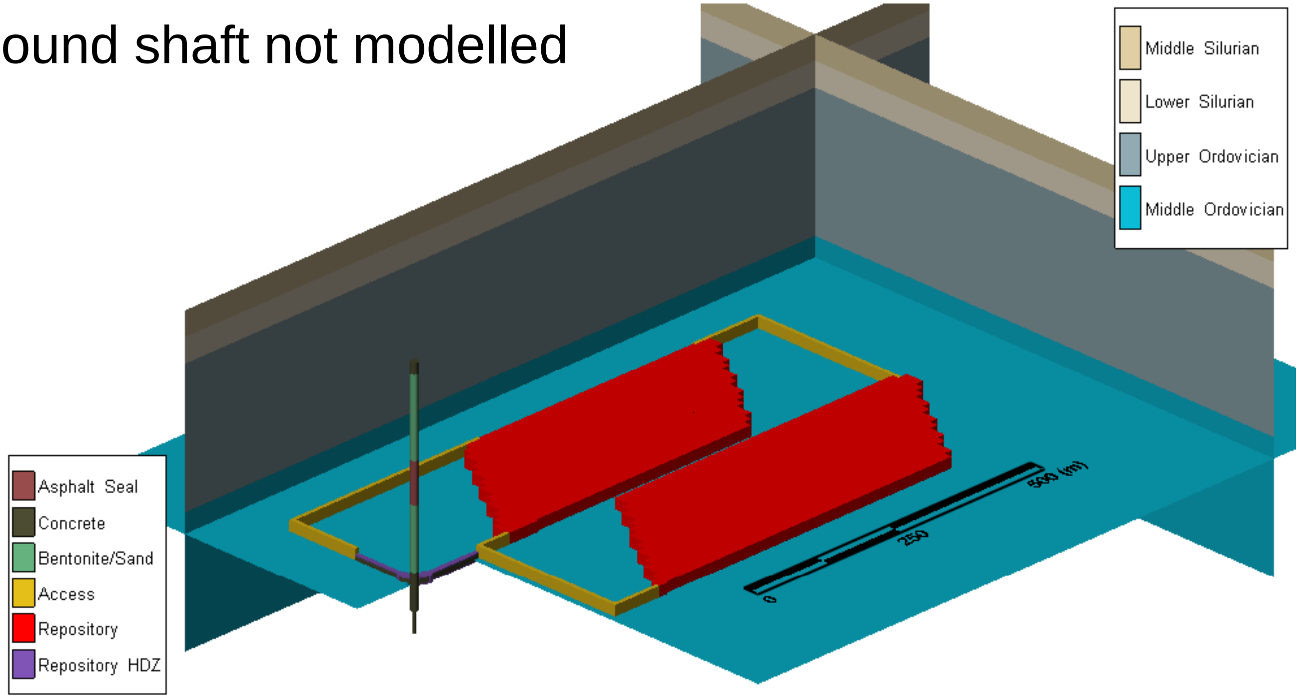


- 2-D model focused on shaft, extends to shallow groundwater system
- 3-D models of deep geosphere and repository
- All rock formations within each domain are explicitly modelled
- Cambrian top is fixed pressure boundary, horizontal flow not considered

T2GGM – Fundamental Aspects (3)

Detailed 3-D model (3DD)

- Two shafts combined into one shaft with same area
- Emplacement rooms, tunnels, room pillars combined into porous panel with same void volume
- 10-m rockfall also included in panels and tunnels
- Service area around shaft not modelled



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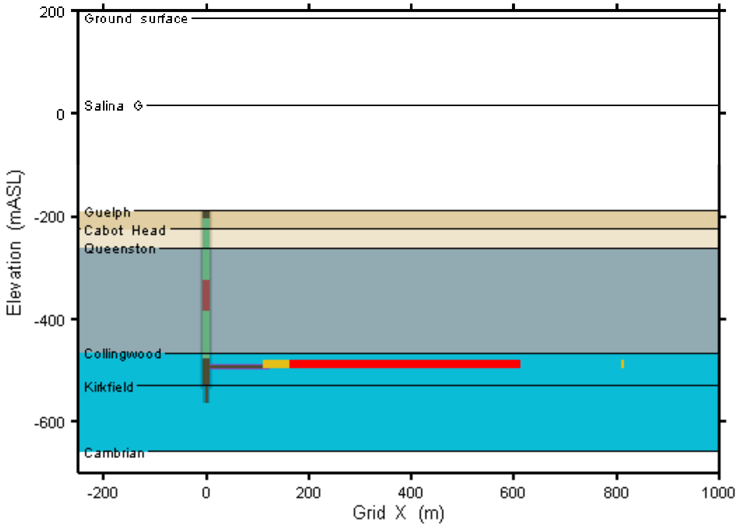
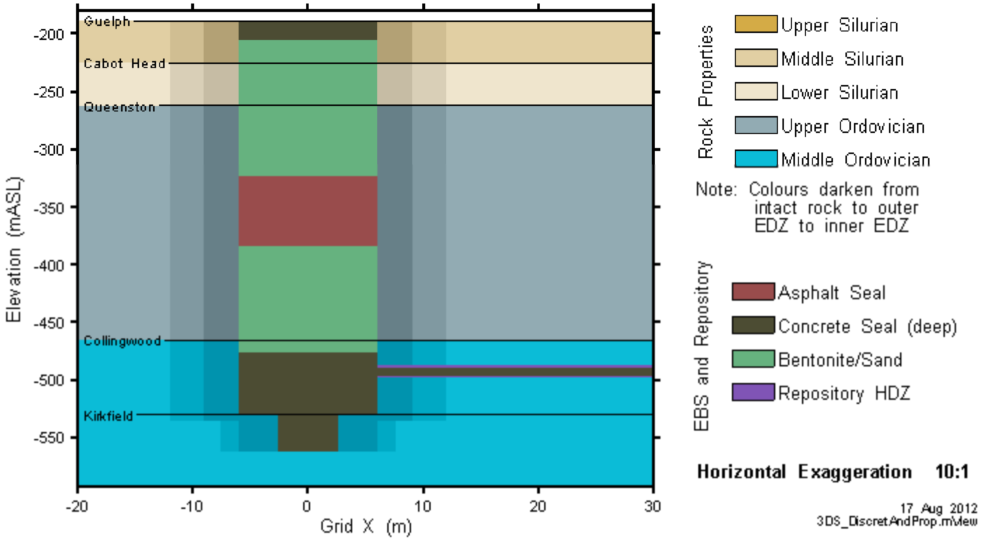
T2GGM – Fundamental Aspects (4)

Shaft model: Detailed 3-D model (3DD) Discretization:

Scale view

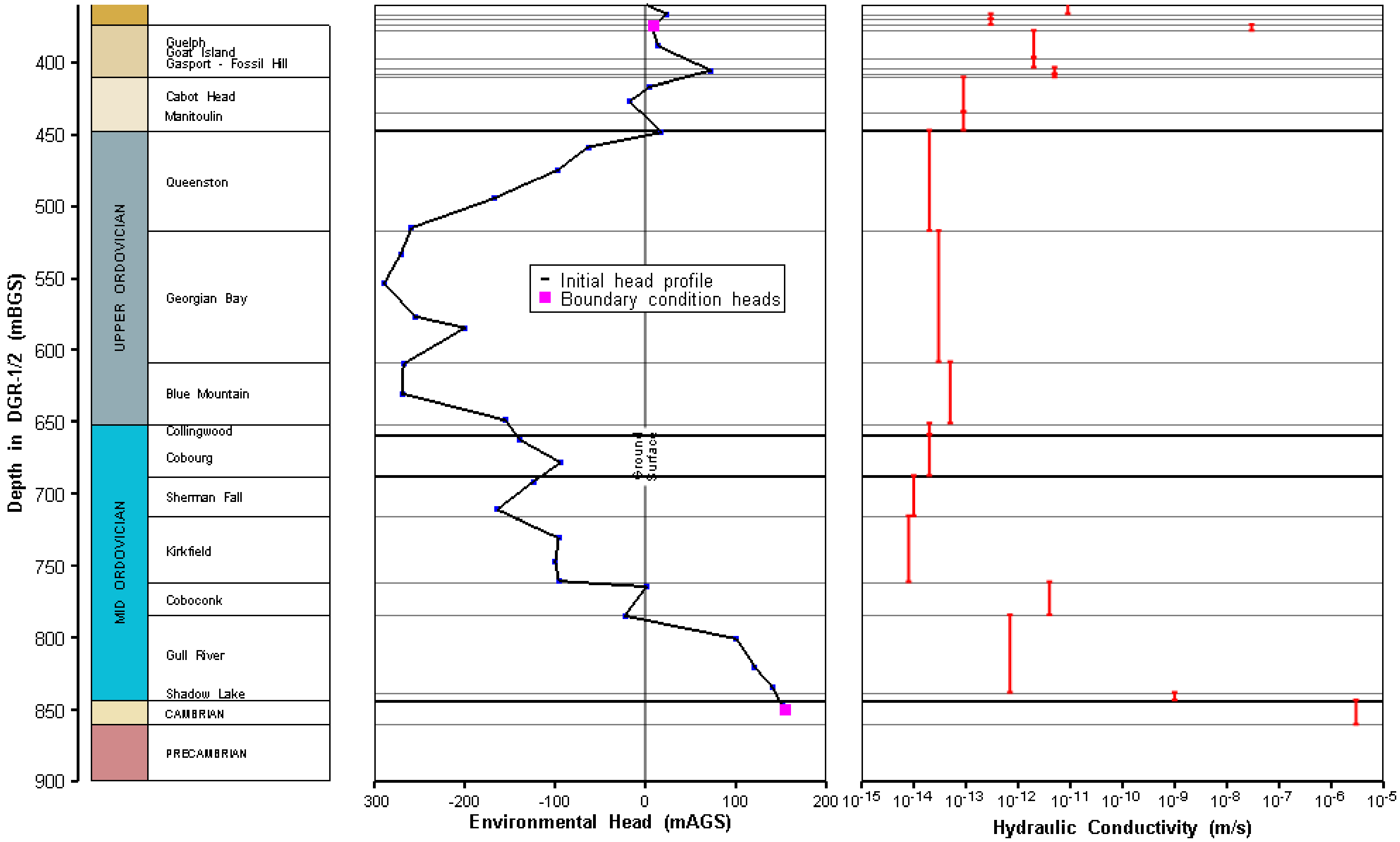


Expanded view



T2GGM – Fundamental Aspects (5)

Initial conditions: Pressure and K parameterization

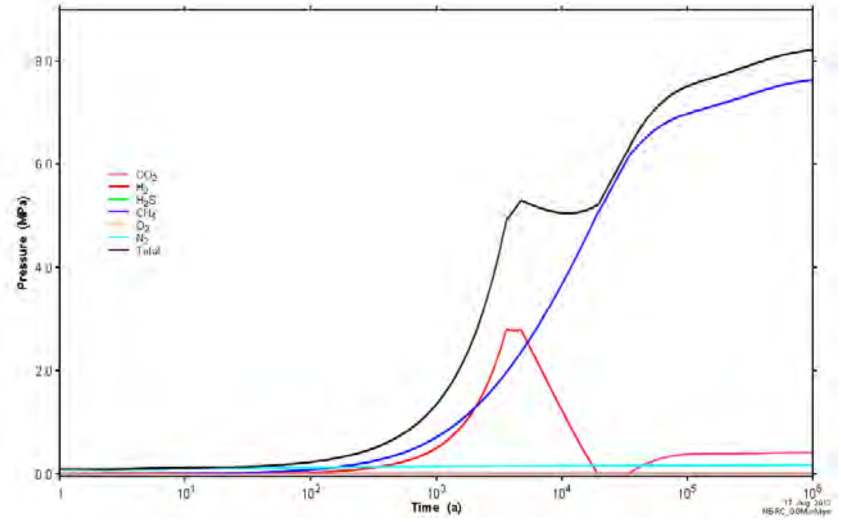


T2GGM – Calibration

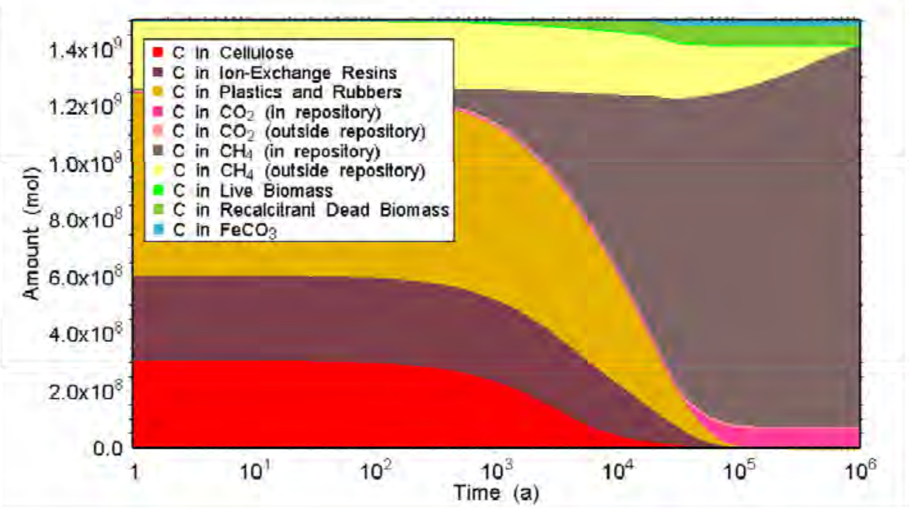
- Input data derived from and traceable to geosynthesis and site characterization program:
  - Permeability and initial pressure – from in-situ measurements
  - Porosity, diffusion and compressibility – from rock core measurements
  - Two-phase flow properties – model parameters calibrated to rock core tests
- No free parameters have been adjusted: all parameters align with site data.

T2GGM – Example Results (1)

Repository gas pressures

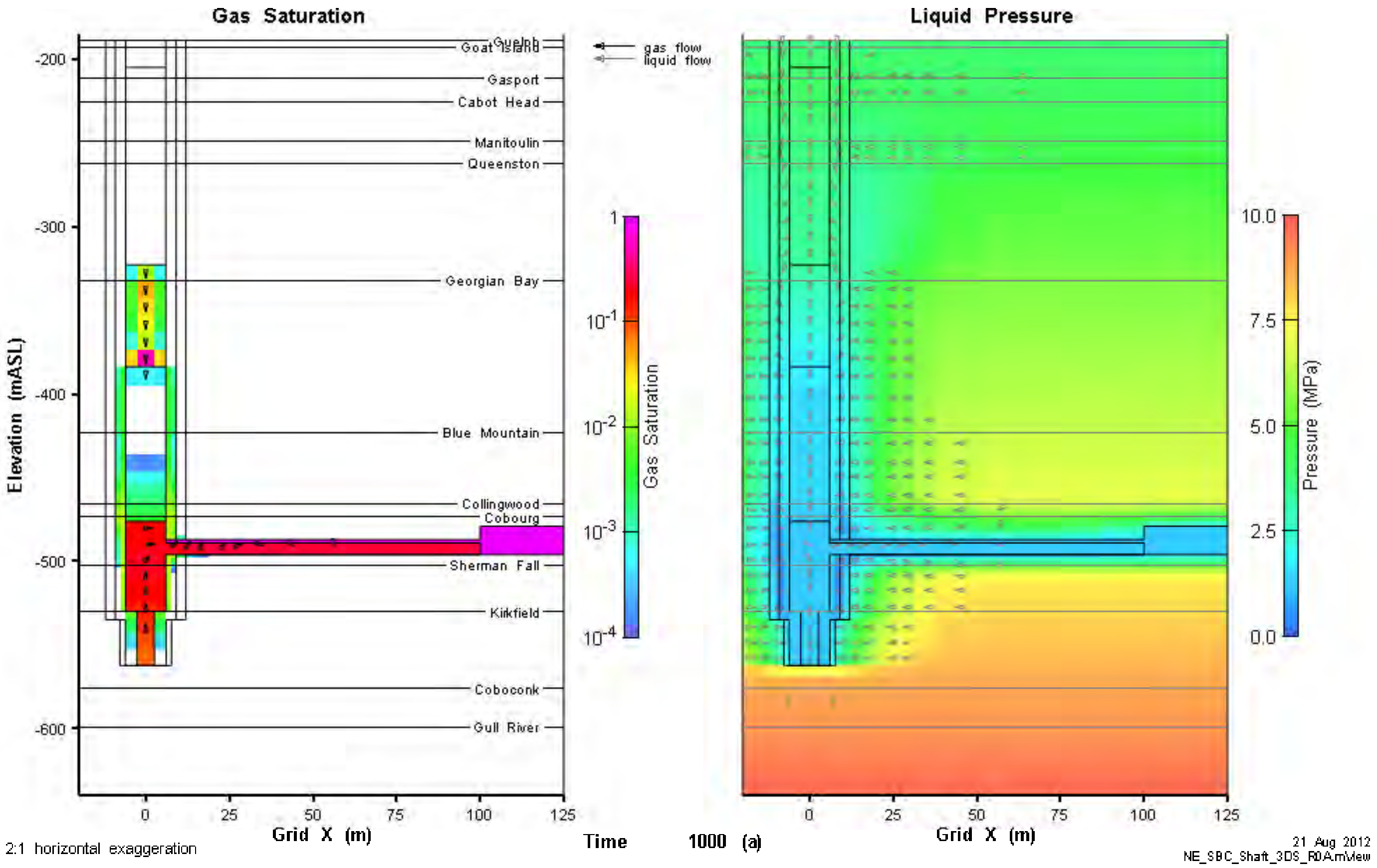


Carbon mass balance



T2GGM – Example Results (2)

Shaft conditions at 1000 years (Reference case)

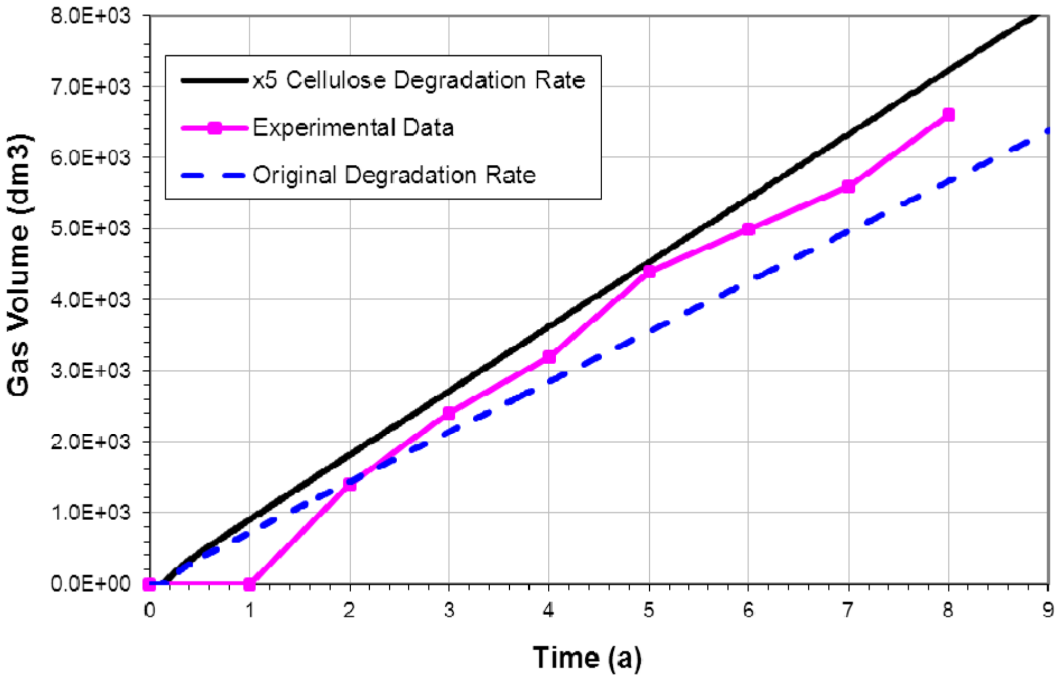


T2GGM – Verification (1)

- Based on TOUGH2 code:
  - Developed / maintained by US Government
  - Used in international waste management programs
- Additions to TOUGH2 under project's QA system
  - Checking of model and data implementation
  - Peer review of model and results
- Used by NWMO in international projects:
  - Swiss HG-A gas permeation experiment at Mont Terri
  - Swedish LASGIT gas experiment at Aspo
  - European code comparison on gas transport in repositories
- Numeric tests:
  - GGM unit verification tests
  - Simulation mass balance
  - Convergence criteria evaluated
- Comparison to simple alternative calculations

T2GGM – Verification (2)

GGM test case: Comparison with Finnish Gas Generation Experiment for short-term gas generation

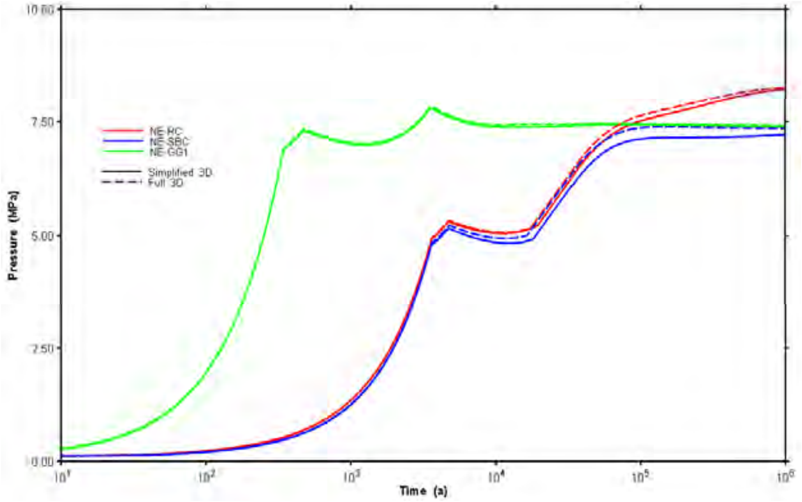


App. B, T2GGM Version 2: Gas Generation and Transport Code. NWMO DGR-TR-2011-33.

T2GGM – Verification (3)

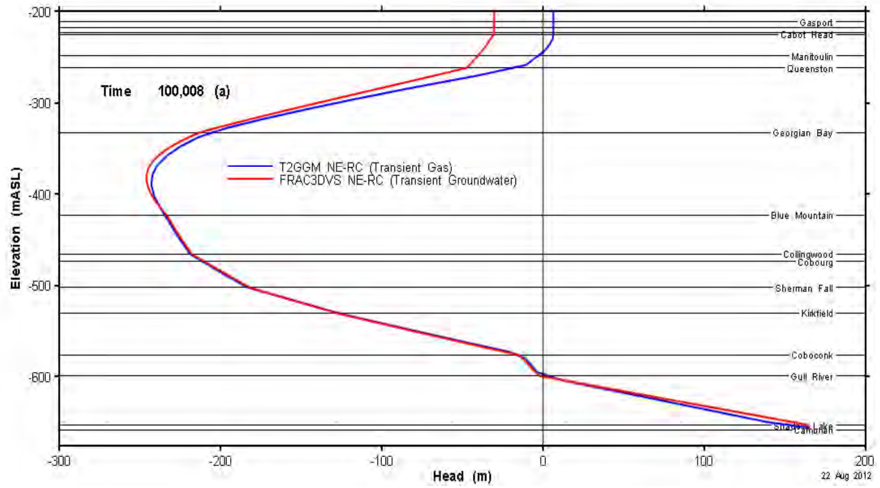
Consistent results for different model discretizations - 3DD and 3DSRS

(note: each color is a different cases, solid and dashed lines are for the different models for each case)



Consistent results for different codes - FRAC3DVS and T2GGM

(transient hydraulic head at 100 ka)



T2GGM – Uncertainty Analysis (1)

Source of Uncertainty	How Addressed in Model

Gas Generation	• Models / data selected to maximize gas generation
	  • Wastes fully degrade
	  • Organic degradation proceeds to gas products
	  • Microbes assumed to be present and active (not limited by salinity or dry conditions)
	• Consumption of water by reactions in repository is conservatively not included in most cases ("NWL")
	• Sensitivity cases:
	  • No microbial activity – sensitivity case NE-NM
	  • Reaction rate – sensitivity cases NE-GG1 / GG2
	  • "What if" no gas generation – NE-NG1 case

T2GGM – Uncertainty Analysis (2)

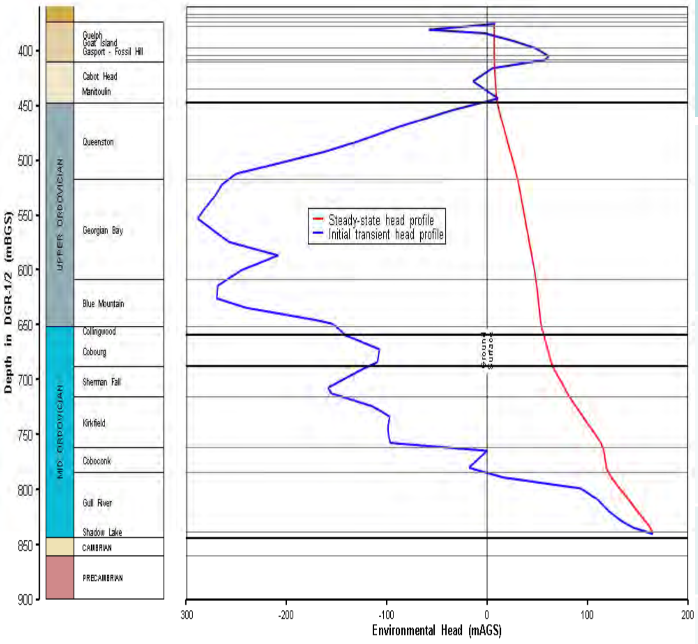
Source of Uncertainty	How Addressed in Model
Rockfall / seismicity	• Assumes effects occur instantly - instant formation of porous panels with enlarged size due to rockfall
Container degradation	• No credit as barrier to waste degradation or radionuclide release (conservative)
Seal permeability	• Higher value adopted within range of data • Sensitivity cases – NE-GT4 and GT5 • "What if" case - SF-BC scenario

Gas transport	• Use of van Genuchten two-phase flow model
	  • Widely used model
	  • Model parameters calibrated to rock core tests
	  • Sensitivity cases – NE-GT1/GT2/GT3, RC1/RC2

Geosphere permeability	• Based on measured values from site • Sensitivity case – NE-AN3
Shaft EDZ	• Conservative estimate of size/thickness • Sensitivity cases – NE-EDZ1

T2GGM – Uncertainty Analysis (3)

Source of Uncertainty:
Geosphere conceptual model

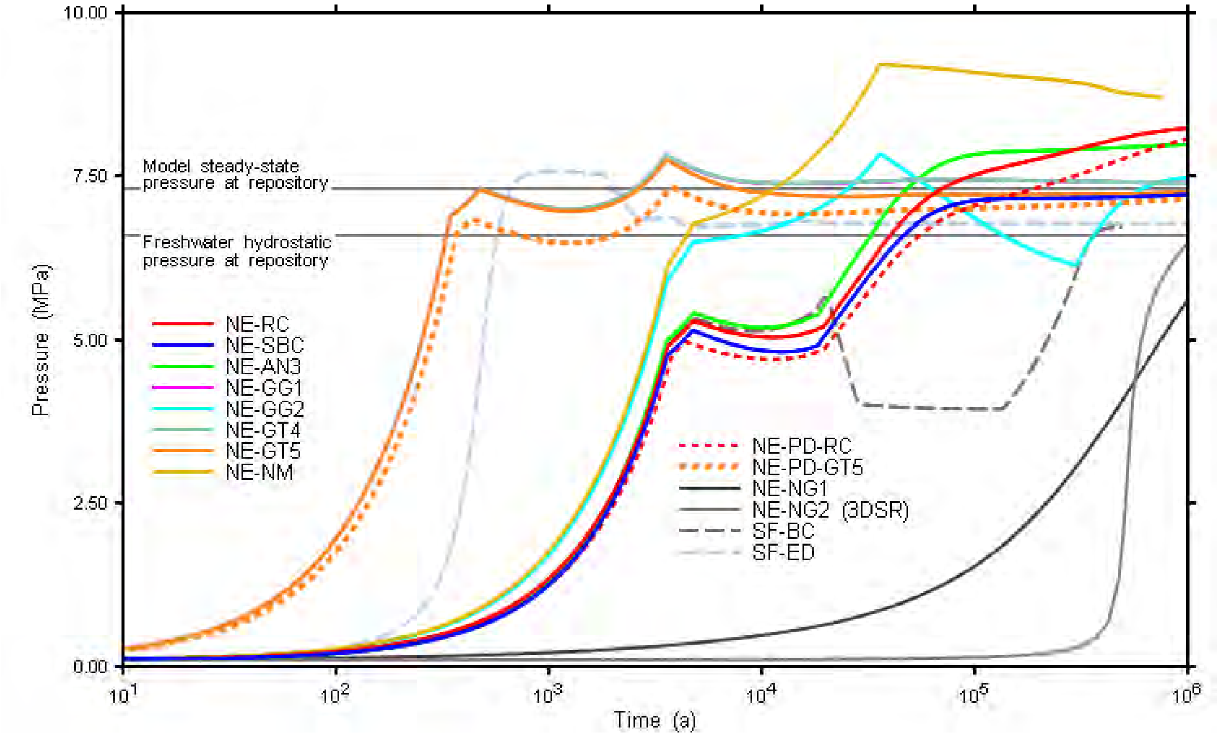


- Reference case – Best estimate basis
  - Includes Ordovician under-pressure
  - Includes some gas in Ordovician rock
- Simplified base case – Conservative basis
  - No Ordovician under-pressure
  - Fully saturated rock
- Cambrian over-pressure – Constant
- Regional flow in Guelph and Salina A1
  - Not included – this maximizes local impact
  - Sensitivity case (NE-HG) with FRAC3DVS-OPG
- Vertical fault near repository
  - Not consistent with site characterization
  - “What if” scenario with FRAC3DVS-OPG

T2GGM – Uncertainty Analysis (4)

Key Findings of Sensitivity Analysis**:**

- Pressure develops to around natural conditions
- Some gas flows up the shaft at long times
- No gas flow above Guelph Formation for Normal Evolution Scenario



Average Repository Gas Pressure for all NWL Cases

T2GGM - Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Use of TOUGH2 code, widely used	++
Gas generation model - maximizes gas generation	++
Use of input data derived from site characterization	+++
Development under a QA system, with peer review	++
Comparison of model results with other codes	+
Comparison of results from different discretizations	+
Uncertainties addressed using conservative assumptions and sensitivity analyses (~20 calculation cases)	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

Outline of Presentation

Part One - Geoscience Modelling

- 3-DGFM
- FRAC3DVS-OPG
- TOUGH2-MP
- MIN3P

Part Two - Repository Evolution Modelling

- FLAC3D
- FRAC3DVS-OPG
- T2GGM
- **AMBER**

Part Three - Radiation Dose Modelling

- MicroShield, MicroSkyshine, MCNP
- Non-Human Biota

Part Four – Environmental Modelling

- AERMOD
- Cadna/A

AMBER (v5.3)

Purpose:

- A general-purpose compartment modelling code developed and maintained by Quintessa
- Typically used to develop models of contaminant release, migration and impact in environmental systems
- A DGR-specific model was developed for this project

Numerical approach:

- Compartment model with two solvers for first-order differential equations: Laplace transform and time-step

Status:

- First developed in 1993, now widely-used commercial code

AMBER – Fundamental Aspects

Features:

- User-specified contaminants and compartments
- User-specified algebraic expressions to represent:
  - Time-varying properties and transfers
  - Contaminant concentrations and fluxes
  - Exposure of humans and other biota
- Contaminant decay and ingrowth
- Probabilistic capability:
  - Latin Hypercube Sampling
  - Monte Carlo Sampling

AMBER – Confidence in Code

- Managed and developed under Quintessa's ISO 9001:2008 registered QA system (incorporates requirements of UK TickIT software quality system)
- Extensive testing of each release against broad set of documented verification tests
- Used by over 85 organizations in more than 30 countries
- Over 100 publications describing assessments in which AMBER has been applied, including:
    - International exercises involving code intercomparison, e.g., ISAM and BIOPROTA
    - Other assessments of geologic repositories, e.g., the Swedish regulator's review of SKB's disposal of LLW and ILW
- Documentation available from: www.quintessa.org/software/amber

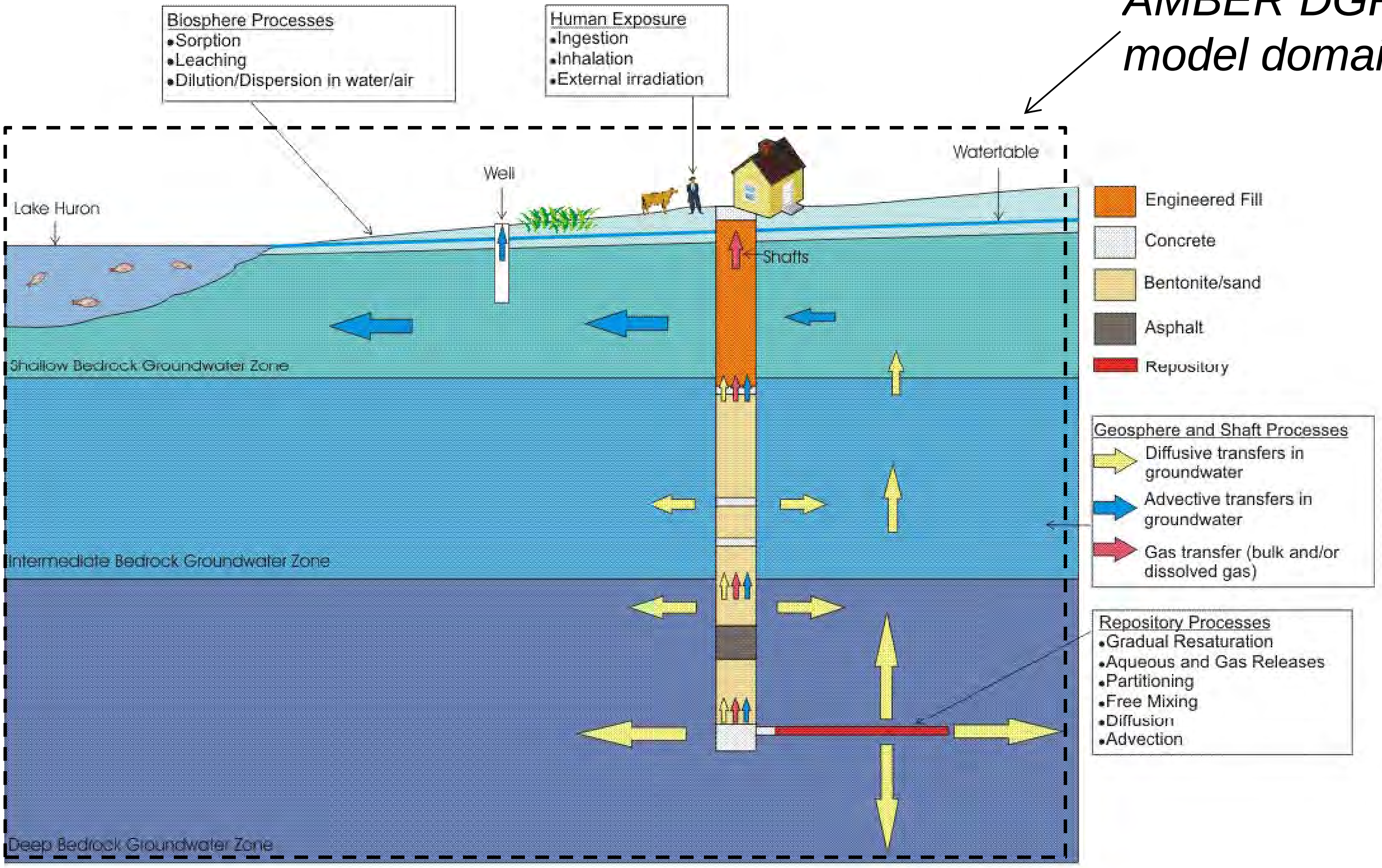
AMBER DGR – Fundamental Aspects (1)

- Specific model implemented in AMBER v5.3 to represent postclosure contaminant release, migration and impacts from OPG's DGR
- Supported by FRAC3DVS-OPG and T2GGM models:
  - To identify contaminant transport pathways to be represented
  - To quantify saturation profiles, gas composition, groundwater and gas fluxes, and well capture fraction used by AMBER
- AMBER DGR model is documented in Normal Evolution Scenario and Disruptive Scenarios reports

AMBER DGR – Fundamental Aspects (2)

Key processes included in AMBER DGR model

AMBER DGR model domain



Biosphere Processes
- Sorption
- Leaching
- Dilution/Dispersion in water/air

Human Exposure
- Ingestion
- Inhalation
- External irradiation

Geosphere and Shaft Processes
- Diffusive transfers in groundwater
- Advective transfers in groundwater
- Gas transfer (bulk and/or dissolved gas)

Repository Processes
- Gradual Resaturation
- Aqueous and Gas Releases
- Partitioning
- Free Mixing
- Diffusion
- Advection

AMBER DGR – Fundamental Aspects (3)

- Key waste and repository assumptions
  - Resaturation rates from T2GGM
  - No credit given to waste packaging as a barrier
  - Instantaneous release on contact with water for most wastes
  - H-3 and C-14 also released as gas due to waste degradation
  - No sorption of contaminants
  - No solubility limitation except for carbon

AMBER DGR – Fundamental Aspects (4)

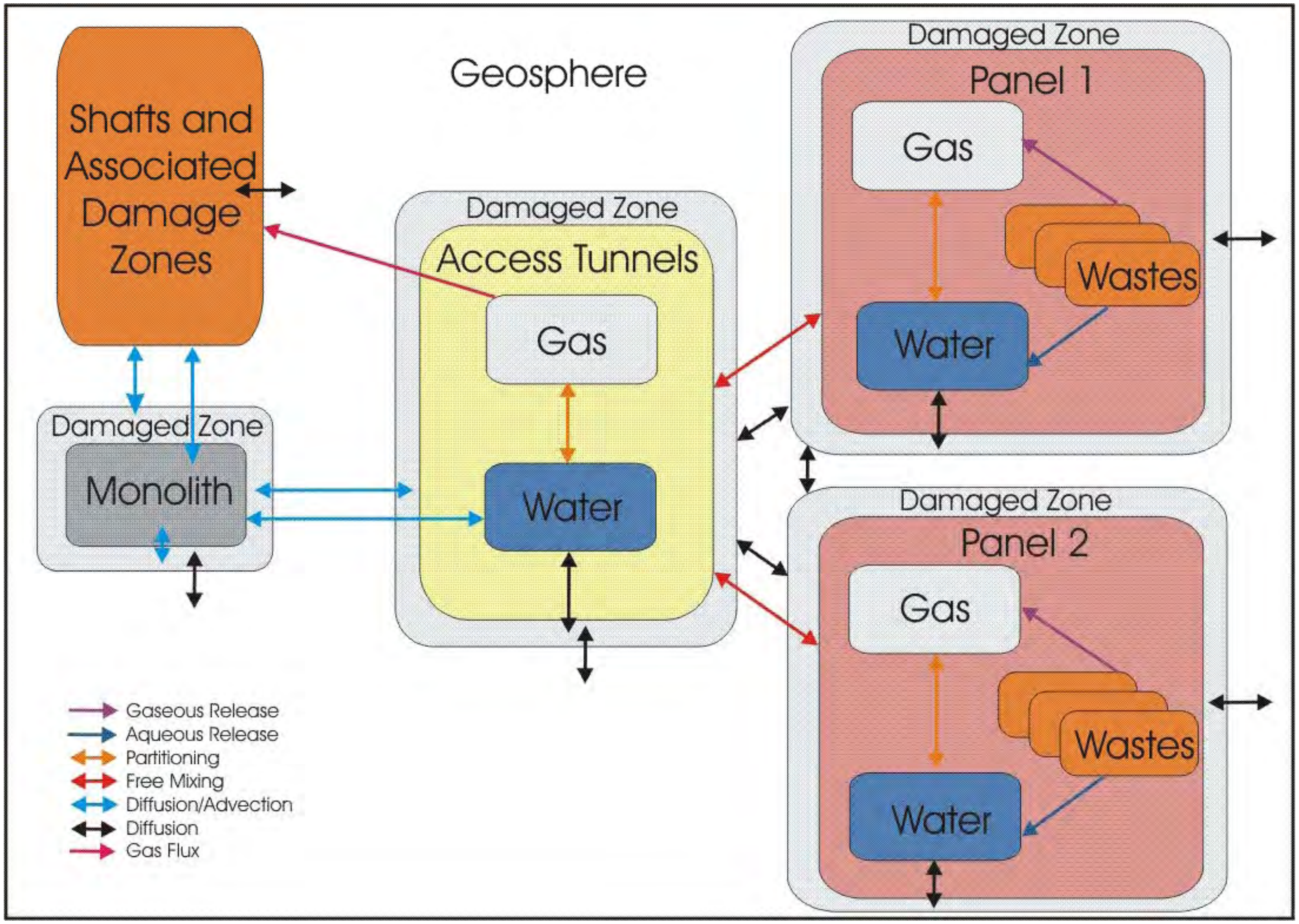
- Key geosphere and shaft assumptions
  - Water and gas fluxes from FRAC3DVS-OPG and T2GGM
  - Sorption of only certain elements (Zr, Nb, Cd, Pb, U, Np, Pu)
  - No solubility limitation
- Key biosphere assumptions
  - Contaminants released via:
    - Well pumping from shallow aquifer
    - Groundwater discharge to near-shore lake bed
    - In certain cases, gas flux into house and soil
  - Self-sufficient family farm located on repository site using well water

AMBER DGR – Fundamental Aspects (5)

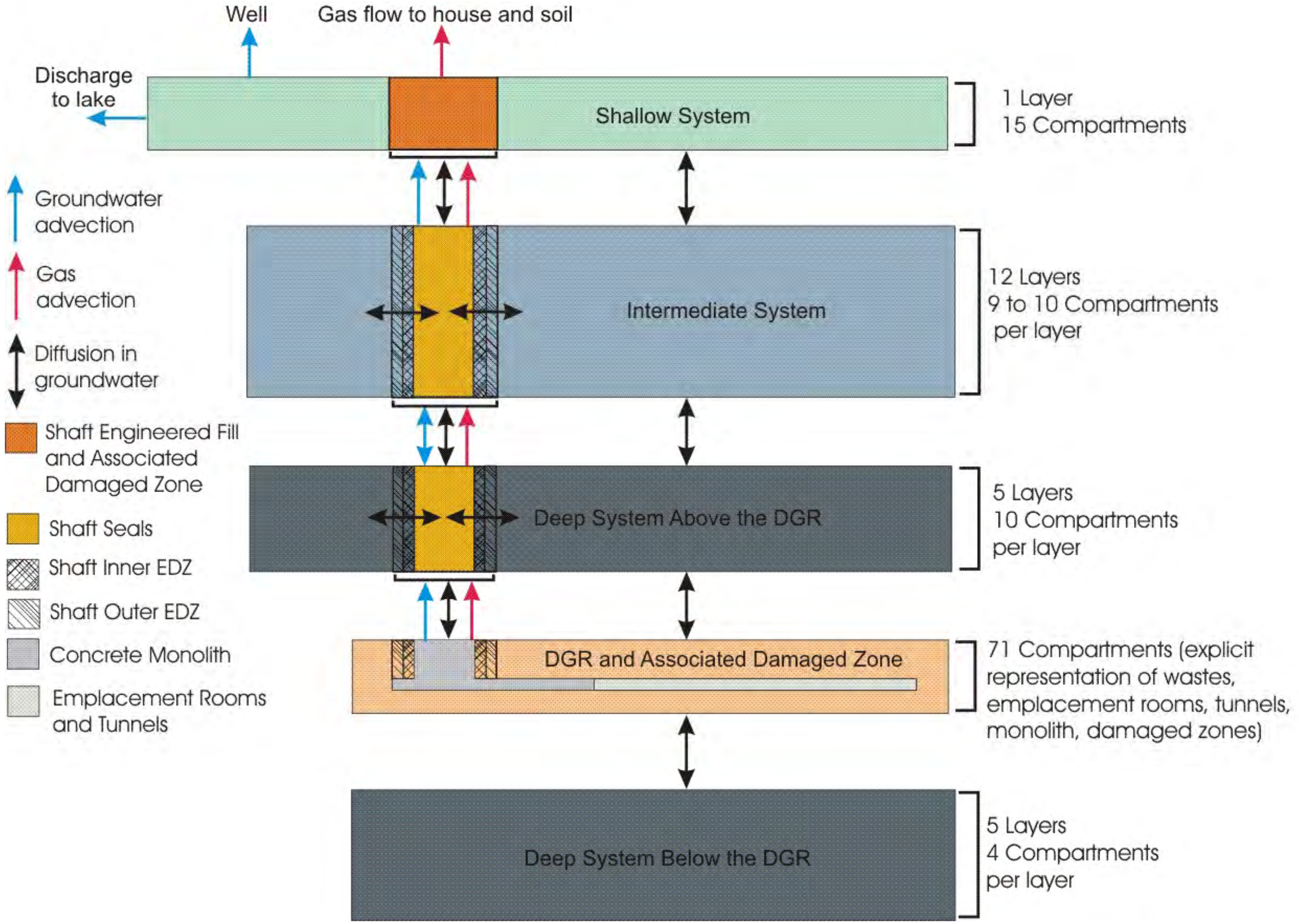
- System discretized into:
  - Wastes - 21 compartments representing waste categories
  - Repository - 50 compartments representing emplacement rooms, tunnels, monolith, rock damaged zones
  - Shafts - 69 compartments representing seals and rock damaged zones
  - Geosphere -188 compartments representing four groundwater zones
  - Biosphere - 7 terrestrial and 8 lake compartments

AMBER DGR – Fundamental Aspects (6)

Schematic of waste and repository discretization

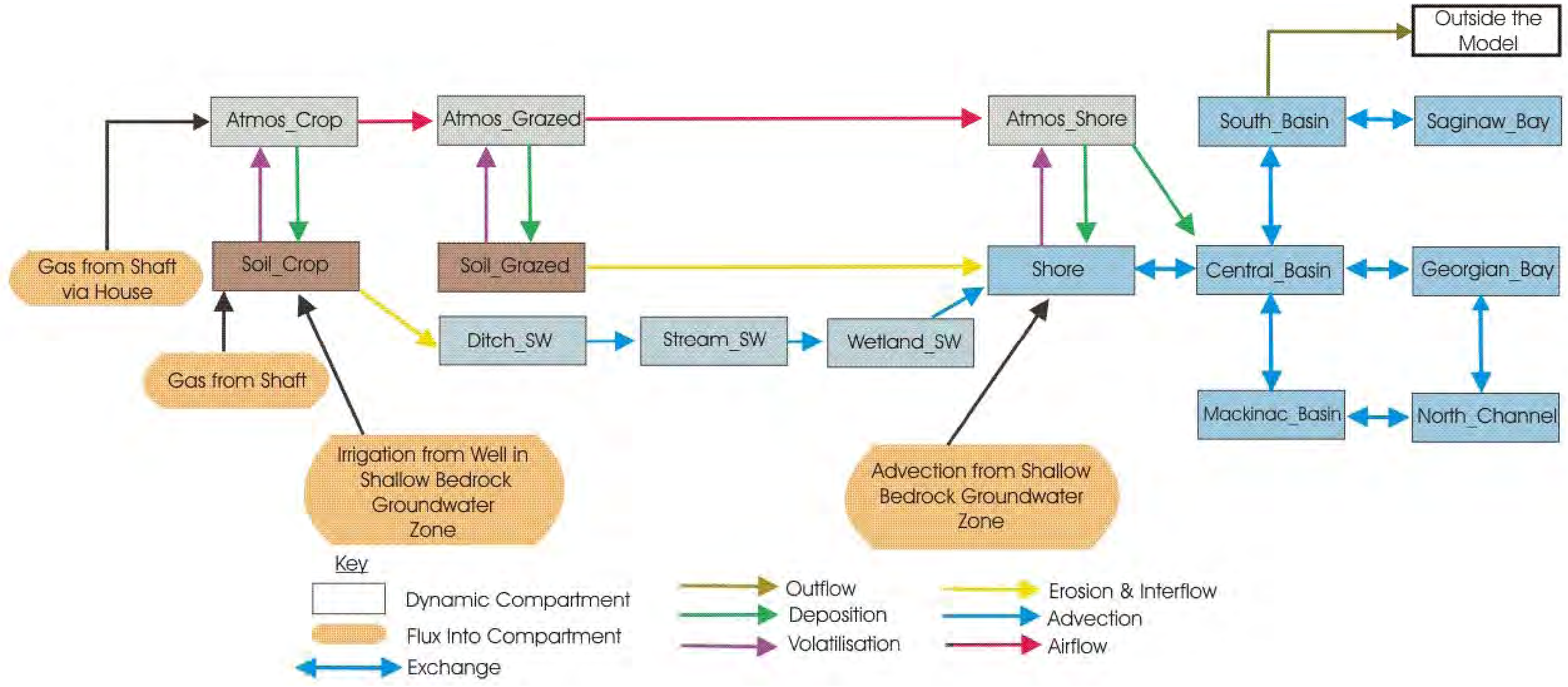


AMBER DGR – Fundamental Aspects (7)



AMBER DGR – Fundamental Aspects (8)

Schematic of biosphere discretization



AMBER DGR – Calibration

- No free parameters have been adjusted
- Input data
  - Mainly derived from and traceable to DGR waste and site characterization programs
  - Groundwater and gas transport data imported directly from FRAC3DVS-OPG and T2GGM
  - Many biosphere data from CSA N288.1-08

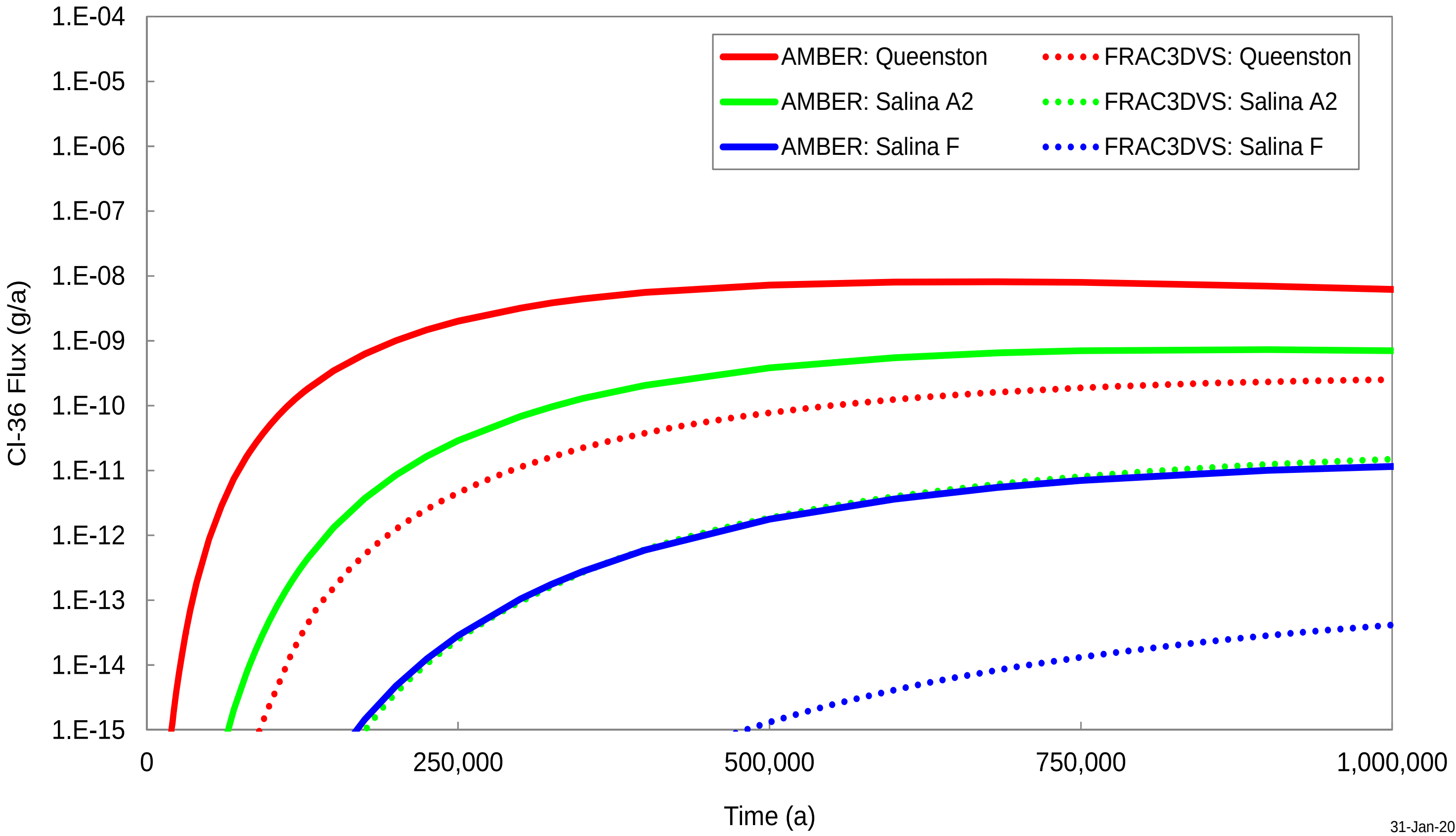
AMBER DGR – Verification (1)

- Uses AMBER code
  - Numerically robust and well verified
  - Used in international waste management programs
- Model implemented iteratively under project's QA system with:
  - Checking of model and data implementation
  - Mass balance checks
  - Peer review of models and results
- Compared with simplified scoping calculations
  - Key contaminants comparable

AMBER DGR – Verification (2)

Model Comparison: AMBER with FRAC3DVS-OPG

- Cl-36 flux through shaft and geosphere
- AMBER results are conservative, as expected



AMBER DGR – Uncertainty Analysis (1)

Source of Uncertainty	How Addressed in Model
Future evolution of DGR system	• Five scenarios assessed • Implemented in the same AMBER DGR model
Model	• Sensitivity cases, e.g.: - with/without Ordovician under-pressures - immediate/gradual repository resaturation - with/without horizontal flow in Guelph & Salina A1
Data	• Mostly taken from DGR waste and site characterization programs, augmented by national/international sources (e.g., CSA, IAEA, ICRP) • Multiple deterministic sensitivity calculations with alternative sets of parameter values • Probabilistic sensitivity to radionuclide release and transport parameters for Normal Evolution Scenario's reference case

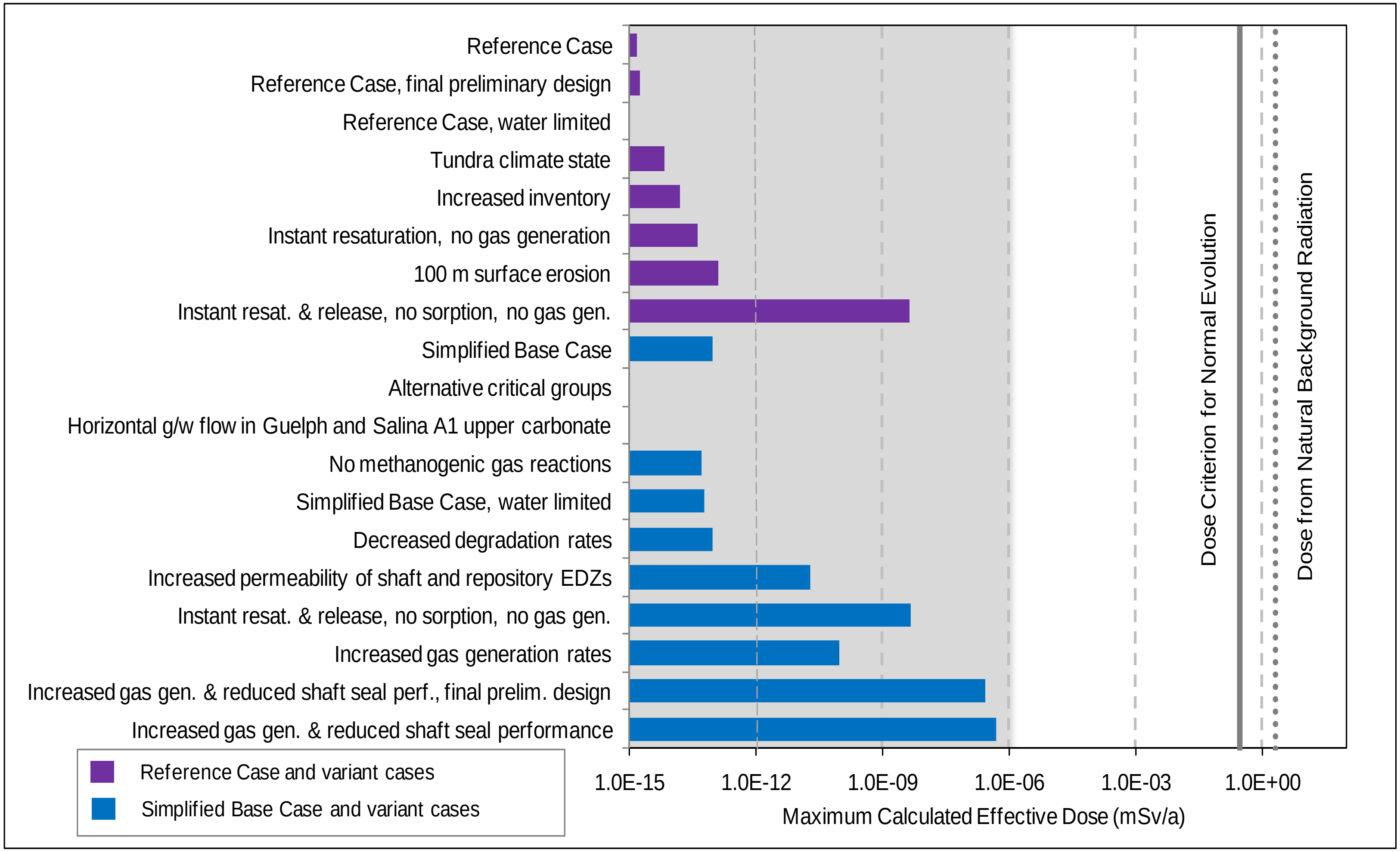
AMBER DGR – Uncertainty Analysis (2)

Model and data uncertainties also addressed using conservative reference case assumptions, e.g.:

- Instantaneous release from all LLW and most ILW waste streams
- No sorption of contaminants in repository
- No solubility limits for contaminants in repository except for carbon
- No sorption for most contaminants in shafts and geosphere
- No solubility limits for contaminants in the shafts and geosphere
- No significant groundwater flow in the Guelph and Salina A1 upper carbonate formations
- Self-sufficient family farm located on repository site using well water

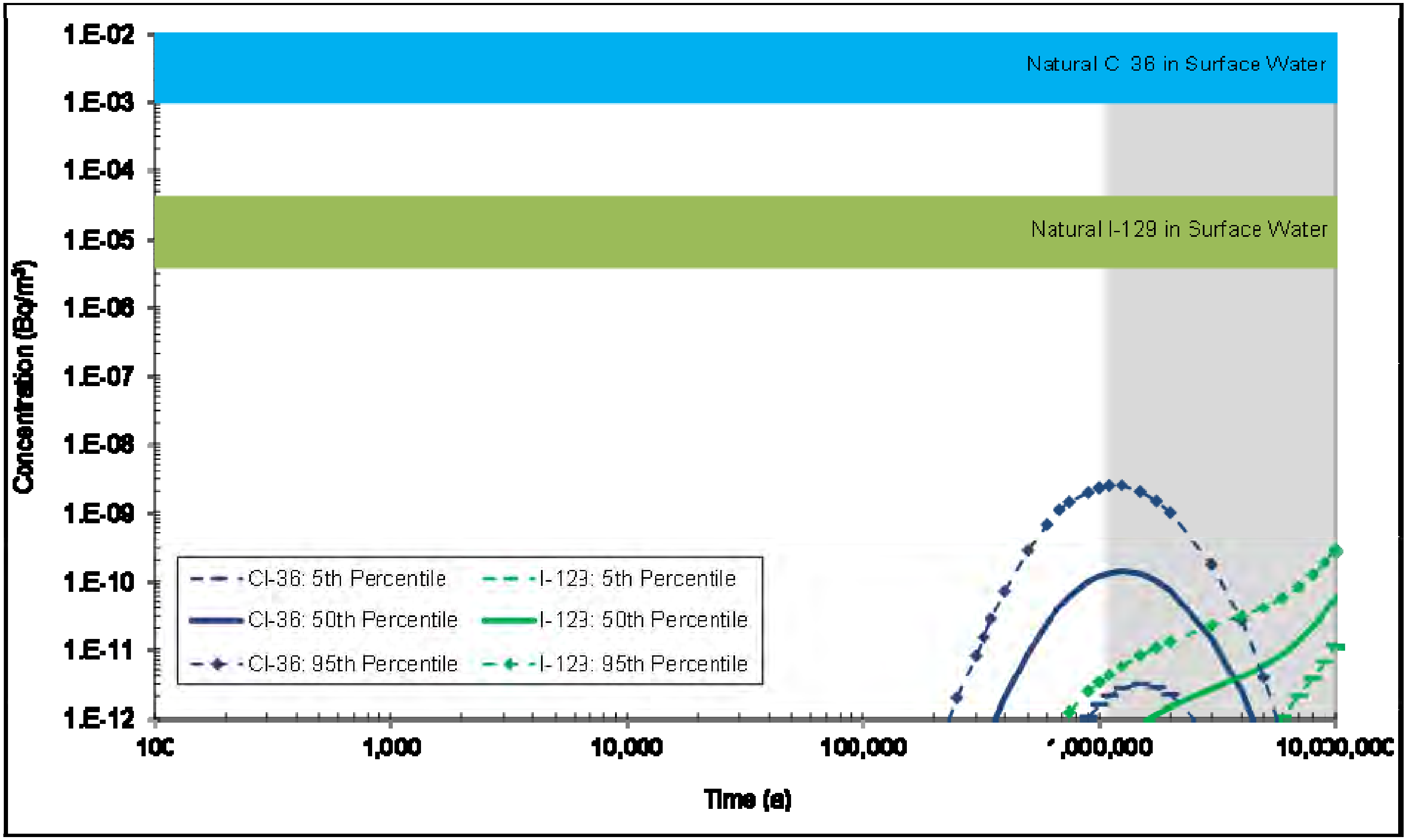
AMBER DGR – Uncertainty Analysis (3)

Sensitivity analysis summary: Doses are most sensitive to gas generation and shaft seal parameters



AMBER DGR – Uncertainty Analysis (4)

Probabilistic analysis for Reference Case: Well concentration remains low even when radionuclide release & transport parameters are varied over plausible range



AMBER DGR – Relative Contribution to Confidence

Line of Evidence	**Relative Contribution**
Use of AMBER code, widely used	++
Use of standard conceptual / mathematical models	++
Use of input data derived from DGR-specific programs and detailed models	+++
Developed under a QA system, with peer review at interim and final stages	++
Comparison of model results with other codes	+
Large safety margin in results	+++
Uncertainties addressed using five scenarios, conservative assumptions and sensitivity analyses	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

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Radiation Dose Modelling

Dose models for exposure during Operations period:

Workers and public:

(a) MicroShield
- Primary DGR radiation dose code (external gamma dose)

(b) MicroSkyshine
- Used to check the gamma “skyshine” pathway

(c) MCNP
- Used to check the gamma “wall scatter “pathway

Non-human biota:

Simple dose model includes internal exposure and external exposure.

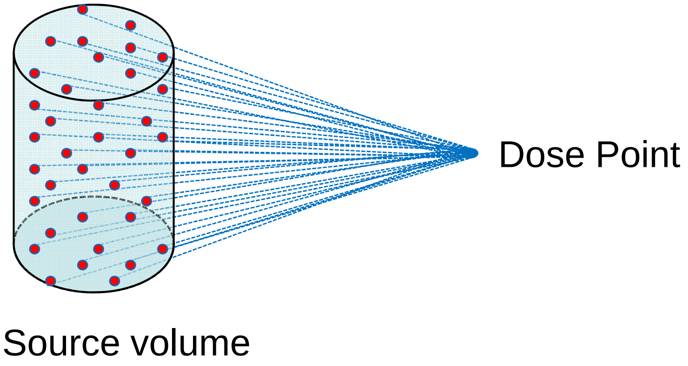
MicroShield (v8.02)

Purpose:

- MicroShield is a photon shielding and dose assessment program
- It was used in DGR project for gamma dose rate calculations and preliminary shielding design

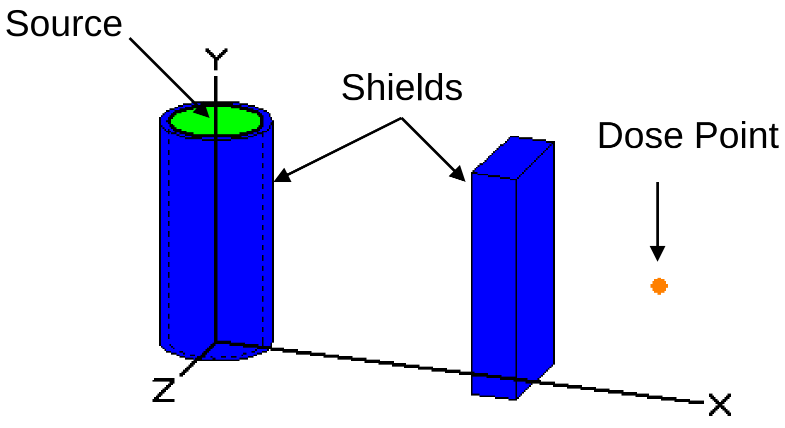
Numerical approach:

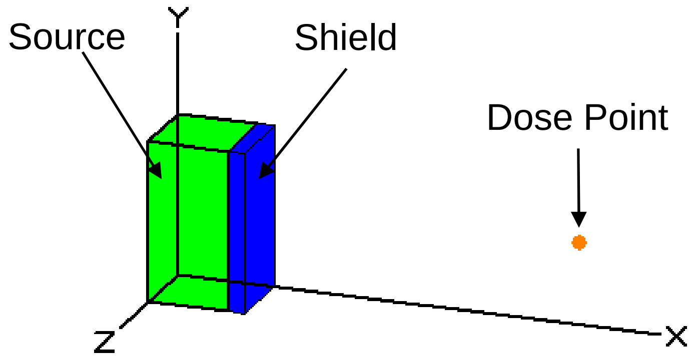
- Point-kernel method, where a volume source is treated as a number of point sources
- The flux from each point source to the dose point is calculated analytically, including attenuation and buildup



MicroShield – Fundamental Aspects

- Uses defined source/shield geometries
- Can include multiple shield layers
- Includes source self-shielding
- Source concentration is assumed to be uniform
- Uses buildup factors to account for source/shield scattering





MicroShield – Calibration

- No calibration
- Input parameters are defined as described later

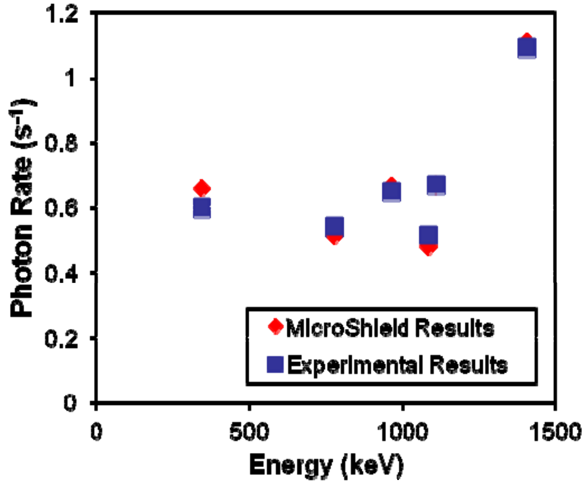
MicroShield – Verification

- MicroShield builds on a series of codes, going back to ISOSHLD(1966), so the basic algorithms have been in use for decades
- Built-in Library data from standard references for:
  - Radionuclides, decay and photons
  - Material attenuation and buildup factors
  - Dose conversion factors
- Widely-used commercial code (OPG, CNSC, IAEA, US NRC, industry, universities)
- Cited in ~200 papers
- Used in support of regulatory / licence applications
  - e.g., OPG dry storage buildings at Darlington and Western Waste Management Facility

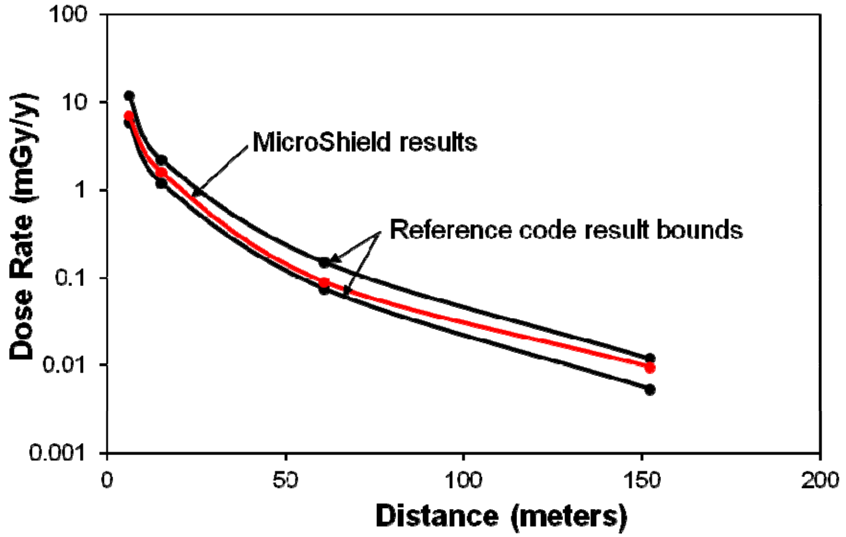
MicroShield – Validation (1)

Literature examples:

Experimental test: Photon rates from an ^{152}Eu standard source with 5.08 cm of stainless steel shielding



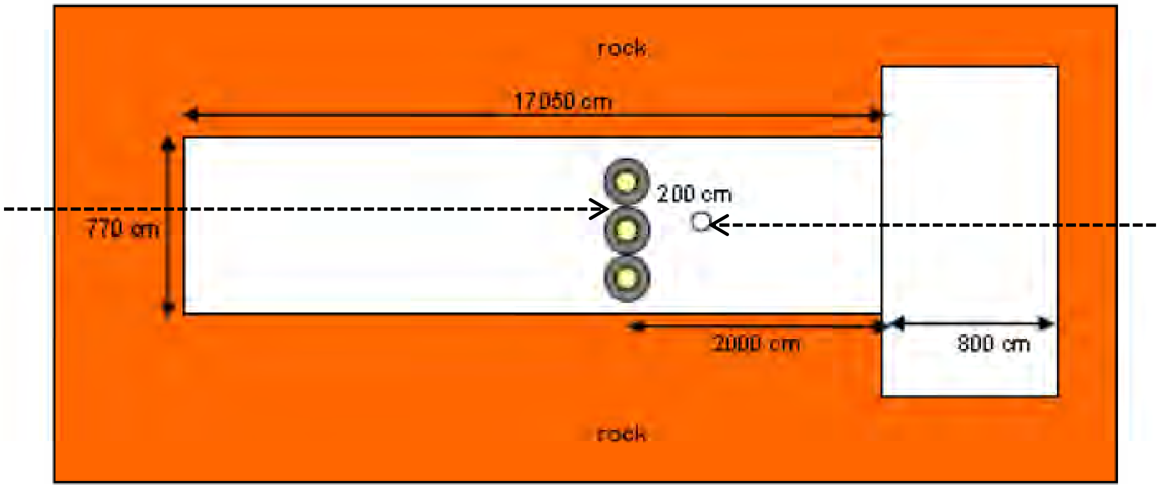
ANSI 6.6.1
Standard problem II.1:
Cylindrical water tank with uniform monoenergetic photon source



MicroShield – Validation (2)

Model comparison: MicroShield with MCNP

Case: Forklift driver in a DGR emplacement room



Resin liner shield packages

Forklift driver (dose point)

MCNP: 0.1 mSv/h   MicroShield: 0.14 mSv/h

MicroShield conservatively over-estimated the dose rate

MicroShield – Uncertainty Analysis

- Model applicability to DGR:
  - Gamma dose dominates
  - Used to calculate direct dose in simple shielding geometries
  - Common radionuclides with photons within 0.015 to 15 MeV range
- Source term:
  - Generally higher dose rate packages considered
  - Calculations considered different LLW or ILW waste packages
- Shielding:
  - Generally standard shield materials (concrete, steel)
  - Conservative choice of buildup material
  - No credit for package internal structure contribution to shielding
- Receptor:
  - Placed at close position consistent with scenario
  - Anterior/Posterior dose model (person facing source)
- Skyshine and wall-scattering contribution:
  - Calculated separately with MicroSkyshine and MCNP

MicroSkyshine (v2.10)

Purpose:

- Dose from overhead (air) scattered gamma radiation

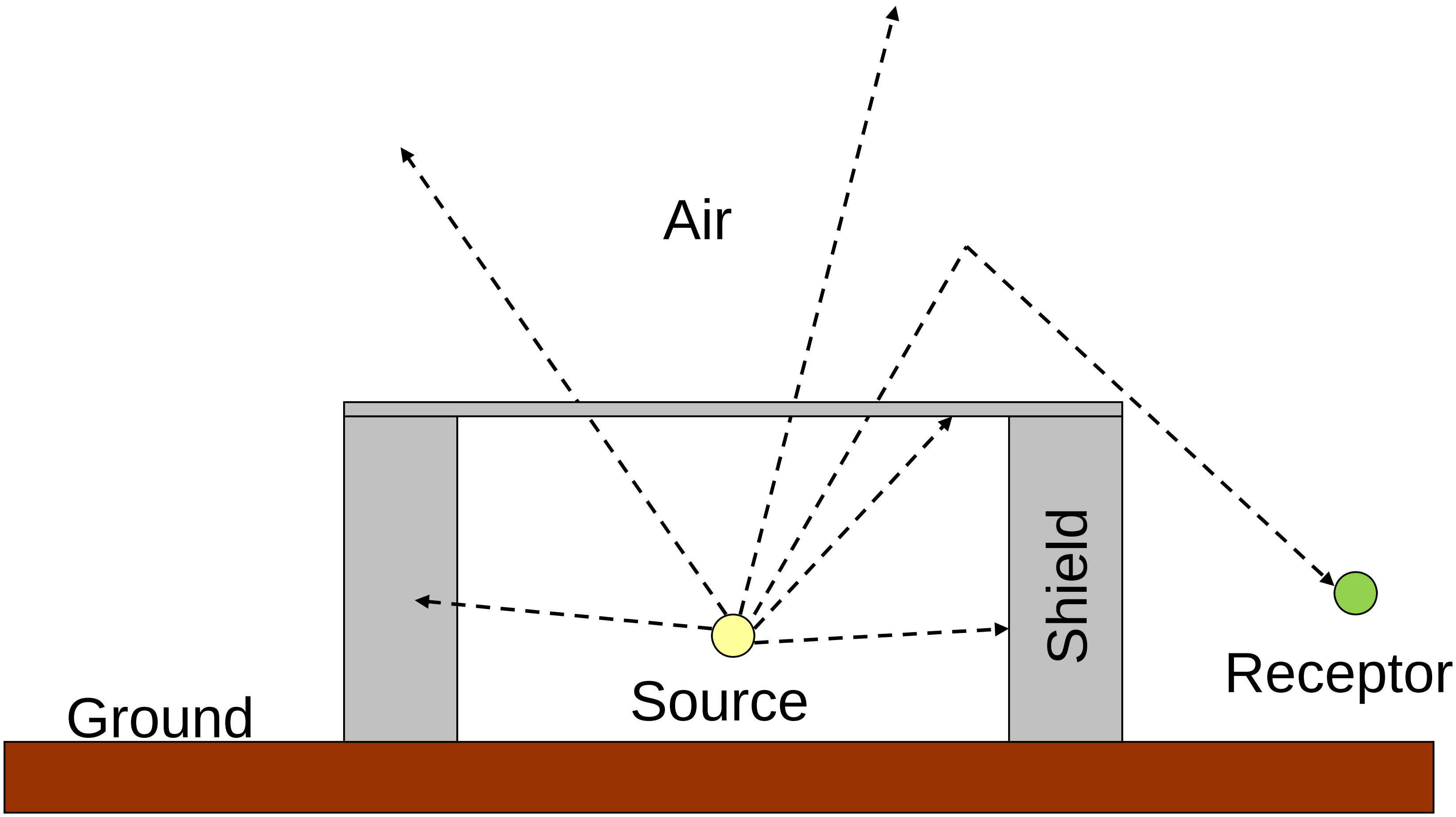
Numerical approach:

- Solution based on use of “beam functions” for a point source
- Line-beam response functions developed from Monte Carlo calculations

Status:

- Commercial code

MicroSkyshine – What is "skyshine"?



MicroSkyshine – Fundamental Aspects

- Standard source geometries
- Standard source and shield materials (e.g., air, water, iron)
- Scattering medium is air
- Vertical wall is a perfect shield, i.e. direct dose through wall is not calculated (it is calculated by MicroShield separately)

MicroSkyshine – Calibration / Verification

- No calibration in DGR application
- Commercial code
  - Recognized by CNSC, US NRC
- Built-in library data (radionuclides, attenuation, buildup)
- Used in support of licence applications, e.g.:
  - OPG dry storage facilities at the Darlington and Western Waste Management Facilities
  - Has been used to evaluate dry storage facility conformance with US 10CFR50, Appendix I, ALARA requirements for public (US NRC 2000 Standard Review Plan)

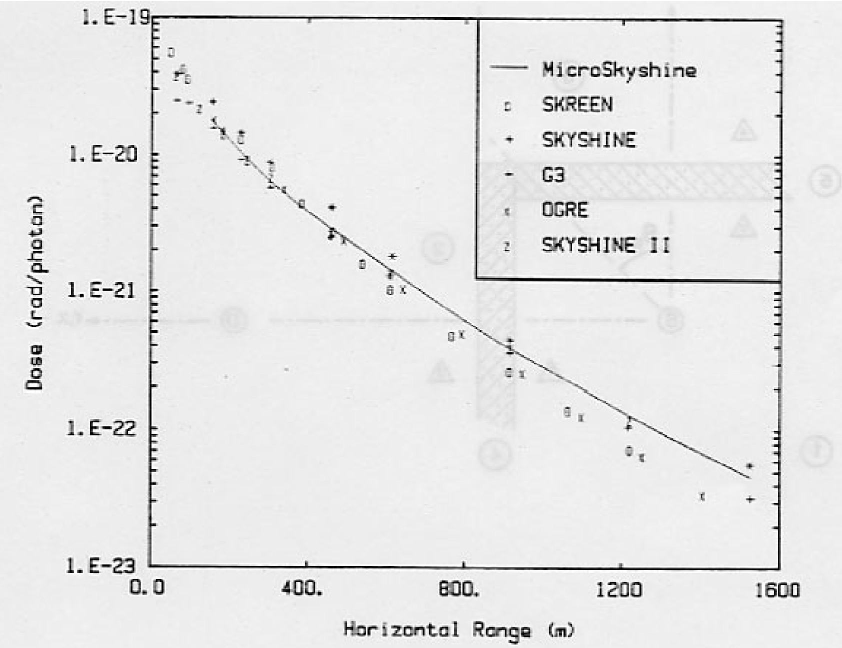
MicroSkyshine – Validation (1)

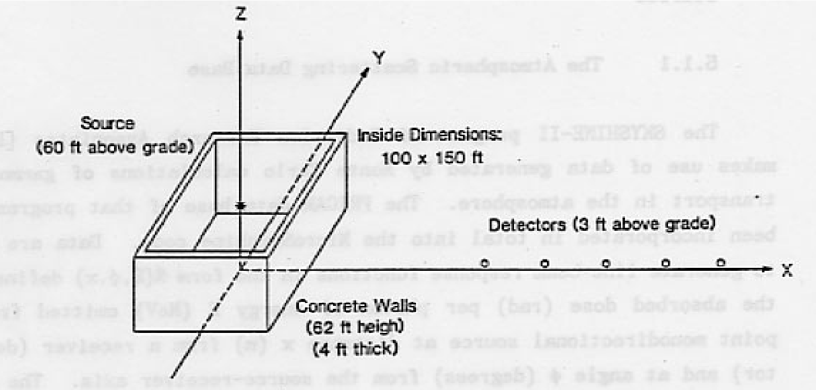
Literature Example:

ANSI-6.6.1 Standard Problem I.2:

Rectangular roofless building having 4 ft thick concrete wall on all four sides

Point source - 6.2 MeV gamma photons from ^{16}N





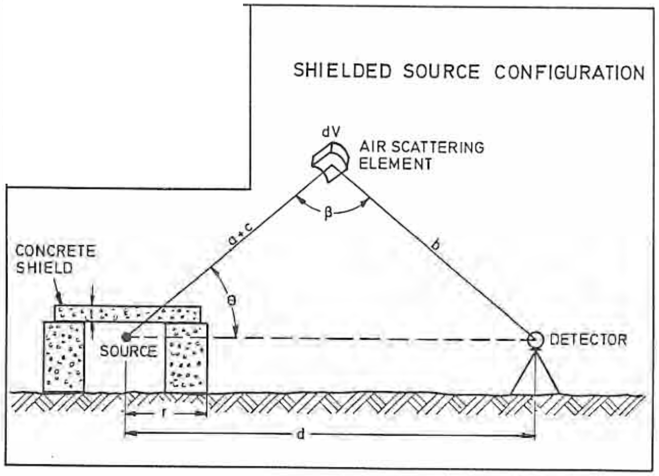
Faw, R.E., and Shultis, J.K., 1987. The MicroSkyshine Method for Gamma-Ray Skyshine Analysis. Report 188. Kansas State University, Manhattan, KS, USA.

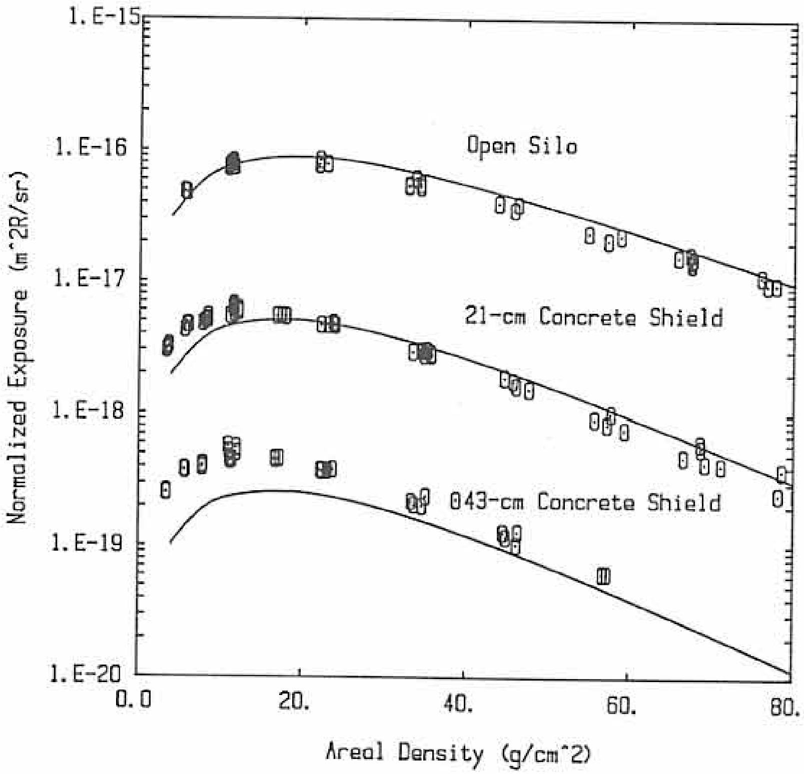
MicroSkyshine – Validation (2)

Literature example:

Kansas State benchmark experiment:

- Cylindrical ^{60}Co source
- Concrete shielding





Shultis, J.K. and R.E. Faw, 1987. Improved Response Functions for the MicroSkyshine Method. Report 189. Kansas State University, USA.

MicroSkyshine – Uncertainty Analysis

- DGR conditions are appropriate for code use
  - Standard radionuclides, main photons from 0.1 to 2 MeV
  - Source-to-receptor distance of 80 m and 1100 m
  - WPRB roof thickness less than 6 mean-free-paths
- Use of conservative source term and closest distance to source
  - Assumes WPRB has 24 LLW or 2 ILW packages
  - Public/non-NEWs at nearest DGR or Bruce site fence
- Large margin in results
  - Skyshine dose rate is small

MCNP (v5)

Purpose:

- Code was developed for modelling of neutron, photon and electron transport
- Used in DGR to evaluate importance of gamma scattering from walls in underground emplacement room

Numerical approach:

- Monte Carlo method
  (simulates the random walk of individual particles; results are statistical averages over many particles)

Status:

- Widely-used commercial code

MCNP – Fundamental Aspects

- Applicable to gamma radiation, neutrons and electrons
- Allows detailed treatment of geometry, including source, shield and surrounding structures
- Allows detailed treatment of particle interaction with materials, including scattering
- Includes options for variance reduction, i.e. numerical methods to obtain faster convergence

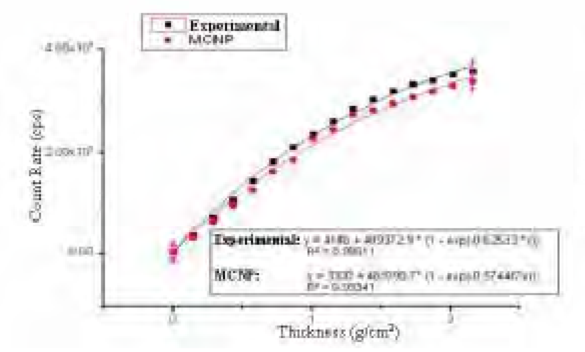
MCNP – Calibration / Verification

- No calibration in DGR application
- Code is developed and maintained by
  US Government through Los Alamos National Laboratory
- Maintained under formal software QA system
  - LANL ASCI SQE Working Group, "LANL ASCI Software Engineering Requirements", LA-UR-02-0888 (2002)
- Nuclear data are available in standard input files
- Widely-used code
  - Referenced in ~17000 articles according to Google Scholar
- Extensive validation/verification
  - From MCNP home web site https://laws.lanl.gov/vhosts/mcnp.lanl.gov/mcnp_publications.shtml#shielding

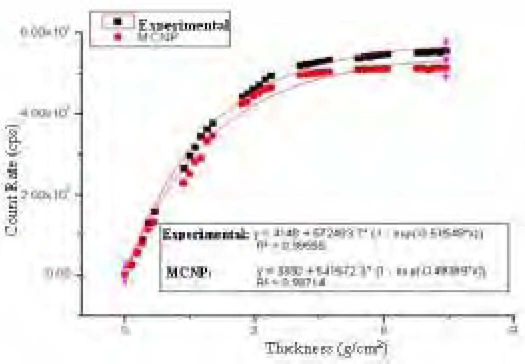
MCNP – Validation

Literature Example: Backscattering experiment:

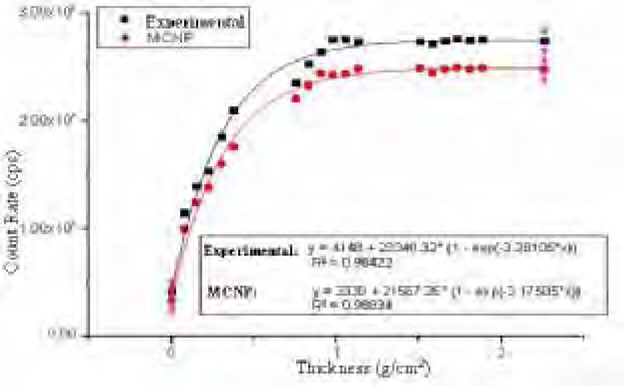
- Backscattering used as thickness measurement
- ^{241}Am low-energy gamma source



Backscatter from Plastic



Backscatter from Aluminum

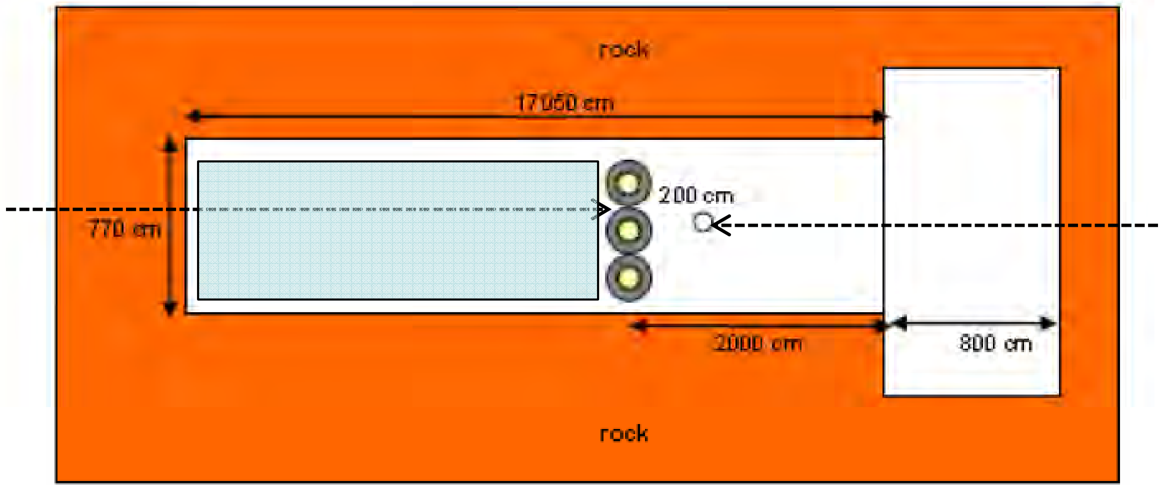


Backscatter from Steel

B.V. Loat, N. Hung, H. Phuong. 2010. Monte Carlo simulation by code of MCNP and experimental check for measuring thickness of materials for the specializing system of MYIO-101. VNU Journal of Science, Mathematics – Physics 26, 43-49.

MCNP – Uncertainty Analysis

Application: Importance of wall scattering to dose rate



Resin liner shield packages

Forklift driver (dose point)

Bounding Assessment

- ILW emplacement room
- Full room with 99 rows x 3 packages per row

Sensitivity analysis

- Influence of scattering: air surrounding room vs. rock surrounding room
- Influence of front row only of waste packages

Worker/Public Dose Models – Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Use of MicroShield code, widely used	++
Simple geometries, standard radionuclides and shielding	+++
QA checking of results	+++
Comparison of model results with other code	+
Uncertainty in scattering contribution evaluated with specialty codes (MicroSkyshine and MCNP)	++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

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Assessment of Doses to Non-human Biota

- Tier-2 approach in compliance with EIS Guidelines and CSA N288.6-12
- Used in other EA work
- For preclosure period only

Non-Human Biota - Fundamental Aspects (1)

- **Key Features**
  - Direct exposure (to Gamma)
    - *Gamma dose = dose rate × exposure period*
  - Indirect exposure (through various pathways)
    - *Total dose = internal dose + external dose*
    - *Internal dose = dose coefficient (int) × concentration of radionuclide in species*
    - *Concentration of radionuclide in species= intake × concentration in intake × transfer factor*
    - *External dose = dose coefficient (ext) × concentration of radionuclide in environmental media*

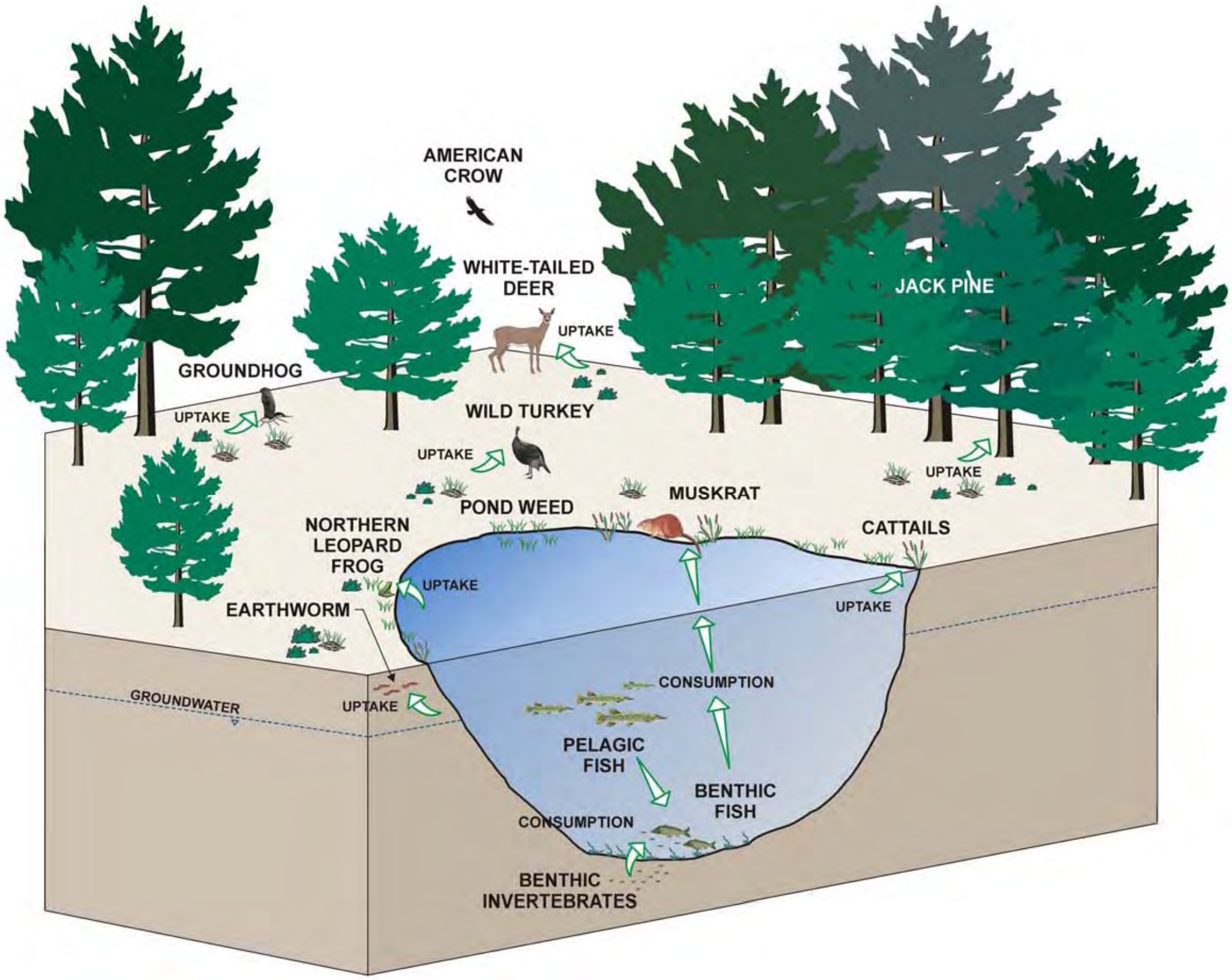
Non-Human Biota - Fundamental Aspects (2)

- Normal Operations – Direct Exposure Scenario:
  - "Disposal ready" package: Point source /inverse square law
  - 1-hour exposure per day at a distance of 10 m
- Normal Operations – Indirect Exposure Scenario:
  - Concentrations assumed to be twice current conditions
  - Receptors: Indicator Animals and Plants – detailed further
  - Located at points of maximum concentrations
  - Exposure Pathways – detailed further
  - Transfer Factors and Dosimetry – detailed further

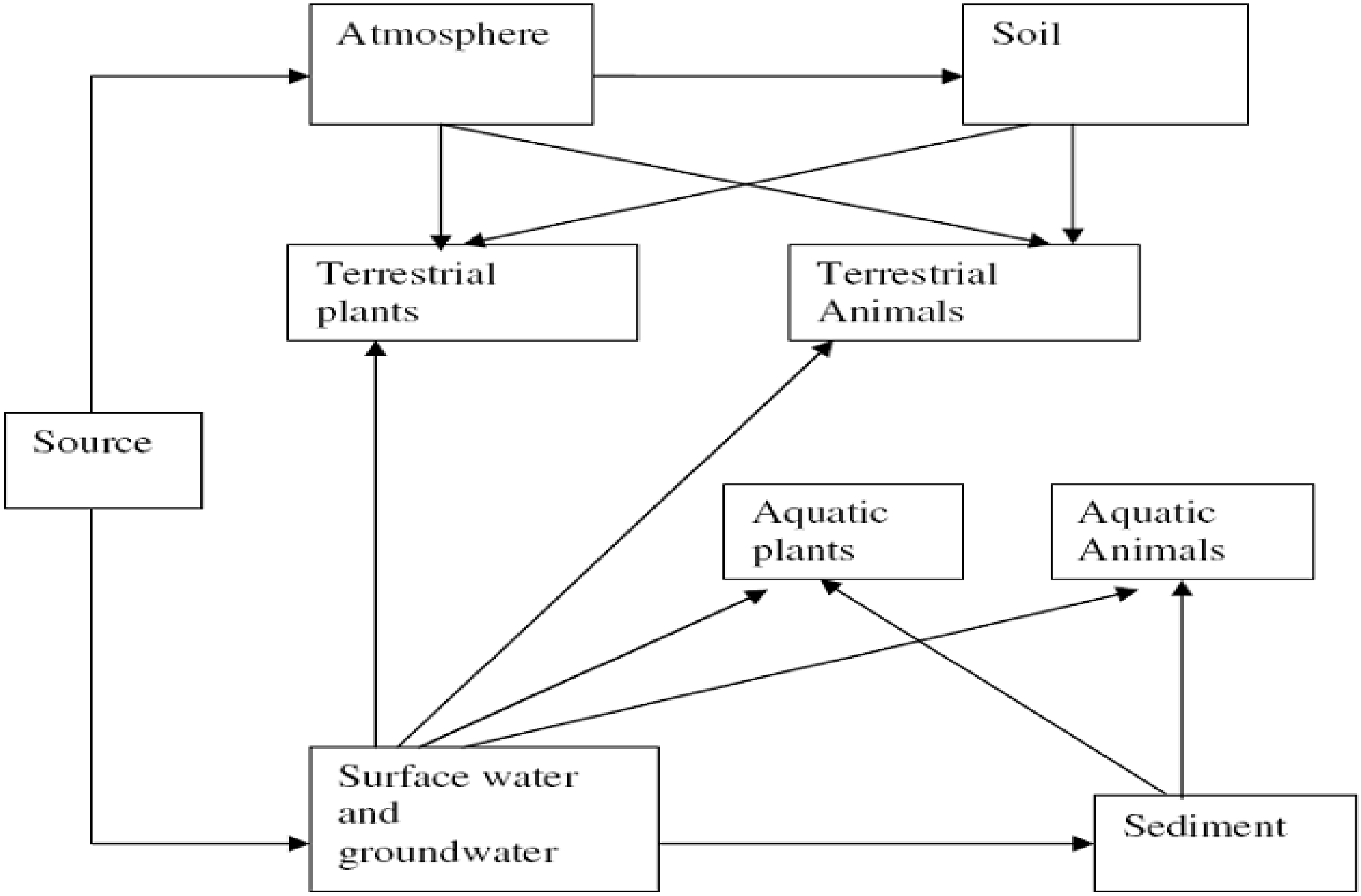
Non-Human Biota - Fundamental Aspects (3)

- Accident Scenario:
    - Bounding accident – From Safety Assessment
    - Inventory: moderator resin fire, 1 outdoors container
    - Receptors: Indicator Animals and Plants – detailed further
    - Maximum estimated air concentrations
    - Exposure period – 24 hours
    - Exposure Pathways – detailed further
    - Transfer Factors and Dosimetry – detailed further

Conceptual Exposure Pathways (1)



Conceptual Exposure Pathways (2)*



* Food pathways not displayed for simplicity

Non-Human Biota - Confidence in Model (1)

Pedigree of Model and Input Data	
Assessment method	Consistent with recent EAs in Canada and relevant international studies and guidance, e.g., FASSET, ICRP108
Concentrations	Based on measured concentrations or DGR Safety Report, appropriate QA pedigree
Dose coefficients	FASSET
Food intake and exposure	US EPA and Survey of Soil Ingestion by Wildlife
Transfer factors	CSA N288.1-08
RBE	FASSET

Non-Human Biota - Confidence in Model (2)

- **Assessment**
    - Independently verified/reviewed
    - AMEC NSS QA program ISO 9001 registered
    - Compliant with CSA Z299.1 as well as the applicable clauses of CSA N286.2, N286-05 and N286.7

Calibration, Validation and Verification

- Calibration:
  - Model source term inputs were based on measured site specific concentrations
- Validation:
  - Non-human biota dosimetry models validated, e.g. by EMRAS Biota Working Group (IAEA, Vienna)
  - Examples: Chernobyl, Perch Lake studies
- Verification:
  - Implementation of the model verified using AMEC NSS QA Procedures

Non-Human Biota – Uncertainty Analysis (1)

Sources of Uncertainty

1. Selection and characterization of indicators
2. Environmental pathways
3. Characterization of contaminants (radionuclides of concern, concentration data)
4. Dose criteria

Non-Human Biota – Uncertainty Analysis (2)

Selection of Indicators

VEC	Indicator(s)
Benthic Invertebrates	Burrowing crayfish
Aquatic Vegetation	Variable leaf pondweed
Benthic Fish	Lake whitefish, Redbelly dace, Creek chub
Pelagic Fish	Smallmouth bass, Spottail shiner, Brook trout
Birds	Double-crested cormorant, Mallard, Yellow Warbler, Red-eyed vireo, Wild turkey, Bald eagle
Terrestrial Invertebrates	Earthworm
Terrestrial Vegetation	Eastern white cedar, Common cattail and Heal-all
Mammals	White-tailed deer, Northern short-tailed shrew, Muskrat, Red fox
Amphibians & Reptiles	Midland painted turtle, Northern leopard frog

Rationale:

- Representative of the species of non-human biota
- Consistent with best practice in Canada
- Consistent with ICRP 108
- Input from public and regulator

Non-Human Biota – Uncertainty Analysis (3)

Characterization of Indicators

Factors:

- Habitation area, intakes

Conservative assumptions and parameters:

- Habitation area:
  - Migrating species: 50% time on-site
  - Non-migrating species: 100% time on site
- Intakes(food, water, soil, and sediment):
  - Wildlife Exposure Factors Handbook by EPA
  - Survey of Soil Ingestion by Wildlife

Non-Human Biota – Uncertainty Analysis (4)

Pathway Factors (Species specific)

Exposure to soil/sediment	Considered
Food/water ingestion	Considered
Soil/sediment intake	Considered
Immersion in water (external)	Considered
Direct radionuclide uptake (from water, for fish)	Considered
Inhalation	Considered
Dermal contact	Not considered*

*Exposure from this pathway is limited due to blockage by fur and feathers

Non-Human Biota – Uncertainty Analysis (5)

Characterization of Contaminants

Factors:

- Radionuclides of concern, concentration values

Conservative assumptions and parameters:

- Concentration values:
  - Normal: based on maximum measured values in different environmental media (water, soil, sediment, air, etc.)
  - Accident (Air): maximum from Preliminary Safety Report
  - Accident (Other media): derived using site specific parameters, consistent with CSA N288.1-08

Selected Dose Criteria (1)

- Estimated No Effect Values (ENEV) used as assessment criteria
- Consistent with the low values in various studies
- Consistent with dose criteria for postclosure period as accepted by CNSC

Selected Dose Criteria (2)

VEC	**Dose Rate Criteria – ENEV (mGy/day)**
Benthic invertebrates	5.0
Aquatic vegetation	2.4
Pelagic fish	0.6
Benthic fish	0.6
Aquatic bird	1.0
Aquatic mammal	1.0
Terrestrial invertebrates	1.6
Terrestrial vegetation	1.6
Terrestrial bird	1.0
Terrestrial mammal	1.0
Amphibian and reptiles	5.0

Summary

- Assessment based on bounding exposure (concentrations)
- Assessment methodology consistent with International and Canadian guidance
- Conservative dose criteria
- Uncertainty in the selection of parameters, in the assessment model and in assessment criteria
- High confidence that the results do not underestimate the doses due to conservatism in the assessment

Non-Human Biota Dose Models – Relative Contribution to Confidence

Line of Evidence	Relative Contribution
Model consistent with relevant Canadian and international studies and guidance	+++
Model and parameters independently validated	+
Assessment based on measured site specific concentrations	+
Implementation of model verified (QA check)	+++
Uncertainties addressed using conservative assumptions	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

Outline of Presentation

Part One - Geoscience Modelling

- 3-DGFM
- FRAC3DVS-OPG
- TOUGH2-MP
- MIN3P

Part Two - Repository Evolution Modelling

- FLAC3D
- FRAC3DVS-OPG
- T2GGM
- AMBER

Part Three - Radiation Dose Modelling

- MicroShield, MicroSkyshine, MCNP
- Non-Human Biota

Part Four – Environmental Modelling

- **AERMOD**
- Cadna/A

AERMOD (v09292) – Background (1)

- Air dispersion modelling of DGR Project done using AERMOD
- Public domain model freely available from the U.S. EPA
- Official regulatory default model in the United States for past six years
- Currently the regulatory default model for most modelling applications in Ontario
- Accepted in other Canadian jurisdictions
- Used widely around the world for dispersion modelling applications

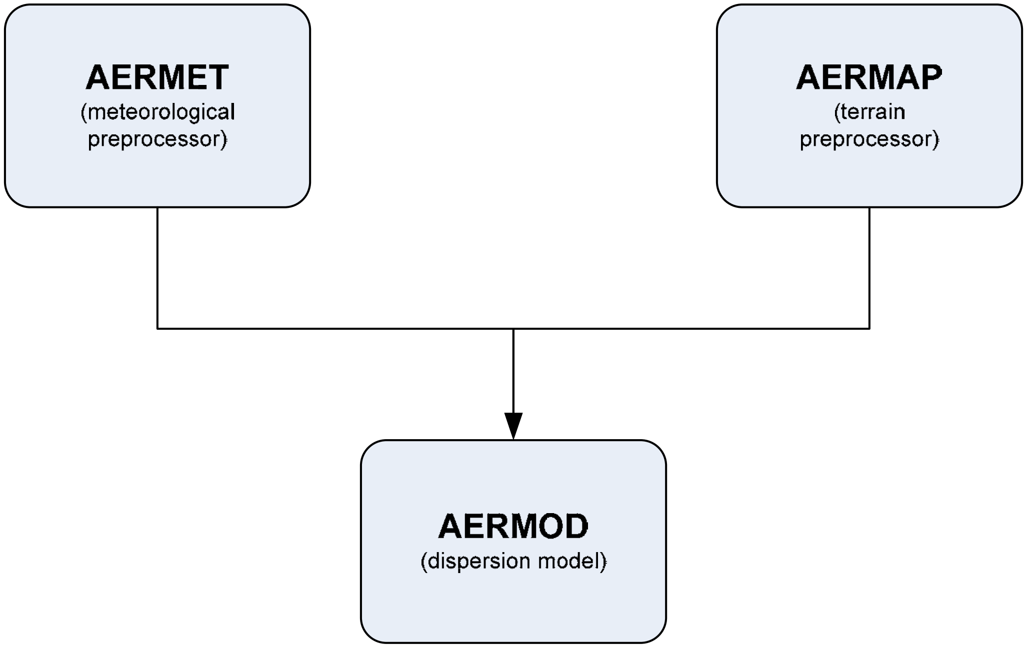
AERMOD – Background (2)

- Developed jointly by U.S. Environmental Protection Agency (U.S. EPA) and American Meteorological Society (AMS) – AERMIC
- To introduce state-of-the-art modelling concepts for local scale air quality models
- Would replace the ISC dispersion model as the regulatory model in the U.S.
- AERMOD originally proposed as the U.S. regulatory model in April 2000
- Adopted as the U.S. regulatory model in December 2006
  - Underwent external scrutiny post-proposal
  - Used on a case-by-case basis post-proposal

AERMOD – Background (3)

- Code and executable files are freely available from the U.S. EPA
- U.S. EPA provides extensive calibration and validation data sets
- Extensive model documentation available online
- Multiple third-party commercial user interfaces have been developed for AERMOD

AERMOD Modelling System

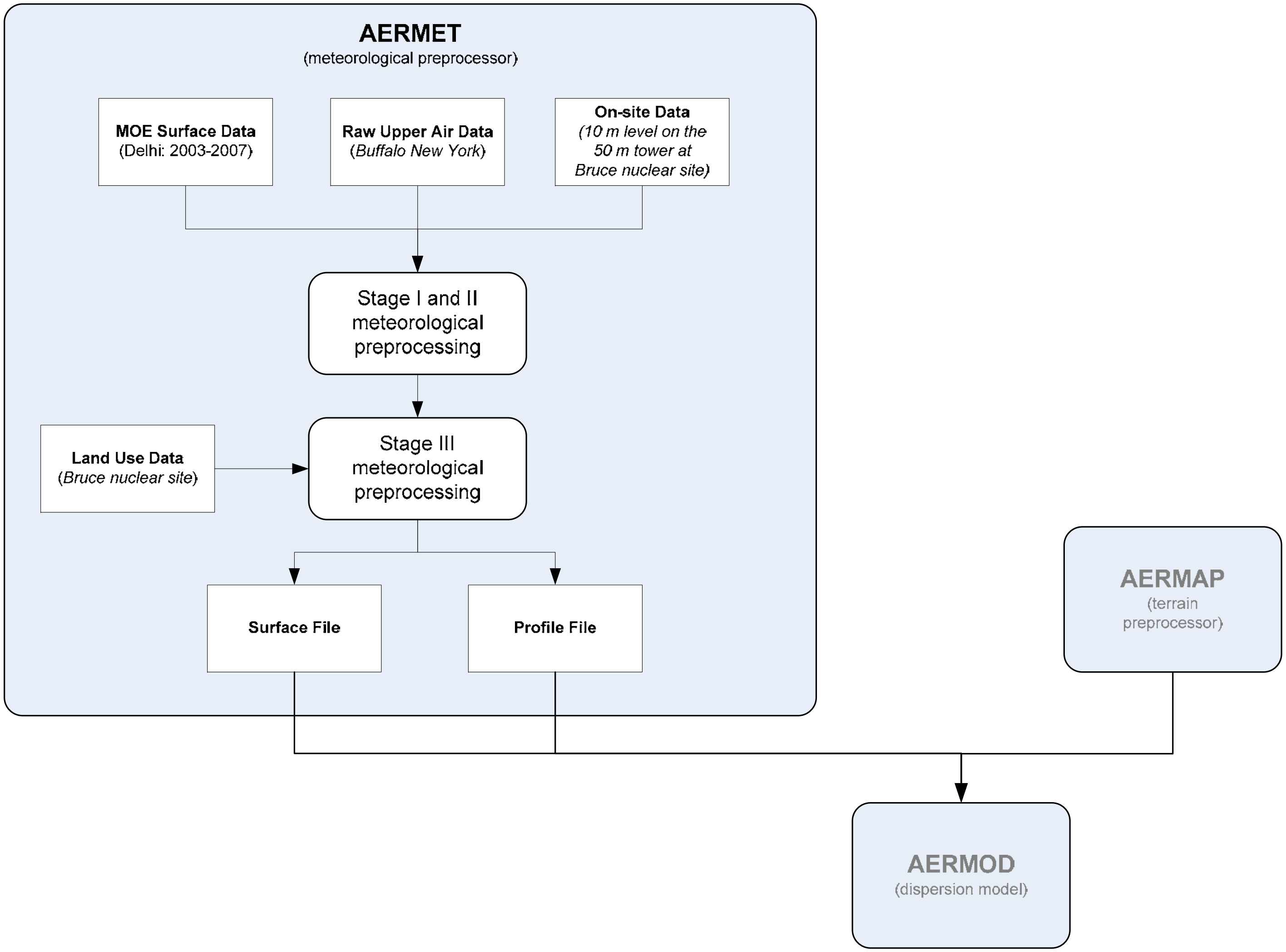


AERMET
(meteorological preprocessor)

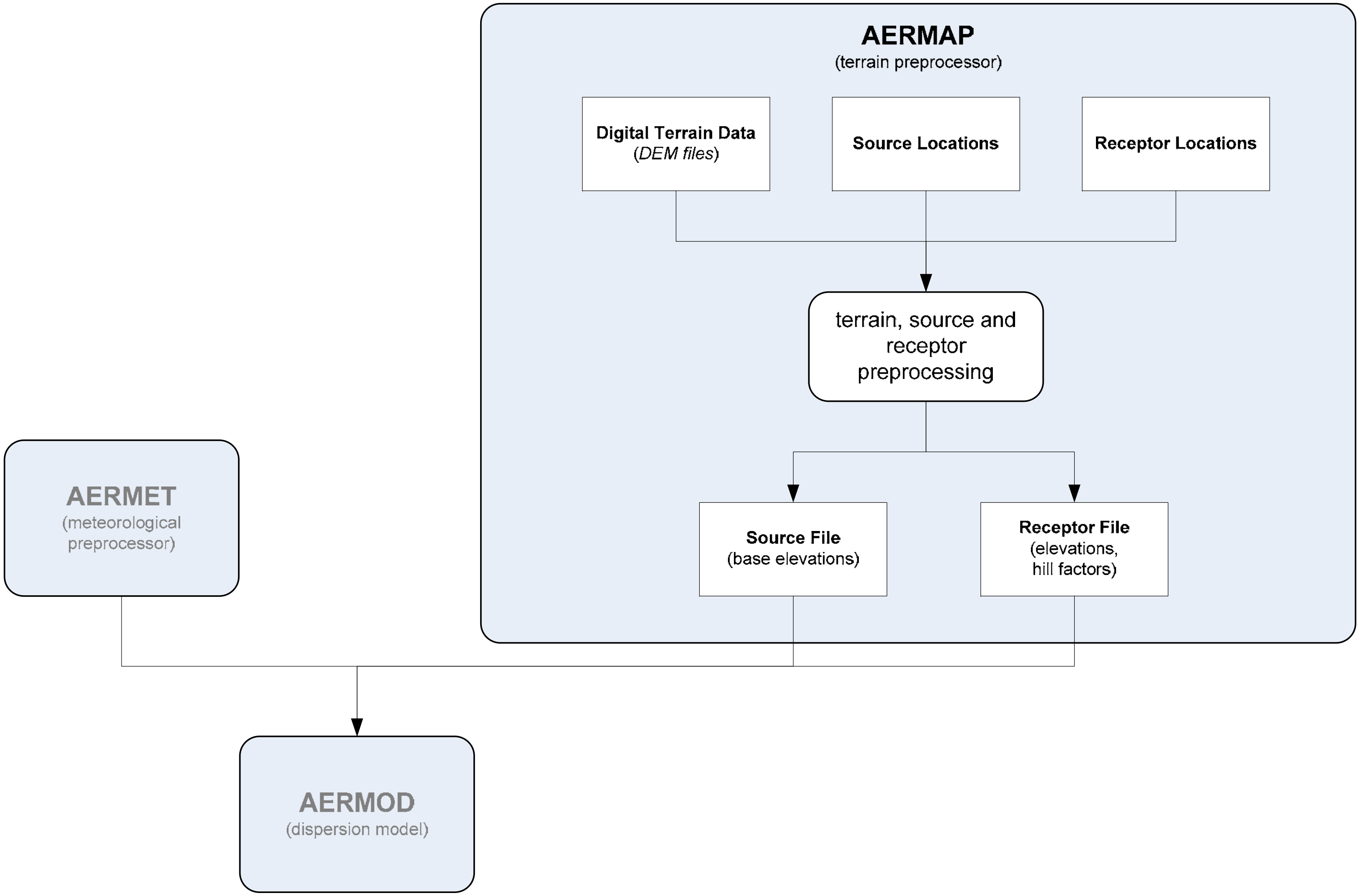
AERMAP
(terrain preprocessor)

AERMOD
(dispersion model)

Overview of AERMET



Overview of AERMAP



AERMAP
(terrain preprocessor)

Digital Terrain Data
(*DEM files*)

Source Locations

Receptor Locations

terrain, source and receptor preprocessing

Source File
(base elevations)

Receptor File
(elevations, hill factors)

AERMET
(meteorological preprocessor)

AERMOD
(dispersion model)

AERMOD – Fundamental Aspects (1)

- Steady-state plume model
- Stable meteorological conditions
  - Horizontal and vertical concentrations: Gaussian distribution
- Unstable meteorological conditions:
  - Horizontal concentrations: Gaussian distribution
  - Vertical concentrations: Bi-Gaussian distribution
- Special features to deal with complex terrain and urban settings
- Building downwash incorporates the PRIME algorithms

AERMOD – Fundamental Aspects (2)

- Modelling is not constrained
- Emissions radiate out from the source in the downwind direction
- Each hour is modelled separately
  - Emissions, meteorology and terrain used to predict hourly concentrations for all receptors
  - Concentrations are combined within the model to estimate 8-hour, 24-hour and annual values
  - Separate runs are done for each compound
- Background concentrations are added to modelled predictions outside of the model

AERMOD - Calibration

- Prior to proposal, AERMIC extensively tested the model by comparing predicted to measured concentrations
- Prior to adoption, AERMOD was extensively tested by external groups to ensure the model was not overly restrictive

AERMOD - Verification

- AERMIC took nine years to develop the AERMOD algorithms to a point where the model was proposed for adoption
- Between proposal and adoption, several major upgrades were made to the model (e.g., incorporating PRIME downwash algorithms)
- Since adoption, there have been seven formal updates to the model codes to address inconsistencies or incorporate the latest understanding of dispersion science

AERMOD – Uncertainty Analysis (1)

Sources of Uncertainty

- Uncertainty relates:
  - Meteorological inputs
  - Emission inputs
  - Model predictions
- Uncertainty managed through:
  - Selection of the best local data sources
  - Selection of best available data
  - Conservatism
  - Multiple simulations

AERMOD – Uncertainty Analysis (2)

Managing Meteorological Uncertainty

- Selection of the best local data sources
  - The on-site 50 m tower is physically adjacent to the DGR Project Area
- Selection of best available data
  - Data collected at Wiarton Airport meets World Meteorological Organization standards
- Conservatism
  - The winds from the 10 m level on the 50 m tower reflects the local processes, such as lake effects and shore breezes, that will influence dispersion in the Project Area
- Full Range of Possible Conditions
  - Use a full five years (43,824 hours, 1,826 days) of meteorology to cover the range of possible conditions

AERMOD – Uncertainty Analysis (3)

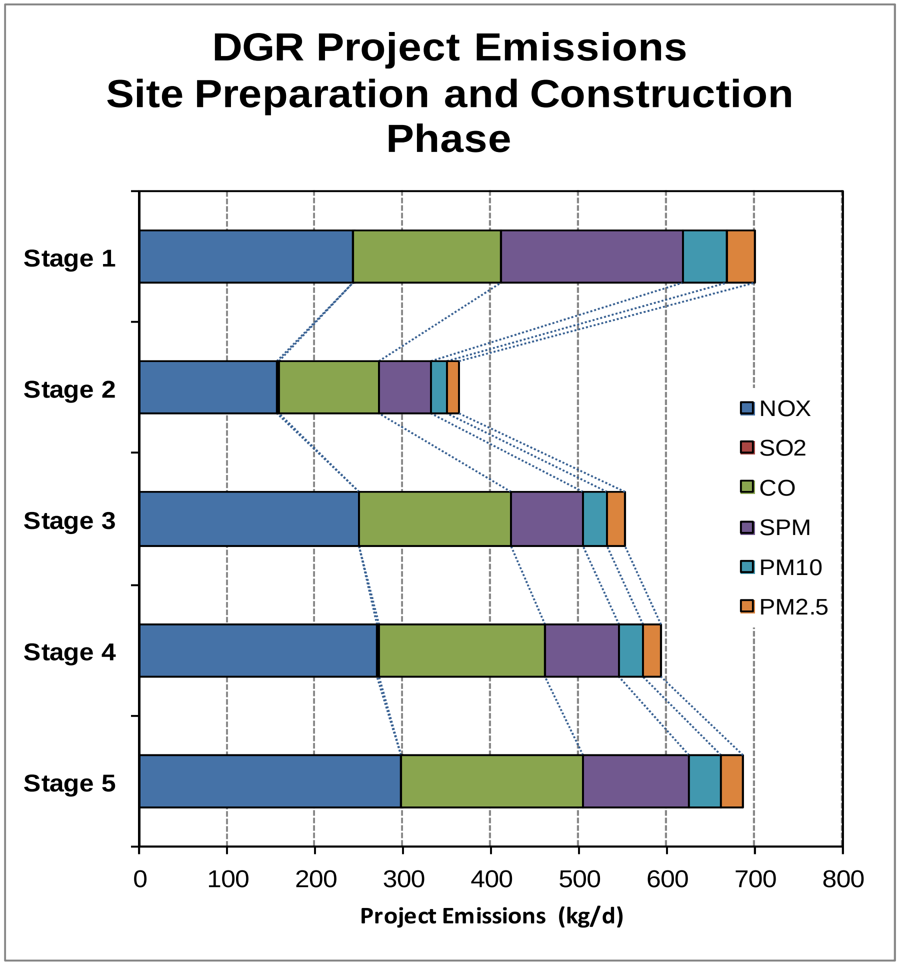
Managing Emissions Uncertainty

- Selection of the best local data sources
  - Actual traffic counts and current approved emission values used when modelling existing sources at the Bruce nuclear site
  - Project emissions based on design information
  - Local precipitation used in calculating fugitive emissions
- Selection of best available data
  - Relied on AP-42 emission factors, widely accepted as being conservative
  - Used published emission limits for exhaust emissions

AERMOD – Uncertainty Analysis (4)

Managing Emissions Uncertainty

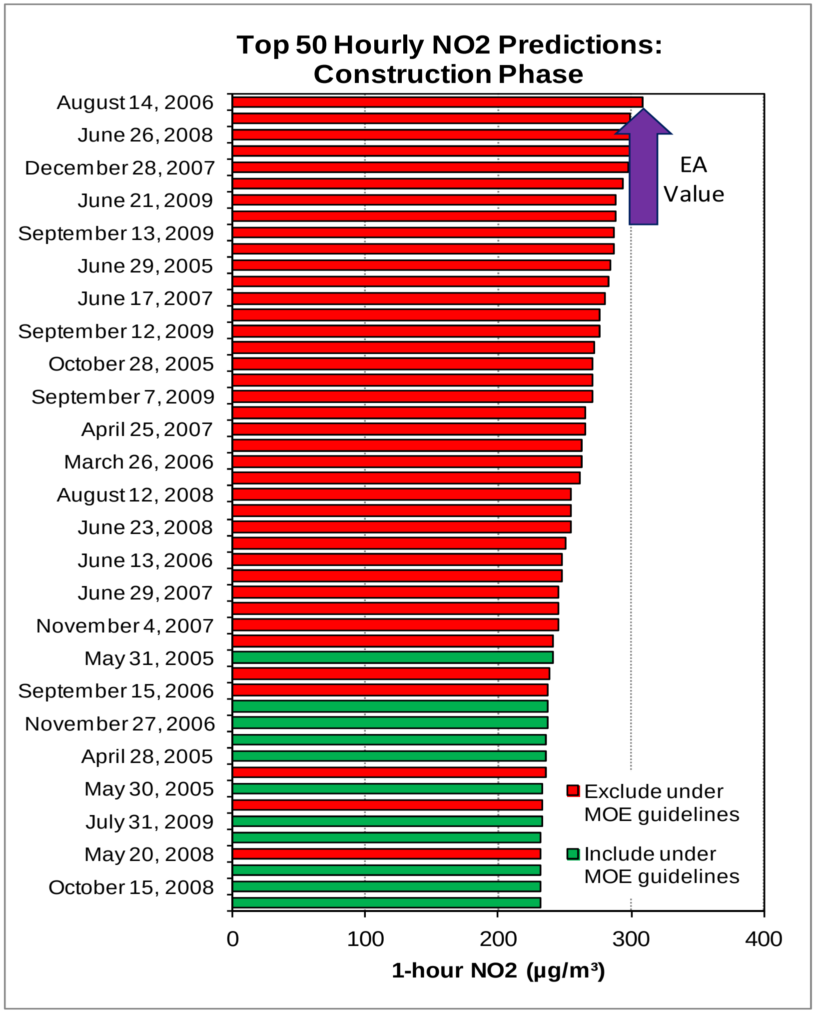
- Conservatism
  - All sources during any one stage of construction assumed to be operating concurrently and continuously
  - Modelled the stage of construction (Stage 1) when emissions were highest (i.e., the bounding case)



AERMOD – Uncertainty Analysis (5)

Managing Prediction Uncertainty

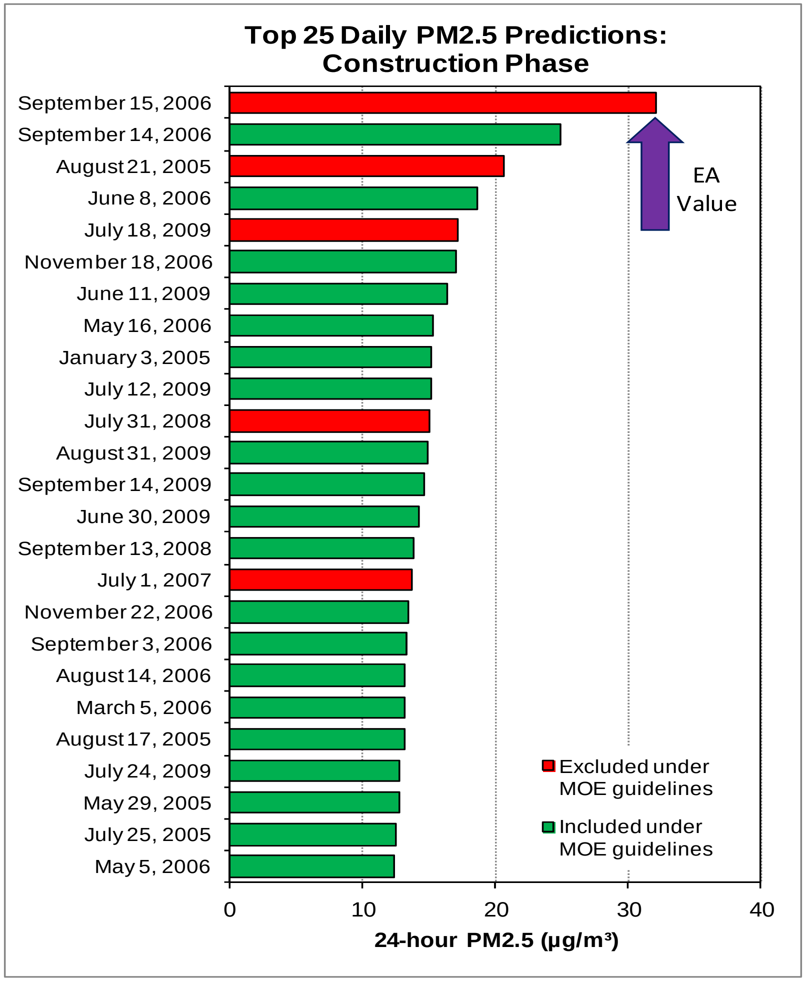
- 43,824 hourly predictions (2005-2009 meteorology)
- Highest hourly value used in the EA
- MOE guidance allows for the highest eight hours in each year to be discarded
- Highest hourly NO_2 about 28% higher than value using MOE modelling guidance



AERMOD – Uncertainty Analysis (6)

Managing Prediction Uncertainty

- 1,826 daily predictions (2005-2009 meteorology)
- Highest daily value used in the EA
- MOE guidance allows for the highest daily prediction in each year to be discarded
- Highest daily $PM_{2.5}$ about 29% higher than value using MOE modelling guidance



Summary of Confidence

- Confident that the air quality modelling does not underestimate the air effects of the DGR Project
    - The use of AERMOD is widely accepted, and is required in Ontario for most applications
    - Modelled conservative bounding assumptions with respect to emissions and activities
    - Used on-site meteorological data in modelling
    - Selected the maximum model predictions for use in the EA

AERMOD – Relative Contribution to Confidence

Line of Evidence	Relative Contribution
AERMOD is a widely-accepted model internationally	++
Regulatory model in Ontario MOE for most applications	++
Extensive verification was done before proposed to U.S. EPA	+++
Extensive third-party verification prior to regulatory adoption	+++
Code and verification data sets publicly available	+
AERMOD undergoes regular reviews and updates	++
Meteorological data used comes primarily from an on-site station	+++
Modelled emissions are conservative	+++
Used maximum predictions in the EA	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

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Part Four – Environmental Modelling

- AERMOD
- **Cadna/A**

Cadna/A – Fundamental Aspects (1)

- Noise assessment focused on human responses to noise
- Basis of noise assessment:
  - Two closest dwellings and Inverhuron Provincial Park
  - Noise predicted as A-weighted, equivalent hourly noise levels (dBA)
- Specific predictions provided to wildlife and human health disciplines

Cadna/A – Fundamental Aspects (2)

- Decibels
  - Logarithmic scale
  - Weighting
- Existing noise levels
- Project noise levels
- Ambient noise levels

Cadna/A – Fundamental Aspects (3)

- Noise modelling done using Cadna/A software (DataKustik)
  - Software in use in 60+ countries
  - Able to implement 30+ noise standards/models
- ISO 9613-2 model used for noise assessment
  - ISO 9613-2 accepted in various jurisdictions to assess road traffic, industrial sources and construction activities
  - ISO 9613-2 used in Ontario for all types of environmental noise assessments
  - Ontario MOE uses ISO 9613-2 version of Cadna/A
  - ISO 9613-2 is the most widely used and accepted noise model world-wide

Basis of ISO 9613-2 Model

- Model is empirically-based:
  - Algorithms derived from measurement data
- Model incorporates ray tracing techniques:
  - Assumes that sound waves behave like rays of light
  - Sound pressure levels (SPL) at receivers are predicted with consideration of travel and intervening objects
  - Modelling approach is an approximation to the 3-D wave equation
- Model can incorporate:
  - Geometric divergence (i.e., spherical spreading)
  - Atmospheric absorption
  - Ground effect
  - Reflections by surfaces
  - Screening by obstacles

Calibration of ISO 9613-2 Model

- Model is empirically-based
  - Algorithms derived from measurement data
- Since publication in 1996, numerous studies have been carried out comparing ISO 9613-2 predictions to measured levels
  - Studies have confirmed the accuracy within the stated assumptions
- Several studies have been carried out comparing ISO 9613-2 to other recognized noise models
  - Have shown that ISO 9613-2 model is typically within 1-2 dB of other models when sources are not screened
  - When sources are screened by objects, ISO 9613-2 model may predict significantly higher noise levels

Cadna/A – Calibration (1)

- Noise emissions for specific on-site sources (back-up generators) are available from previous measurements
- General noise emissions from on-site activities were derived from previous on-site measurements
  - Measurements at specific locations within the site to capture emissions from large areas
- Site-specific propagation of noise to receptors calibrated using previous and current measurements
  - Spot measurements (i.e., short-term) and monitoring (i.e., long-term) at off-site receiver locations
  - Attenuation factors, were adjusted to achieve the measured results, specifically, ground effect, reflections and screening

Cadna/A – Calibration (2)

- Noise predicted as A-weighted, equivalent hourly noise levels (dBA)
- Predicted at two closest dwellings and Inverhuron Provincial Park
- Factors considered in noise predictions:
  - All receptors are down-wind
  - Wind speeds were less than or equal to 18 km/h
  - All sources operating simultaneously
  - Sources modelled appropriately as points, areas or lines
  - Used proposed site layout plan, buildings and equipment list for predicting off-site noise levels
  - Topographic data and existing ground conditions incorporated into noise model

Cadna/A – Verification

- International Standards Organization (ISO) has one of the most rigorous verification protocols prior to adoption of any standard
- ISO 9613-2 model is currently undergoing consideration for acceptance by the Canadian Standards Association (CSA) and the American National Standards Institute (ANSI)
- Currently undergoing consideration for acceptance by the American National Standards Institute (ANSI)
- 2005: Golder verified implementation of ISO 9613-2 algorithms in Cadna/A software package

Cadna/A – Uncertainty Analysis (1)

Sources of Uncertainty

- Noise emissions
  - Amount of noise energy emitted
  - Timing of noise emissions
- Factors affecting noise propagation
  - Screening (e.g., presence of foliage)
  - Directivity of sources
  - Ground effects
- Model accuracy
  - Model predictions are ± 3 dB within 1 km

Cadna/A – Uncertainty Analysis (2)

Managing Uncertainty in Emissions

- Input data based on measurements of similar sources using type 1 analyzers (± 1 dB)
- Noise inputs based on worst-case noise emissions from sources (e.g., loader with full bucket loading a truck vs. loader idling)
- Back-up generator included as part of normal operations
- All sources operating simultaneously during every hour for each of six construction stages
- Maximum level of activities operating simultaneously for operations

Cadna/A – Uncertainty Analysis (3)

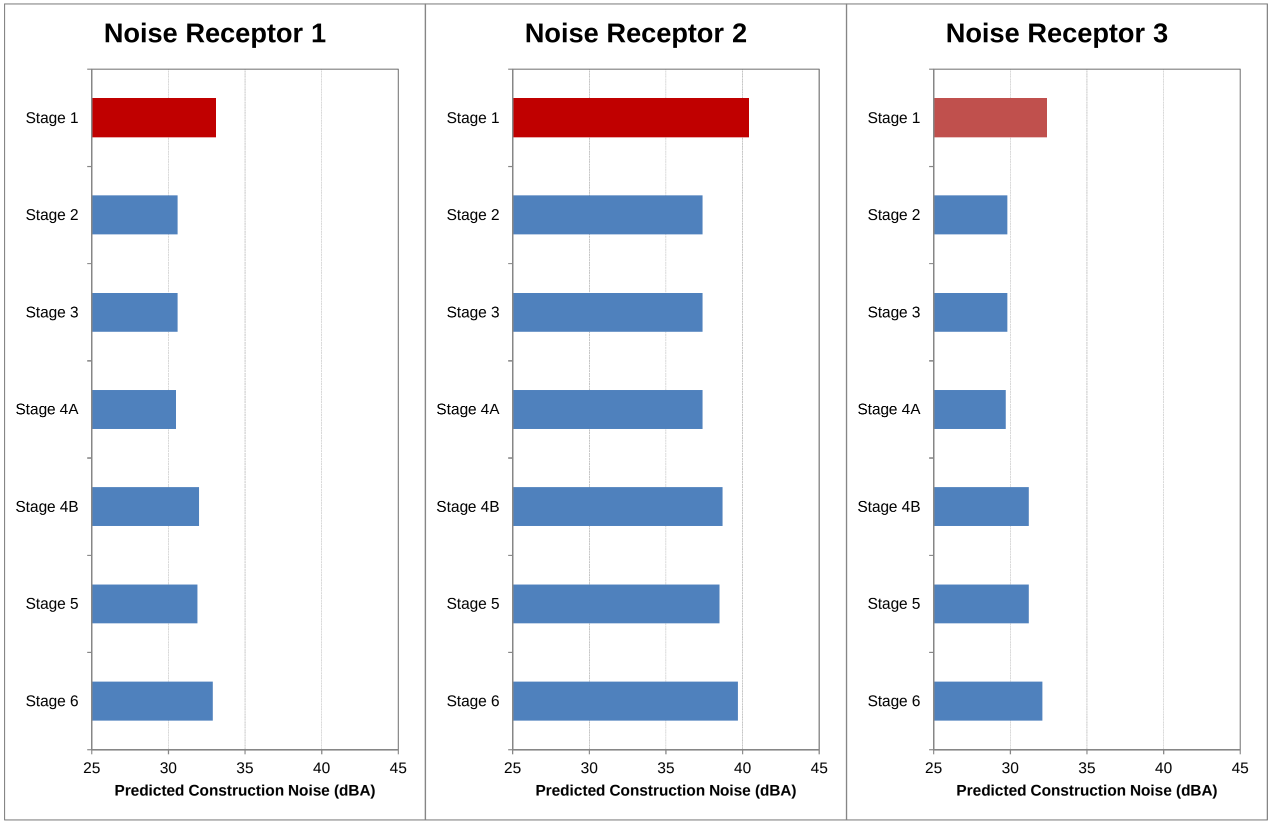
Managing Uncertainty in Propagation

- Screening:
  - No screening from trees was assumed in the model
- Directivity:
  - Only included for vent exhausts
- Ground effects:
  - Used site-specific ground conditions
- All receptors assumed downwind from all sources at the same time:
  - No reduction in noise level considered for upwind receivers

Cadna/A – Uncertainty Analysis (4)

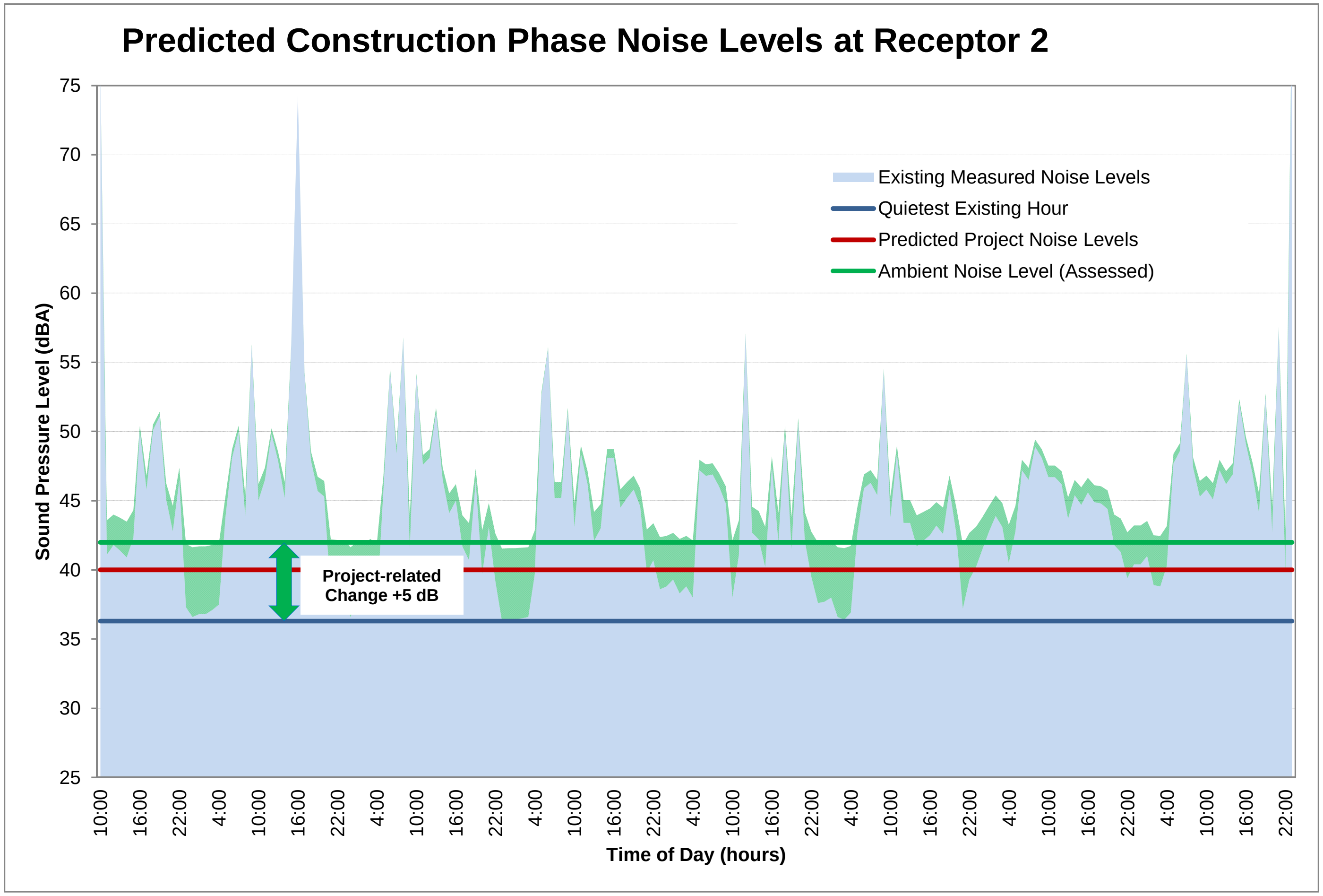
Managing Prediction Uncertainty

- Modelled six construction stages and used highest prediction for each receptor



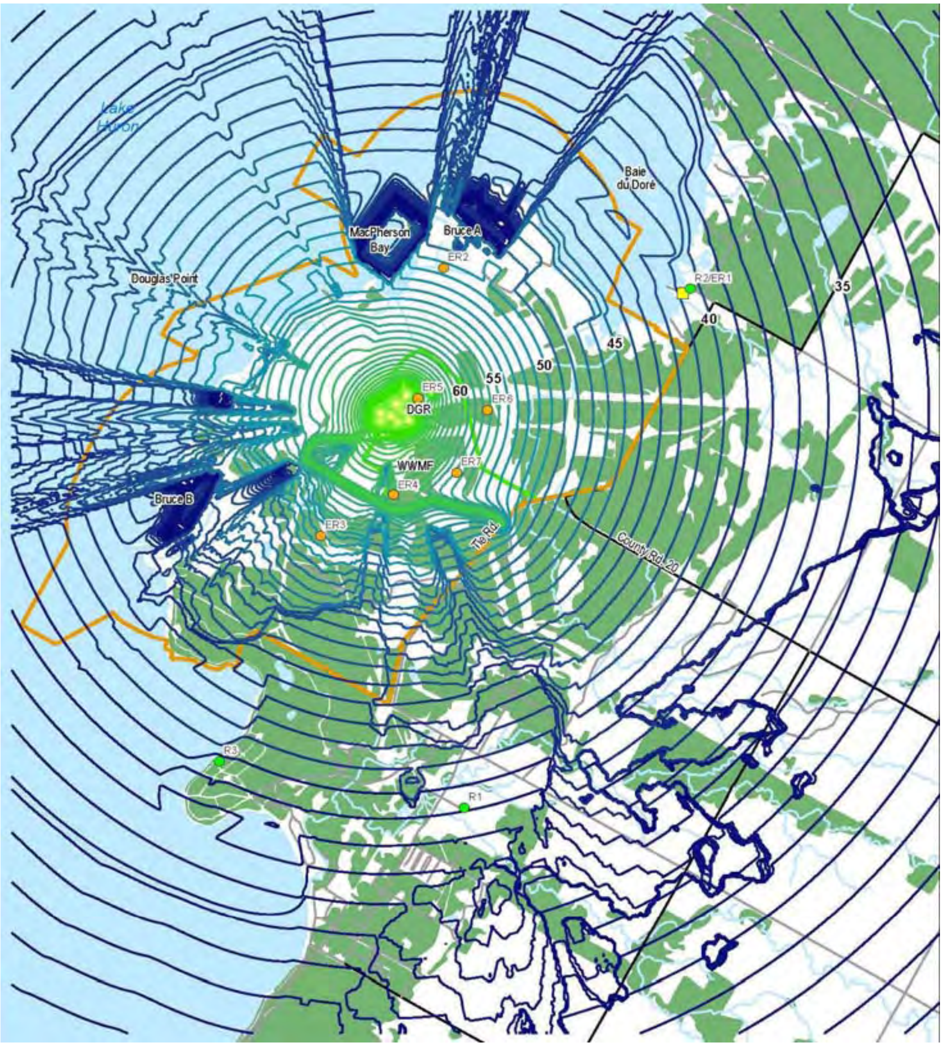
Cadna/A – Uncertainty Analysis (5)

- Compared predicted levels to the quietest existing hour



Cadna/A Spatial Output

- Shielding effects from on-site buildings
- Localized differences in ground effect



Noise Predictions for Other Disciplines

- Wildlife
  - Seven on-site ecological locations
  - Predicted linear, equivalent hourly noise levels (dB_{lin})
  - Assessment of noise effects in the Terrestrial Environment TSD
- Human Health
  - Two closest dwellings and Inverhuron Provincial Park
  - Predicted percent highly annoyed (%HA) and specific impact or impulse noise (HCII)
  - Assessment of health effects in Appendix C of the EIS

Summary of Confidence

- Confident that the noise effects at all receptors will be lower than predicted
  - Conservative bounding assumptions with respect to emissions and activities
  - Have not taken credit for all attenuation
  - Adverse effect based on existing quietest hour
  - Adverse effects predicted to occur during late night/early morning hours when people are indoors
  - Predictions for construction and operations are at or below Ontario MOE noise level limits

Cadna/A - Relative Contribution to Confidence

Line of Evidence	Relative Contribution
ISO 9613-2 widely accepted model	+++
Ontario MOE uses ISO 9613-2 model in the Cadna/A software	++
Model propagation calibrated using site-specific measurements	+++
Model algorithms derived from measured data	++
Model verified by ISO and accepted by CSA / CAA	++
Emissions based on measurements of comparable equipment	+++
Worst-case noise emissions (e.g., full load)	++
Maximum levels of activity occurring simultaneously and continuously	++
Conservative propagation (e.g., no trees)	++
Comparison to quietest hour	+++
Overall Confidence	**+++**

Note: + Lower; ++ Medium; +++ Higher

Thank You