WIPP PERFORMANCE ASSESSMENT: RADIONUCLIDE RELEASE SENSITIVITY TO DIMINISHED BRINE AND GAS FLOWS TO/FROM TRANSURANIC WASTE DISPOSAL AREAS

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The Waste Isolation Pilot Plant (WIPP) transuranic waste repository located east of Carlsbad, New Mexico, USA, consists of 10 waste panels located in the southern end and operations and experimental areas located in the northern end. Waste panels are to be separated from each other and from the northern areas by panel closure systems that consist of run-of-mine-salt that will compact and reconsolidate over time along with the creep closure of open areas of the repository. To more fully assess the sensitivity of predicted repository releases to currently implemented material parameters, the application of modified parameters in the operations and experimental (non-waste) areas of the repository is undertaken to simulate an accelerated (instantaneous) creep closure, the inclusion of capillary pressure effects on relative permeability, and an increase in initial/residual brine saturation and residual gas saturation in the operations and experimental areas of the repository. The resulting sensitivity analysis (CRA14_SEN2) is then compared to the most recent compliance recertification application results presented for CRA-2014 PA (CRA14). The modifications to the repository model result in increased pressures and decreased brine saturations in waste areas and increased pressures and brine saturations in the operations and experimental areas. The slight pressure increases in repository waste regions yield very slightly decreased brine saturations (on average) in those areas. Brine flows up the borehole during a hypothetical drilling intrusion are nearly identical to those found in the CRA14. Brine flows up the repository shaft are decreased as compared to CRA14 due to restricted flow within the operations and experimental areas. The modified operations and experimental area parameters essentially halt the flow of gas from the southern waste areas of the repository to the northern non-waste areas, except as transported through the marker beds and anhydrite layers. The combination of slightly increased waste region pressure (on average) and very slightly decreased brine saturations result in a modest increase in spallings and no significant effect on direct brine releases due to the pressure/saturation trade-off. Total releases from the Culebra and cuttings and cavings releases are not affected. Overall, the effects on total high-probability ($P(R) > 0.1$) mean releases from the repository are entirely insignificant, with total low-probability ($P(R) > 0.001$) mean releases minimally increased (~4%) and the associated 95% confidence level on the mean reduced (~20%). It is concluded that the baseline modeling assumptions associated with the operations and experimental areas of the repository have an insignificant effect on the prediction of total releases from the repository and/or adequacy of the current (CRA14) model to demonstrate compliance with the regulatory limits.

I. INTRODUCTION

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

The sensitivity of the CRA-2014 PA (CRA14) to modified parameters and modeling assumptions for the operations and experimental areas of the repository has been requested by the U.S. Environmental Protection Agency for specific parameter values (EPA 2016). The objective of the sensitivity analysis was to evaluate the effect on pressures and saturations of gas/brine in waste and non-waste areas of the repository under the conditions that the operations and experimental areas creep closed in short time duration to properties that are similar to intact halite. An understanding of the types and quantities of flow subject to the near-halite material properties and the modeling of two-phase flow with active capillary pressure effects on relative permeability was desired. Particularly, flows across the northernmost panel closure to/from the north rest-of-repository area and to/from the operations and experimental areas of the repository were of interest. Modified repository north-end parameters implemented herein were used to respond to an official request by the EPA for this sensitivity study. As such, the parameter values modified for this analysis should not be interpreted as being developed by Sandia National Laboratories. The CRA14_SEN2 sensitivity analysis was performed under AP-164, Analysis Plan for the 2014 WIPP Compliance Recertification Application Performance Assessment (Camphouse 2013).

II. APPROACH

The modeling of the operations and experimental areas of the repository with relatively low constant porosity and relatively high constant permeability has been implemented in WIPP PA as a feature of the repository since the original Compliance Certification Application (DOE 1996). This approach facilitated the maximization of brine flow from north to south in the repository to enhance brine saturation in the waste areas, corresponding to enhanced gas generation and pressures. Increased brine volume and pressure in the waste areas is understood to typically enhance direct brine releases.

The code BRAGFLO is the WIPP PA code used to model brine and gas flow in and around the repository. The current (CRA14) numerical grid and material map used to represent the WIPP in BRAGFLO are shown in Figure 1. As seen in that figure, the current disturbed rock zone (DRZ) above and below the operations and experimental (OPS/EXP) areas is modeled as the same material representing the DRZ above and below the waste areas. The EPA-requested parameter changes for DRZ properties apply only to the DRZ above and below the OPS/EXP areas, so a change to the BRAGFLO material map is necessary in order to implement the requested parameter changes. The BRAGFLO grid and material map that incorporates the requested OPS/EXP area property changes is shown in Figure 2. The modified grid separates the material in the DRZ, located above and below the OPS/EXP area, so that it may be treated separately from the DRZ above and below the waste areas of the repository. The new material regions for the OPS/EXP area DRZ as well as the pre-existing material regions for the operations and experimental areas, themselves, are thus available for application of the requested parameter modifications.

The application of the requested modified parameters to the repository model used in WIPP PA has the potential of altering calculated brine and gas flow behaviors. The PA code BRAGFLO is used to ascertain changes to repository performance due to the modified parameters. BRAGFLO provides flow results for the undisturbed repository as well as several disturbance scenarios used to represent inadvertent human intrusion after facility closure. The scenarios include one undisturbed scenario (S1-BF), four scenarios that include a single inadvertent future drilling intrusion into the repository during the 10,000 year regulatory period (S2-BF to S5-BF), and one scenario investigating the effect of two intrusions into a single waste panel (S6-BF). Two types of intrusions, denoted as E1 and E2, are considered. An E1 intrusion assumes the borehole passes through a waste-filled panel and into a region of pressurized brine that may exist under the repository in the Castile formation. An E2 intrusion assumes that the borehole passes through the repository but does not encounter pressurized brine. Scenarios S2-BF and S3-BF model the effect of an E1 intrusion occurring at 350 years and 1000 years, respectively, after the repository is closed. Scenarios S4-BF and S5-BF model the effect of an E2 intrusion at 350 and 1000 years. Scenario S6-BF models an E2 intrusion occurring at 1000 years, followed by an E1 intrusion into the same panel at 2000 years. The six scenarios modeled by BRAGFLO are summarized as follows: S1-BF = Undisturbed Repository, S2-BF = E1 intrusion at 350 years, S3-BF = E1 intrusion at 1,000 years, S4-BF = E2 intrusion at 350 years, S5-BF = E2 intrusion at 1,000 years, S6-BF = E2 intrusion at 1,000 years followed by E1 intrusion at 2,000 years.

The most recent PA done to demonstrate WIPP regulatory compliance is that performed for the CRA-2014 (DOE 2014). The CRA-2014 PA considered four distinct cases with detailed descriptions of the four cases considered in the CRA-2014 PA found in Camphouse (2013) and a summary of results given in Camphouse et al. (2013). The final of the four cases considered in the CRA-2014 PA, identified as CRA14-0, is referenced herein as CRA14 and utilized as the baseline analysis for comparison with the modified parameter sensitivity case called CRA14_SEN2. All three replicates evaluated under CRA14 are similarly run for CRA14_SEN2, over the six scenarios.

Table I provides a summary of original parameters used for CRA14 and the modified parameters implemented for CRA14_SEN2 per the EPA request (EPA 2016). The startup material used for the operations and experimental area in the -5 to 0 year time frame is CAVITY_3 for both analyses, with the parameters for POROSITY, PRMX_LOG, PRMY_LOG, PRMZ_LOG, COMP_RCK, CAP_MOD, PCT_A, PCT_EXP, RELP_MOD, SAT_IBRN, SAT_RBRN, and SAT_RGAS differing between the two analyses. The operations area material (OPS_AREA) and the experimental area material (EXP_AREA) in the time from to 0 to 10,000 years both have the same modified parameters as specified for CAVITY_3 under the CRA14_SEN2 analysis.

The modified POROSITY parameter implements a cavity porosity that is equal to the sampled value for S_HALITE plus one half of the standard deviation of the S_HALITE sampled parameter value. The log of intrinsic permeability in all directions (PRMX_LOG, PRMY_LOG, PRMZ_LOG) for the cavity is specified as the sampled S_HALITE value plus 1, or at an order of magnitude greater than that for intact halite. Similarly, the rock compressibility parameter (COMP_RCK) for the cavity is set equal to the sampled S_HALITE value. As these are implemented over all times, the effect is to model the operations and experimental areas of the repository in a "closed" configuration with porosity, permeability, and rock compressibility at or near the values sampled for intact halite. For the disturbed rock zone surrounding the operations and experimental areas, the porosity, permeability, and rock compressibility parameters are all set equal to the sampled values for S_HALITE, simulating a fully-healed disturbed rock zone for the entire simulation duration. To separate the parameter modifications for the disturbed rock zone surrounding the operations and experimental areas, new materials (DRZ_OE_0 and DRZ_OE_1) are introduced with equivalent values and applied individually to cover the entire simulation duration.

In addition to the material parameter changes discussed above, modifications to parameters that control the application of the 2nd modified Brooks-Corey relative permeability model (specified by RELP_MOD = 4) are applied in the CRA14_SEN2 analysis for both the operations and experimental area cavities and the associated disturbed rock zone (Camphouse 2013a). Although unchanged, the pore size distribution parameter (PORE_DIS) is listed for clarity and remains at λ=0.7, equal to the pore size distribution parameter for S_HALITE. In the 2nd modified Brooks-Corey relative permeability model, the capillary pressure is a function of the threshold capillary pressure that is determined as function of the permeability of the material (k) and the PCT_A (a) and PCT_EXP (ν) parameters using the following equation:

$$P_t = ak^{\nu}$$

To activate capillary pressure effects on relative permeability by utilizing a nonzero threshold capillary pressure in the operations and experimental area cavities and associated disturbed rock zone, the PCT_A and PCT_EXP parameters are specified as a = 0.56 and ν = -0.346, respectively, for CRA14_SEN2. Again, these values are equal to those utilized for the S_HALITE material. The initial brine (SAT_IBRN) saturations in the operations and experimental areas and associated disturbed rock zone are set to 0.95 for CRA14_SEN2, increasing the cavity saturations from 0 under CRA14 and slightly decreasing the disturbed rock zone saturation from 1 under CRA14. The residual brine (SAT_RBRN, S_{wr}) and residual gas (SAT_RGAS, S_{gr}) saturations for CRA14_SEN2 are modified from 0 values under CRA14. Significantly higher values of S_{wr} = 0.6 and S_{gr} = 0.398 are utilized in the 2nd modified Brooks-Corey relative permeability model per the following equations for effective saturation (S_{e1}, S_{e2}), capillary pressure (P_c), relative brine permeability (k_{rw}), and relative gas permeability (k_{rg}):

$$S_{e_1} = \frac{S_w - S_{wr}}{1 - S_{wr}} \qquad S_{e_2} = \frac{S_w - S_{wr}}{1 - S_{gr} - S_{wr}} \qquad P_c = \left| \begin{array}{ll} 0 & \text{if } S_w \le S_{wr} \\ \dfrac{P_t}{S_{e_2}^{1/\lambda}} & \text{if } S_g \le S_{gr} \\ \dfrac{P_t}{S_{e_2}^{1/\lambda}} & \text{otherwise} \end{array} \right.$$

$$k_{rw} = \left| \begin{array}{ll} 0 & \text{if } S_w \le S_{wr} \\ S_{e_1}^{(2+3\lambda)/\lambda} & \text{if } S_g \le S_{gr} \\ S_{e_1}^{(2+3\lambda)/\lambda} & \text{otherwise} \end{array} \right. \qquad k_{rg} = \left| \begin{array}{ll} 1 & \text{if } S_w \le S_{wr} \\ 0 & \text{if } S_g \le S_{gr} \\ \left(1 - S_{e_2}\right)^2 \left(1 - S_{e_2}^{(2+\lambda)/\lambda}\right) & \text{otherwise} \end{array} \right.$$

Finally, the capillary pressure is modified by the application of a CAP_MOD = 2 flag that limits the capillary pressure to a value of PC_MAX = 1E8 Pa for CRA14_SEN2. All modified parameters for CAVITY_3, OPS_AREA, EXP_AREA, DRZ_OE_0, and DRZ_OE_1 that are defined in Table I as a function of the corresponding S_HALITE parameter are established for each of the 300 vectors to correlate the sampled/calculated parameter values on a vector by vector basis.

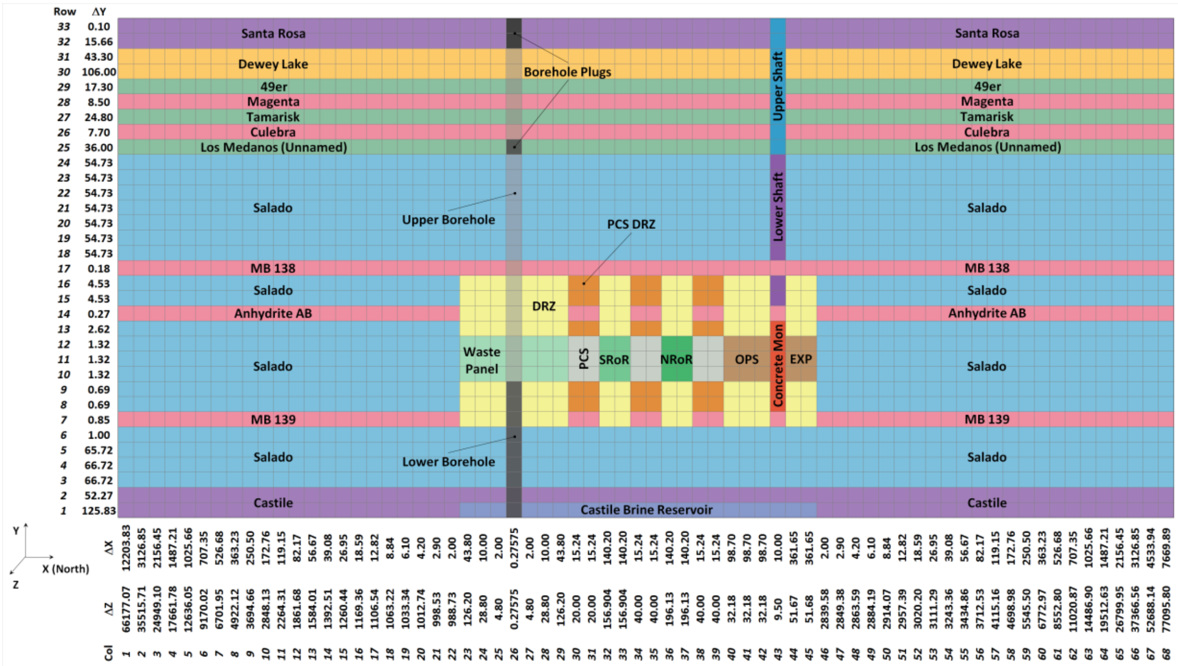

Fig. 1. The CRA14 BRAGFLO Repository Representation

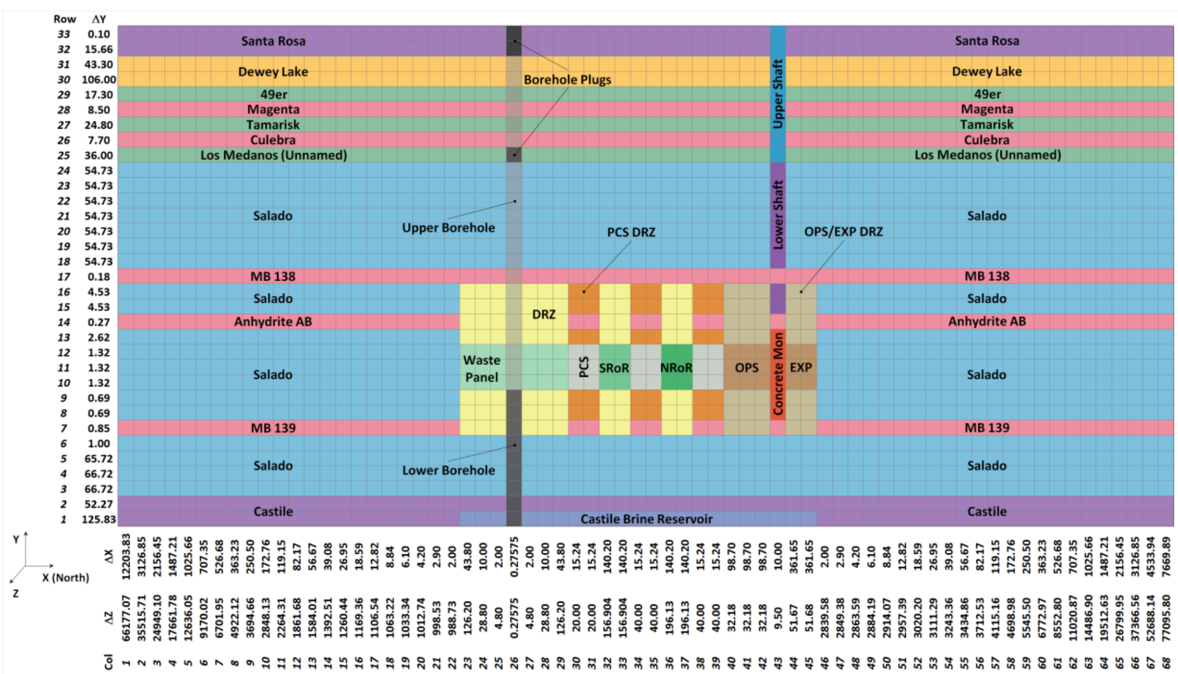

Fig. 2. The CRA14_SEN2 BRAGFLO Repository Representation

Table I. CRA14 and CRA14_SEN2 Modified Parameters

Experimental and Operations Areas												
Material	Time (yr)	POROSITY	PRMX_LOG PRMY_LOG PRMZ_LOG	COMP_RCK	PORE_DIS	CAP_MOD	PCT_A	PCT_EXP	RELP_MOD	SAT_IBRN	SAT_RBRN	SAT_RGAS
CRA14 (Camphouse 2013)												
CAVITY_3	-5 - 0	1	-10	0	0.7	1	0	0	11	0	0	0
OPS_AREA	0 - 10,000	0.18	-11	0	0.7	1	0	0	11	0	0	0
EXP_AREA	0 - 10,000	0.18	-11	0	0.7	1	0	0	11	0	0	0
CRA14_SEN2 (EPA 2016)												
CAVITY_3	-5 - 0	S_HALITE + 1/2*STDEV	S_HALITE + 1	S_HALITE	0.7	2	0.56	-0.346	4	0.95	0.6	0.398
OPS_AREA	0 - 10,000	S_HALITE + 1/2*STDEV	S_HALITE + 1	S_HALITE	0.7	2	0.56	-0.346	4	0.95	0.6	0.398
EXP_AREA	0 - 10,000	S_HALITE + 1/2*STDEV	S_HALITE + 1	S_HALITE	0.7	2	0.56	-0.346	4	0.95	0.6	0.398
Disturbed Rock Zone Adjoining Experimental and Operations Areas												
Material	Time (yr)	POROSITY	PRMX_LOG PRMY_LOG PRMZ_LOG	COMP_RCK	PORE_DIS	CAP_MOD	PCT_A	PCT_EXP	RELP_MOD	SAT_IBRN	SAT_RBRN	SAT_RGAS
CRA14 (Camphouse 2013)												
DRZ_0	-5 - 0	S_HALITE + 0.0029	-17	7.41E-10	0.7	1	0	0	4	1	0	0
DRZ_1	0 - 10,000	S_HALITE + 0.0029	sampled	7.41E-10	0.7	1	0	0	4	N/A	0	0
CRA14_SEN2 (EPA 2016)												
DRZ_OE_0	-5 - 0	S_HALITE	S_HALITE	S_HALITE	0.7	2	0.56	-0.346	4	0.95	0.6	0.398
DRZ_OE_1	0 - 10,000	S_HALITE	S_HALITE	S_HALITE	0.7	2	0.56	-0.346	4	0.95	0.6	0.398

Legend:

[shaded box] CRA14_SEN2 values that differ from CRA14

III. RESULTS

Salado flow results obtained after inclusion of modified material parameters and two-phase flow properties in the operations and experimental areas and associated disturbed rock zone are now presented, and compared to those obtained in the CRA-2014 PA (CRA14). Results are discussed in terms of overall means. Overall means are obtained by forming the average of all realizations obtained for a given quantity and scenario. In WIPP PA, a replicate consists of 100 calculated realizations. Three replicates are used to generate results for CRA14 and CRA14_SEN2. Means and statistics presented for these two analyses are calculated over all three replicates.

Results are presented for undisturbed scenario S1-BF. Results associated with intrusions are presented for scenarios S2-BF and S4-BF, as these are representative of the intrusion types considered in scenarios S2-BF to S5-BF with the only differences being the timing of drilling intrusions. Results from BRAGFLO scenario S6-BF are also discussed. Pressure and brine saturation results only for the southernmost waste panel are presented due to the direct impact on total repository releases which are also presented and discussed.

III.A. Pressure

The reduced flow of gas from the waste areas into the operations and experimental areas of the repository results in an increase in pressure in the repository waste areas for CRA14_SEN2 in comparison to CRA14 over all BRAGFLO scenarios as illustrated for the southernmost waste panel in Figure 3.

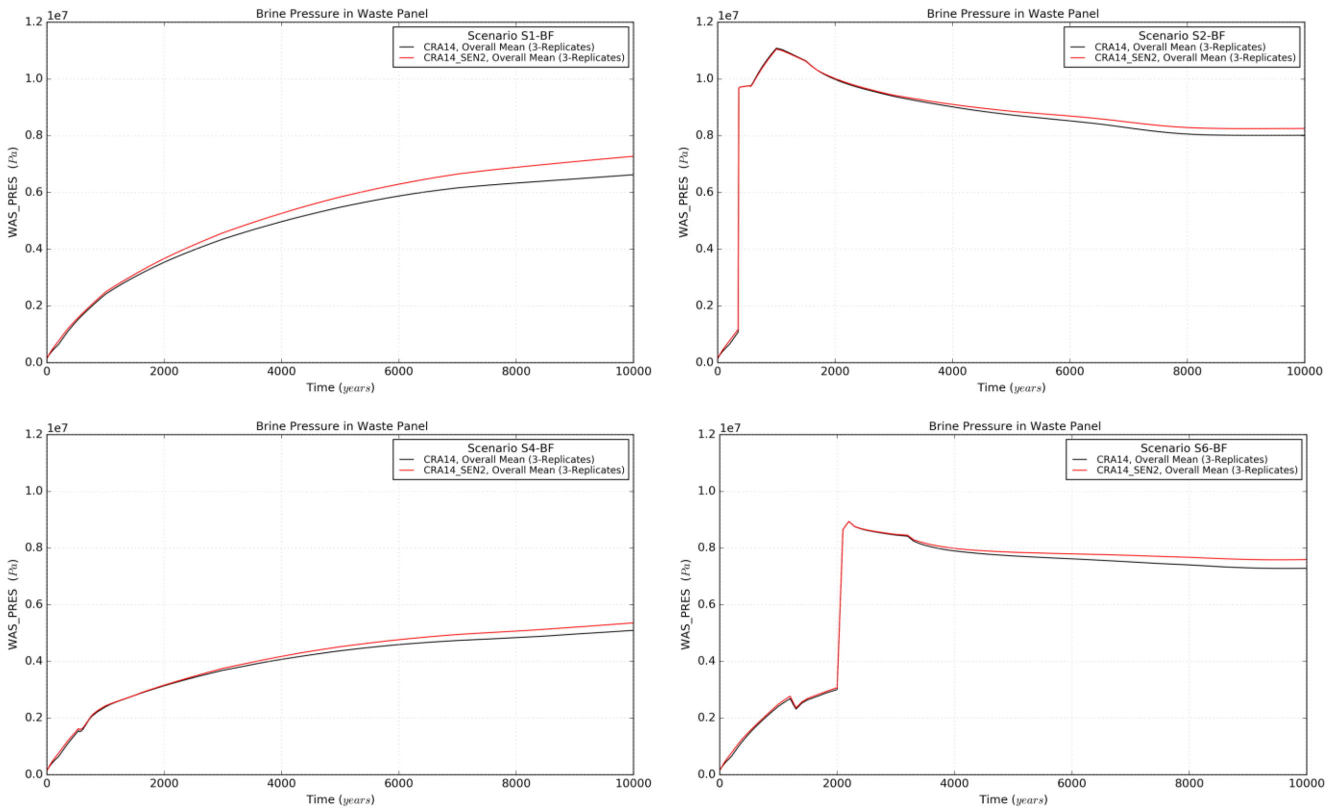

Fig. 3. Brine Pressure Means for the Waste Panel, Scenarios S1-BF, S2-BF, S4-BF, S6-BF

III.B. Brine Saturation

Increased pressures in the waste areas result in a corresponding decrease in mean brine saturations for CRA14_SEN2 in comparison to CRA14 over all BRAGFLO scenarios as illustrated for the southernmost waste panel in Figure 4.

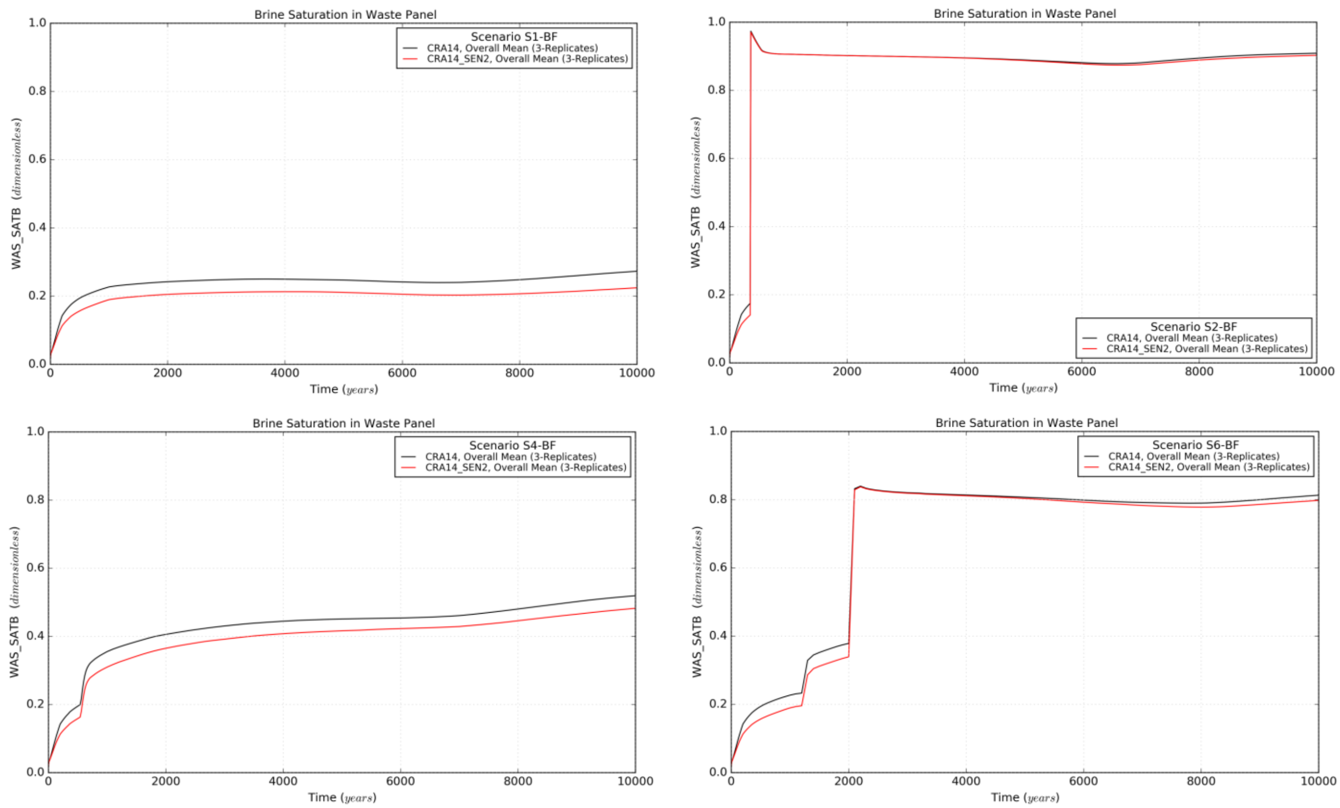

Fig. 4. Brine Saturation Means for the Waste Panel, Scenarios S1-BF, S2-BF, S4-BF, S6-BF

III.C. Impacts to Regulatory Compliance

The impacts of the modified operations and experimental area and associated disturbed rock zone parameters are a slight pressure increase in repository waste regions accompanied by very slight decreases to brine saturation (on average). The tightening of the northern non-waste areas, application of capillary pressure effects on relative permeability, and the use of associated two-phase flow parameters with increased residual gas and brine saturation effectively halt flow of brine and gas to/from these areas. The resulting pressure increases and brine saturation decreases in the waste areas of the repository result from an enhanced buildup of gas within these areas.

For the release mechanisms considered in WIPP PA, cuttings and cavings are not dependent on repository pressures or brine saturations, and so are not impacted at all by the modified northern non-waste area parameters. Spallings releases are a function of repository pressure and the waste inventory. Increases in pressure necessarily translate to increased spallings release volumes. As a result, spallings releases are increased with the application of two-phase flow parameters in the operations and experimental areas that are modeled as crept-closed over the full simulation duration, as compared to CRA14 results. Brine flows up the intrusion borehole obtained in CRA14_SEN2 and CRA14 are nearly identical. Consequently, volumes of brine flowing up the borehole to the Culebra are primarily unaffected by the sensitivity analysis parameter modifications. Thus, transport releases through the Culebra and across the land withdrawal boundary are negligibly different from results calculated for CRA14. Direct brine releases (DBRs) require sufficient waste panel pressure and brine saturation in order to occur. The repository pressure near the drilling location must exceed the hydrostatic pressure of the drilling fluid, which is specified to be 8 MPa in WIPP PA. The brine saturation in the intruded panel must exceed the residual brine saturation of the waste, a sampled parameter in WIPP PA. As seen, the sensitivity analysis parameters tend to slightly increase waste region pressure while very slightly decreasing waste region brine saturation as compared to CRA14. Due to this pressure and saturation trade-off, the modified sensitivity analysis parameters have a negligible impact on DBRs.

Total releases are calculated by totaling the releases from each release pathway: cuttings and cavings releases, spallings releases, DBRs, and transport releases (there were no undisturbed releases to contribute to total release). The overall mean CCDF is computed as the arithmetic mean of the mean CCDFs from each replicate. Mean CCDFs of the individual release mechanisms that comprise total normalized releases are plotted together in Figure 5, as well as the CRA14_SEN2 total release overall mean. As seen in that figure, total normalized releases obtained for CRA14_SEN2 are dominated by cuttings and cavings releases and DBRs. Contributions to total releases from spallings and Culebra transport are much less significant, although spallings have been increased in comparison to CRA14.

Overall means for total normalized releases obtained for CRA14 and CRA14_SEN2 are plotted together in Figure 6. Overall, total normalized releases insignificantly increase from CRA14 to CRA14_SEN2 due to an insignificant change to all contributing release components (with the exception of spallings which is a non-dominant release mechanism). A comparison of the statistics on the overall mean for total normalized releases obtained for CRA14 and CRA14_SEN2 can be seen in Table II. At a probability of 0.1, values obtained for the mean total release and upper 95% confidence interval for CRA14_SEN2 are essentially identical to CRA14. At a probability of 0.001, the mean total release is very slightly higher for CRA14_SEN2 (~4%) in comparison to CRA14 with the upper 95% confidence level significantly lower (~20%).

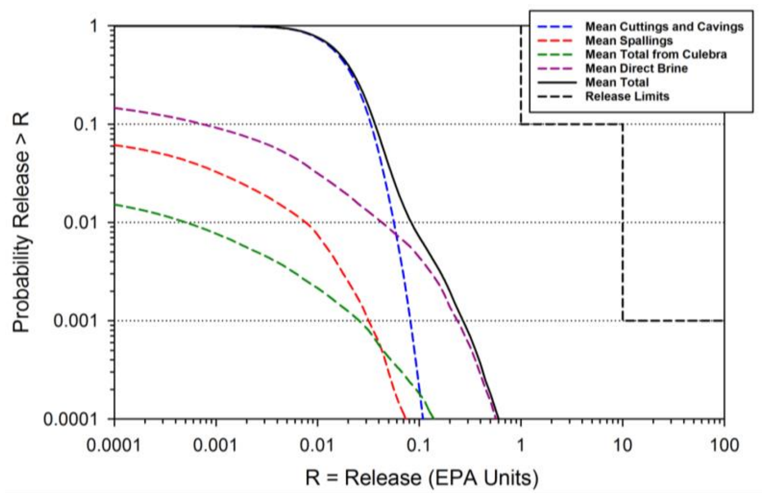

Fig. 5. Comparison of Overall Means for Release Components of CRA14_SEN2

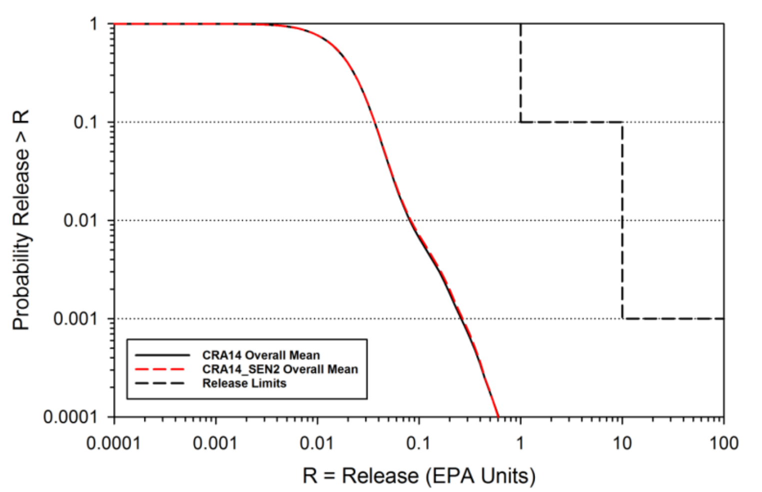

Fig. 6. CRA14 and CRA14_SEN2 Overall Mean CCDFs for Total Normalized Releases

TABLE II. CRA14 and CRA14_SEN2 Statistics on the Overall Mean for Total Normalized Releases in EPA Units at Probabilities of 0.1 and 0.001

Probability	Analysis	Mean Total Release	Lower 95% CL	Upper 95% CL	Release Limit
0.1	CRA14	0.0367	0.0352	0.0384	1
	CRA14_SEN2	0.0369	0.0354	0.0383	1
0.001	CRA14	0.261	0.109	0.384	10
	CRA14_SEN2	0.271	0.201	0.319	10

III. RESULTS

The application of modified parameters in the operations and experimental (non-waste) areas of the repository to simulate an accelerated (instantaneous) creep closure, the inclusion of capillary pressure effects on relative permeability, and an increase in initial/residual brine saturation and residual gas saturation resulted in increased pressures and decreased brine saturations in waste areas and increased pressures and brine saturations in the operations and experimental areas. The slight pressure increases in repository waste regions yielded very slightly decreased brine saturations (on average) in those areas. Brine flows in general were reduced and brine flows up the borehole during a hypothetical drilling intrusion were nearly identical to those found in the CRA14. Brine flows up the repository shaft were decreased as compared to CRA14 due to restricted flow within the operations and experimental areas. The modified operations and experimental area parameters essentially halted the flow of gas from the southern waste areas of the repository to the northern non-waste areas, except as transported through the marker beds and anhydrite layers. The combination of slightly increased waste region pressure (on average) and very slightly decreased brine saturations resulted in a modest increase in spallings and no significant effect on direct brine releases due to the pressure/saturation trade-off. Releases from the Culebra and cuttings and cavings releases were not affected. Overall, the effects on total high-probability ($P(R) > 0.1$) mean releases from the repository were entirely insignificant, with total low-probability ($P(R) > 0.001$) mean releases minimally increased (~4%) and the associated 95% confidence level on the mean reduced (~20%). It is concluded that the modeling assumptions associated with the operations and experimental areas of the repository have an insignificant effect on the prediction of total releases from the repository and/or adequacy of the current (CRA14) model to demonstrate compliance with the regulatory limits.

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