OFFICE OF RADIATION AND INDOOR AIR
WASHINGTON, D.C. 20460

September 5, 2024

Mr. Michael Gerle, Director
Environmental Regulatory Compliance Division
Carlsbad Field Office
U.S. Department of Energy
P.O. Box 3090
Carlsbad, New Mexico 88221-3090

Re: Sixth set of questions on the Replacement Panels Planned Change Request (RPPCR)

Dear Mr. Gerle:

The U.S. Environmental Protection Agency is continuing its review of the U.S. Department of Energy's submittal of the RPPCR. This letter transmits a set of agency technical questions on the borehole permeability updates in the RPPCR. The EPA would appreciate a timely response to these questions to help expedite its review. The Agency also suggests a follow-up call and/or technical exchange to discuss these questions.

If you have any questions concerning this request, please contact Jonathan Major at (202) 343-9891 or at Major.Jonathan@epa.gov.

Sincerely,

Peake, Tom
Digitally signed by Peake, Tom
Date: 2024.09.05 08:45:24 -04'00'

Tom Peake
Director
Center for Waste Management and Regulations

ENCLOSURE
1. Sixth set of technical questions on the RPPCR

cc: Anderson Ward, DOE CBFO
Justin Marble, DOE EM
Lee Veal, EPA

Ray Lee, EPA
Winifred Okoye, EPA
EPA Docket

Enclosure 1: Sixth set of technical questions on the RPPCR

Information requests for DOE related to the selection of a new upper bound on the permeability of a degraded borehole.

Summary

The U.S. Department of Energy (DOE) submitted a Planned Change Request (PCR) to the Environmental Protection Agency (EPA) in March 2024 for the use of Replacement Panels 11 and 12, also referred to as the Replacement Panel Planned Change Request (RPPCR). A major change since the CRA-2019 PA was a revision by DOE of the long-term borehole permeability model used for hypothetical future abandoned and degraded exploration boreholes that may intersect waste in the repository allowing fluid flow in and out. This proposed change is significant because it reduces repository releases by every pathway except cuttings and cavings. This proposal is documented in Gjerapic et al. (2023) and is referred to as the "Gjerapic model" in this document.

The main change proposed by Gjerapic et al. (2023) decreased the maximum, upper bound borehole permeability by three orders of magnitude from 10^{-11} to 10^{-14} m^2. The change was based on new information obtained since the 1996 WIPP Compliance Certification Application (CCA) on borehole casing corrosion and concrete grout degradation, in conjunction with a new salt creep model developed by Sandia National Labs.

EPA completed an initial technical review of the updated borehole permeability model, starting by reviewing the evolution of the model from its original form in the CCA (i.e. Thompson et al. 1996, referred to as the "Thompson model") through modifications developed in response to EPA's review of that model (i.e. the PA Verification Test or PAVT), and to the latest proposed changes. EPA found the Gjerapic et al. (2023) report to consist of a series of studies that point to lower maximum permeability values for degraded borehole fill. However, the studies are only weakly linked, and the overall report lacks a clearly stated conceptual model to provide continuity. Many of the studies are cited without describing their relevance to conditions at the WIPP, and others are presented without clear statements describing the physical processes that could lead to the postulated state of degradation within a borehole. In addition, no clearly defined conceptual model was presented that links the combined effects of these semi-independent processes into a consistent, technically supported whole.

A common concern throughout the Agency's review was the difficulty in finding explanations why the permeability could not reasonably be higher than the upper bound values proposed by Gjerapic et al. (2023). Information provided by both Thompson et al. (1996) and Gjerapic et al. (2023) indicates that the true value of this parameter is highly uncertain. The selection of a log-uniform distribution for this parameter indicates that little is known about the shape of the distribution but that the end points (the lower and upper bound values) can be reasonably identified such that a high level of confidence exists that the true value is highly unlikely to be lower than the minimum or higher than the maximum.

EPA's review found that use of the upgraded salt creep model provided good insights into the more rapid borehole closure predicted under the lower stresses occurring in the Salado above the repository. The modeling results show that the permeability of a degraded borehole above the repository may decrease by an order of magnitude within about 1,000 years. This is similar to the permeability decrease currently modeled below the repository. However, the model results only predict changes in

permeability and a base, starting point permeability must be independently identified and justified. EPA did not find a well justified, technical basis in Gjerapic et al. (2023) for selecting the initial upper bound permeability of the degraded borehole fill. The requests in this enclosure for additional information are intended to get at a more defensible initial upper bound permeability value.

In its review of this update, EPA finds that the report fails to establish a cohesive, consistent update to the conceptual model parameterization that is adequately justified. The Agency believes that responses to the requests for additional information will help in determining whether a change in the current upper bound permeability for degraded borehole fill is justified.

Italicized text below provides introductions, further explanations, or backgrounds to the questions and comments. Questions and comments have been organized and grouped by topic and section of the report.

Topic 1: Requests related to Gjerapic et al. (2023, Section 2.1) on the hydraulic conductivity of degraded steel, and the relevance and applicability of permeable reactive barrier (PRB) granules as a surrogate for degraded steel casing.

The Agency recognizes that direct measurements of the permeability of corroded iron are uncommon but concludes that the arguments put forth by Gjerapic et al. (2023) do not adequately demonstrate 1) that corroded PRB granules are reasonable surrogates for corroded borehole casing; 2) that the PRB column tests of Moraci et al. (2016) adequately simulate borehole conditions at WIPP; 3) that the proposed maximum corrosion product permeability of 10^{-15} m^2 is actually bounding; and 4) that the test results are consistent with the Thompson conceptual model for changes in borehole degradation processes with depth. It is also not clear how Gjerapic et al. intend to use the permeability information from PRB granules.

RPPCR6-Bhperm-1: PRB granules as surrogates for corroded borehole casing

Please provide justification that include relevant experiments, data, and literature citations for the assumption that corroded PRB granules are reasonable surrogates for corroded borehole casing.

RPPCR6-Bhperm-2: discrepancy in upper bound permeability for degraded steel casing

Please clarify the following discrepancy. The concluding paragraph on p. 7 for Section 2.1 of Gjerapic et al. (2023) identifies 10^{-15} m^2 as an upper bound permeability for degraded steel casing but on p. 13 of Section 3.1, 10^{-10} m^2 is identified as the upper bound. EPA understands that the objective of the Gjerapic et al. analysis is to identify a single upper bound value and finds these statements to be contradictory.

RPPCR6-Bhperm-3: PRB column test conditions

Please explain the conditions under which the PRB column tests of Moraci et al. (2016) were performed and how well those tests adequately simulate borehole conditions at WIPP.

RPPCR6-Bhperm-4: scatter and uncertainty in experimental results of Moraci et al. (2016)

The experimental results of Moraci et al. (2016) on PRB permeability shown in Gjerapic et al. (2023, Figure 2) illustrate scatter and uncertainty that do not appear to have been taken into account in identifying 10^{-15} m^2 as a bounding permeability. Please discuss and evaluate the impact of this uncertainty on the proposed bounding permeability of 10^{-15} m^2.

RPPCR6-Bhperm-5: relevance of Moraci et al. column tests to WIPP conditions

The PRB permeability in the Moraci et al. (2016) experiments decreased by five orders of magnitude in one year, presumably due to corrosion. The corrosion rate in those experiments appears to far exceed the corrosion rates observed in Delaware Basin boreholes (see discussion in Section 5.2 and Appendix B.5.1 of Thompson et al., 1996). Please describe the physical characteristics of the PRB granules and experimental conditions under which the results of Moraci et al. (2016) column tests were obtained and explain why the results of Moraci et al.'s tests are relevant to the chemical and physical conditions associated with borehole casing corrosion at WIPP.

RPPCR6-Bhperm-6: PRB corrosion test results and Thompson model

A statement in the Executive Summary of Gjerapic et al. (2023, p. iii) indicates that no changes to the existing borehole permeability model are proposed except for the upper limit of degraded borehole permeability. EPA therefore assumes that other elements of the Thompson model, including the depth-related chemical constraints on iron corrosion, are incorporated into the Gjerapic model. If this assumption is correct, please explain how the PRB corrosion test results fit into the effects of depth in the Thompson model. If this assumption is wrong, please provide a detailed description of the Gjerapic model, explaining and justifying any additional differences from the Thompson model.

> *In Section 2.1, Gjerapic et al. (2023) cite Zeitler (2018a, 2018b) and Roselle (2013) in support of the statement that the intermediate casing in the WIPP repository environment is not likely to fully degrade during the 10,000-year regulatory period under expected mean conditions but may exhibit full degradation under the maximum reported corrosion rates. Further discussion of this statement and its significance to the upper bound permeability of corroded casing are not provided. EPA notes that this statement is consistent with the conclusions of Thompson et al. (1996), that above depths of 300 to 350 m the casing is expected to corrode completely by general corrosion within 200 years but below these depths the corrosion rates may be significantly reduced because of hydrogen fugacity limitations and complete corrosion of iron casing may not occur in 10,000 years. It is not clear that the PRB corrosion results described above, where no depth limitations were imposed by Gjerapic et al. (2023) on their application, are consistent with the depth-dependent conclusions of Thompson et al. (1996).*

RPPCR6-Bhperm-7: PRB degredation and incomplete degredation

Please explain how the findings of Moraci et al. (2016) for PRB degradation are incorporated into the Gjerapic borehole degradation conceptual model in a manner consistent with the findings of Zeitler (2018a, 2018b), Roselle (2013), and Thompson et al. (1996) that iron at the WIPP repository depth may not be completely degraded in 10,000 years.

> *EPA found references throughout the Gjerapic et al. (2023) report to studies supporting lower permeabilities for iron corrosion or cement-based grouts derived under conditions that are "less favorable" than the WIPP environment. In this context, the Agency believes the term "less favorable" indicates that Gjerapic et al. believe the WIPP environment would support even lower permeabilities. Such comments were made, for example, in reference to studies by Saiyouri et al. (2011) and Allan and Philippacopoulos (1999). Such references were generally cited without*

further explanation of how the studies were performed, why conditions at WIPP are more favorable (to even lower permeabilities?- an explanation of what ' favorable' means would help), and in what way are the studies relevant to WIPP. Without this kind of supporting information, it is difficult for the Agency to properly evaluate the significance of these studies as justification for the proposed database change.

Gjerapic et al. (2023, p. 6) cite Popielak et al.'s (1983) report of gypsum and halite precipitation, exsolution of gases under reduced pressures, and wellhead and casing corrosion when testing the brine reservoirs encountered in the vicinity of the WIPP site as evidence of more severe chemical conditions at (or near) the WIPP that could result in lower PRB permeabilities than those measured by Moraci et al. (2016). However, not all boreholes that penetrate the WIPP waste area are postulated in WIPP PA to intersect a brine reservoir and in the interest of establishing an <u>upper bound</u> permeability, chemical conditions that could reasonably support higher permeabilities should be identified and evaluated.

Topic 2: Requests related to Gjerapic et al. (2023, Section 2.2) on the hydraulic conductivity of degraded cement, its derivation, and the applicability of the Hazen equation:

In the absence of undissolved constituents in the degraded grout, the Agency agrees that the permeability of degraded concrete grout would be expected to be low. However, Gjerapic et al. (2023, p. 8) preface their proposed low-permeability, complete degradation model with the phrase "for simplicity." The question of complete versus partial dissolution of the grout during the degradation process is important and complex. The presence or absence of undissolved constituents is a key element in assessing the permeability of degraded grout and requires a more substantial technical basis than the approach taken by Gjerapic et al. to estimate an upper bound permeability.

RPPCR6-Bhperm-8: concrete grout degrading to silt-like powders

Please provide a technical justification, including relevant experiments, calculations, and literature citations for the apparent assumption that a completely degraded concrete grout will consist only of silt-like particles represented by cement powders and that no undissolved, coarser degradation products could reasonably be expected to be present that could increase the permeability.

Estimating permeability based on grain size distributions can be associated with considerable uncertainty that is not discussed by Gjerapic et al. (see, for example, Wang et al. 2017). Furthermore, this concern is magnified by the report's application of the Hazen equation to a material that is known to be outside the bounds of its direct applicability.

RPPCR6-Bhperm-9: uncertainty in predicted permeability of Hazen equation

Please provide a discussion of the uncertainty associated with the predicted permeability of the Hazen equation for materials that fall within the range of its direct applicability as well as the presumed increased uncertainty when applied to materials outside that range and apply the results to justifying the proposed upper bound permeability for degraded concrete grout.

Topic 3: Requests related to Gjerapic et al. (2023, Section 2.3) on the upper bound permeability of a debris-filled borehole:

RPPCR6-Bhperm-10: coarser grained materials in degredation debris and permeability

The Thompson model for borehole degradation debris includes not only degraded grout and iron corrosion products, but also native material that has sloughed off the walls of the borehole. These native materials, along with other possible insoluble materials and products of incomplete degradation and corrosion, could add a coarser granularity to the debris that was included in the Thompson model (by treating the debris as a silty sand) but does not appear to be included in the Gjerapic model (which appears to ignore the possible presence of coarser grained materials). Please provide justification for the apparent exclusion of coarser grained materials from the degradation debris, or if such materials are assumed to be present, why they would not contribute to higher permeabilities.

> *Gjerapic et al. (2023, p. ii) identify the borehole fill debris as dominated by cement materials with an upper bound permeability on the order of 10^{-14} m^2 when under limited confinement and on the order of 10^{-15} m^2 when under increased confinement. Gjerapic et al. (2023, Section 2.3) therefore conclude that the upper bound permeability of degraded, borehole fill is between 10^{-14} and 10^{-15} m^2. This conclusion is consistent with Gjerapic et al.'s conclusion that the upper bound permeabilities of two constituents of this fill, the corroded iron casing and degraded concrete grout, are both of this same order of magnitude. However, the Gjerapic model appears to ignore other constituents of the degradation debris that were included in the Thompson model.*

RPPCR6-Bhperm-11: relevance of microannuli permeability laboratory results

Please describe the relevance of the microannuli permeability laboratory results of Stormont et al. (2018) to identifying the maximum permeability of a degraded borehole plug at the WIPP.

> *Gjerapic et al. (2023, Appendix B, p. 8) cite a laboratory study by Stormont et al. (2018) of thermally de-bonded gaps (called microannuli) between the concrete grout and steel casing and report a maximum permeability of 6.7×10^{-15} m^2. Since this was a laboratory study that included surface-corroded casing but apparently did not include degraded grout, the relevance of results to the long-term degradation of boreholes at the WIPP is unclear.*

RPPCR6-Bhperm-12: relevance of continuity calculation

Given that the stated objective of Gjerapic et al.'s (2023) analysis is to identify a maximum permeability for loose, degraded borehole fill for the approximately 1,000 m thickness of the salt section and not just the 400 m thickness of the Salado above the repository, please explain the relevance of the continuity calculation (Appendix B, p. 8) to that objective.

> *In a concluding calculation, Gjerapic et al. (2023, Appendix B, p. 8) assume that the 40 m long Rustler plug has a degraded permeability of 10^{-15} m^2 and that the borehole between that plug and the repository is about 400 m long and is open, providing no resistance to flow. Assuming continuity, the equivalent borehole fill permeability is 1/10th of the plug permeability, or 10^{-14} m^2. Although this calculation appears to be intended to support a conservative maximum permeability of degraded borehole fill of 10^{-14} m^2, it is presented without context to any previously presented scenarios, and it is based on a fraction of the borehole length in question.*

Topic 4: Requests related to Gjerapic et al. (2023, Section 3) on the application of the new salt constitutive model to estimate permeability of degraded borehole fill

RPPCR6-Bhperm-13: description and significance of maximum creep volume loss

Please provide a detailed conceptual description of the development and significance of the maximum creep volume loss of 41.8% for a debris-filled borehole and the segments of the borehole where this conceptual model is applicable.

Instead of calculating the time required for a given porosity reduction as was done in the Thompson model, Gjerapic et al. (2023, p. 12) used the creep closure model to calculate closure rates and decreases in porosity as the maximum creep volume loss was approached. Little description was provided of the conceptual basis for the maximum volume loss.

With the production casing pulled, the open volume of the borehole in the salt section is 41.8% of the total borehole volume. Gjerapic et al. (2023, p. 12) state that the maximum volume loss under salt creep is therefore 41.8% of the initial borehole volume. If it is assumed that all degradation debris that fills the open volume of the borehole in the salt section is from the casing and grout in the salt section, and that no sloughing occurs from above that introduces extra mass, then the increase in porosity from the expanding degradation products would be equal to the fraction of open volume, or 41.8%. The maximum creep volume loss that could occur would therefore be the loss required to eliminate this extra porosity. This volume loss would restore the degradation products to the porosity of their original, undegraded state. The Agency is uncertain of the accuracy of this conceptual description.

RPPCR6-Bhperm-14: uncertainty associated with predicted permeability using Kozeny-Carman relationship

Please provide a discussion of the uncertainty associated with the predicted permeability of the Kozeny-Carman relationship and its effect on the conclusions of maximum borehole permeability drawn from the salt creep analysis.

Use of the Kozeny-Carman relationship for estimating permeability based on grain size distributions raises Agency concerns similar to those for use of the Hazen equation. Uncertainty can be associated with the Kozeny-Carman relationship that is not discussed by the authors (see, for example, Wang et al. 2017).

RPPCR6-Bhperm-15: explanation and timeline of conceptual model for surface hole, upper salt section, and lower salt section

Please provide a summary explanation and timeline of the Gjerapic conceptual model for borehole degradation and subsequent compression for a) the surface hole; b) the upper salt section borehole above the repository; and c) the lower salt section borehole below the repository.

RPPCR6-Bhperm-16: sample calculations using Kozeny-Carman method

Please provide sample calculations showing application of the Kozeny-Carman method used to develop the curves shown in Figures 7 and 8 of Gjerapic et al. (2023), specifically including calculation of a permeability of 10^{-15} m^2.

RPPCR6-Bhperm-17: applicability of Kozeny-Carman model for fine-grained borehole degredation debris

Please provide a justification for the apparent assumption that the Kozeny-Carman model for estimating permeability reductions resulting from porosity reductions is applicable to the fine-grained borehole degradation debris expected in the Gjerapic conceptual model and is valid for the very low permeabilities and steep permeability declines depicted in Gjerapic et al. (2023, Figure 8).

Topic 5: Questions relating to the effects of backpressure on closure rates

In its review, EPA combined several tables for Case 3 found in Gjerapic et al. (2023), which are based Reedlunn et al.'s (2022) creep closure model, into a summary table (Table 1 below). Case 3 simulates the greatest backpressure and results in the slowest creep closure rates and permeability reductions, which can help bound a maximum permeability.

Table 1. Time (Years) Required to Reach Permeability Reductions at Specified Borehole Depths for Castile Brine Reservoir (Case 3) Backpressures. Permeability reduction times from Gjerapic et al. 2023, Tables A-4 through A-7. Maximum closure times from Gjerapic et al. 2023, Table A-3. Note that 200 years should be added to each of the times in the table to account for the initial period before general corrosion is assumed to be complete.

k/k_o	250 m Depth	450 m Depth	650 m Depth	850 m Depth
1 x 10^{-1}	3,779	756	329	176
1 x 10^{-2}	5,732	1,144	500	269
1 x 10^{-3}	6,681	1,331	583	314
1 x 10^{-4}	7,130	1,419	622	335
1 x 10^{-5}	7,341	1,466	640	346
1 x 10^{-6}	7,409	1,509	649	356
Maximum Closure	7,523	1,500	656	354

Under the Thompson model assumption that general corrosion occurs above depths of 300 to 350 m, after 200 years the casing and grout have completely degraded and back pressure is only from borehole fill. Thompson et al. (1996, p. D-2) concluded that it is not unreasonable to ignore this backpressure because it would be small for closures up to the maximum of 23% needed to achieve a one order of magnitude decrease in permeability. They also state that ignoring backpressure will probably not be reasonable for closures larger than 23% and concluded that "… additional closure will be increasingly resisted, making it likely that the one order of magnitude reduction in permeability from the effects of creep used here will not be exceeded with additional time." (Thompson et al. 1996, p. D-2).

This conclusion suggests that recovery of the maximum borehole volume loss of 41.8% in the Gjerapic model may not be physically achievable because backpressure from the consolidating borehole fill may exceed the applied confining stress from salt creep, particularly at shallower depths. If this conclusion is correct, the permeability loss in the Gjerapic model may be limited to one, or perhaps two orders of magnitude instead of the five or six orders of magnitude shown in Table 1. If the permeability reduction cannot reasonably exceed one or two orders of magnitude in the Gjerapic model, the permeability would decrease under salt creep from 10^{-10} m^2 to 10^{-11} or 10^{-12} m^2, which are of the same order of magnitude as the maximum permeability assumed in the Thompson model.

RPPCR6-Bhperm-18: initial permeability of degraded borehole debris used in creep closure analysis

Please explain the technical basis for the initial permeability of 10^{-10} m^2 assumed for the degraded borehole debris in the creep closure analysis.

RPPCR6-Bhperm-19: effect of backpressure buildup on reductions in permeability in updated modeling

Thompson et al. (1996, p. D-2) stated that backpressure buildup from the consolidated borehole fill makes it likely that one order of magnitude reduction in permeability due to salt creep would not be exceeded with additional time. Please describe the effect of backpressure buildup on the reductions in permeability determined from the updated modeling described in Gjerapic et al. (2023, Section 3.1) and provide justification that a reduction of five or six orders of magnitude is possible.

This second question asks how the results should be used. There are two interrelated elements to this question. How should the creep closure rates in salt be considered in PA and how should an initial, degraded borehole permeability be selected as a starting point for that closure?

Topic 6: Question on the initial degraded borehole permeability and effects of Closure Rates on PA

Regarding the initial degraded borehole permeability, the Agency considers the following conceptual assumptions in the Thompson model (not the PA simplification of that model) that were apparently accepted by Gjerapic et al. (2023) as defining the circumstances under which the upper bound permeability of the initial loose, uncompacted fill material should be determined.

a) During the first 200 years after borehole drilling/abandonment and at depths below 300 to 350 m, pitting corrosion of the borehole casing occurs but the casing retains enough strength after 200 years to resist creep closure and maintain an open borehole for another 1,000 years that is filled with degradation debris falling from above.

b) During the first 200 years after borehole drilling/abandonment and at depths above 300 to 350 m, general corrosion begins and by 200 years the borehole casing and grout have completely degraded from general corrosion and the debris from expanding degradation products as well as geologic materials sloughed from above have completely filled the borehole from the Bell Canyon plug (or the lower Salado plug, whichever is uppermost) to above the Culebra member of the Rustler Formation.

c) *The degradation debris filling the borehole at 200 years is a loose, uncompacted material for which a revised upper bound permeability is being proposed. Although this material is later subject to compaction from salt creep, this subsequent compaction does not affect its initial permeability.*

Based on information provided by Gjerapic et al. (2023), EPA has identified several candidates for the upper bound, initial permeability of the loose, uncompacted borehole degradation debris envisioned in the Thompson model. These are summarized in Table 2 below.

Table 2. Summary List of Candidates for the Upper Bound Permeability of Degraded Borehole Fill and EPAA Evaluation

Candidate Permeability	**Discussion**
10^{-10} m^2	Initial permeability used by Gjerapic et al. (2023, p. 13) in calculating creep closure with upgraded Reedlunn et al. (2022) model; may be related to permeability of uncorroded iron PRB granules.
10^{-11} m^2	Upper bound permeability proposed by Thompson et al. (1996, p. 20) for a mixture of completely degraded grout, corroded casing, and sloughed geologic materials; this conceptual model was accepted by EPA.
10^{-13} m^2	Upper bound permeability cited by Gjerapic et al. (2023) and reported by Curtice and Mallow (1979) for samples of hydrothermal cement cured more than 14 days; EPA questions relevance to long-term degradation at WIPP.
10^{-14} m^2	Upper bound permeability proposed by Gjerapic et al. (2023, p. 8) for degraded borehole fill debris dominated by cement materials with limited confinement; primarily based on particle size distribution for a silty material (such as cement powders) and Hazen's equation correlating grain size distribution with permeability; EPA questions conceptual basis and uncertainty associated with this value.

Note: Studies already considered by Thompson et al. (1996) were not included in this table.

RPPCR6-Bhperm-20: uncertainty regarding borehole debris fully consolidating to 10^{-15} m^2 permeability at repository depth

Please provide an assessment, based on an integrated conceptual model, of the uncertainty in the conclusion on page 15 that at the repository depth of about 650 m, the borehole debris is expected to fully consolidate under salt creep to a permeability on the order of 10^{-15} m^2, but under limited confinement would achieve the proposed maximum permeability of 10^{-14} m^2. Please address in this assessment the combined uncertainty resulting from the assumption of an initial degradation debris permeability of 10^{-10} m^2, uncertainty in the Reedlunn et al. (2022) creep model, uncertainty resulting from the creep model assumption that compressive strength of the degradation debris and pitted casing can be ignored, and uncertainty in the Kozeny-Carman model and its application to permeability reduction.

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