Review and perspectives on spillings release models in the 1996 Performance Assessment for the Waste Isolation Pilot Plant

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Abstract

The Waste Isolation Pilot Plant was licensed for disposal of transuranic wastes generated by the U.S. Department of Energy. The facility consists of a repository mined in a bedded salt formation, approximately 650 m below the surface. Regulations promulgated by the U.S. Environmental Protection Agency require that performance assessment calculations for the repository include the possibility that an exploratory drilling operation could penetrate the waste disposal areas at some time in the future. Release of contaminated solids could reach the surface during a drilling intrusion. One of the mechanisms for release, known as spillings, can occur if gas pressures in the repository exceed the hydrostatic pressure of a column of drilling mud. Calculation of solids releases for spillings depends critically on the conceptual models for the waste, for the spillings process, and assumptions regarding driller parameters and practices. This paper presents a review of the evolution of these models during regulatory review of the Compliance Certification Application for the repository. A summary and perspectives on the implementation of conservative assumptions in model development are also provided.

Key Words:

CCA, Compliance Certification Application, drilling intrusion, performance assessment, radioactive waste, release mechanism, repository science, risk assessment, spillings, transuranic waste, Waste Isolation Pilot Plant, WIPP

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1. Background

The Waste Isolation Pilot (WIPP) is a mined, geologic repository designed for permanent disposal of transuranic waste. The facility, located in southeastern New Mexico, was developed by the U.S. Department of Energy (DOE). WIPP received certification for operations by the U.S. Environmental Protection Agency (EPA) in the spring of 1998. The certification process required that the DOE demonstrate that the WIPP complies with EPA regulations [1]. Compliance with the applicable regulations was demonstrated by comparing a summation of probable releases over the 10,000-year regulatory period to an allowable standard [2]. Releases were calculated through incorporation of stochastic uncertainty in a series of performance assessment (PA) calculations included in the WIPP Compliance Certification Application (CCA).

The repository horizon is located approximately 650 m below the surface in a sequence of bedded salt deposits. Potential release pathways include indirect releases via groundwater transport of contaminated fluids from the disposal areas to the regulatory boundary, and direct release of material from the repository to the surface. Disposal of wastes in salt is considered advantageous because over time the salt will creep, closing around the waste and permanently isolating it from the biosphere. Because salt inherently has low permeability, transport along groundwater pathways is severely limited. Regulations state that PA calculations must include effects of inadvertent and intermittent intrusion by drilling for resources. Evaluation of the events associated with petroleum exploration led to formulation of a set of four mechanisms whereby contaminated material could be transported from a penetrated waste panel to the surface during a drilling operation. These mechanisms constitute the only means to release waste material directly to the surface (direct releases). Direct releases consist of:

1. cuttings, which include material intersected by the rotary drilling bit;
2. cavings, which include material eroded from the borehole wall during drilling;
3. direct brine releases, which include contaminated brine that may flow to the surface during drilling; and
4. spillings, which include solid material carried into the borehole during rapid depressurization of the waste-disposal region.

For each modeled intrusion, a quantitative value for release of contaminant material was calculated. Evaluation of repository performance depends on the volume of material released, and on the radioactive loading, or activity of the contaminated material. The activity was estimated from that of the expected waste inventory. The probability of

encountering a waste stream with high or low activity was considered in the development of a summation of released materials [3].

The CCA included a summation of direct releases to the surface and indirect releases along groundwater pathways which was significantly below the regulatory limit [2,3]. Direct releases to the surface during an intrusion event are the most important contributor to total releases calculated in the CCA. Sensitivity analyses showed that direct releases due to spillings comprises a large fraction of these releases. This paper presents a review of the models used for calculation of spillings releases from WIPP. Peer review of the initial model found that "... this model is not adequate for predicting future states of the repository" [4]. Studies were then conducted to show that, although the model was not adequate for prediction of future states of the repository, the volume of releases predicted by this model was reasonable, a conclusion supported by the peer review panel.

2. CCA modeling strategy

Understanding the WIPP scenarios requires a perspective on the repository and disposed waste. Disposal rooms are mined from the salt in a series of panels, as described by Larson [5]. Each panel consists of ten rooms, and will be filled with waste and magnesium oxide (MgO) backfill material. Waste destined for disposal at WIPP consists of diverse materials. Table 1 summarizes the relative amounts of waste types and backfill material.

Although the incumbent salt formation has relatively little water, field evidence suggests that some brine will flow into waste areas from the host rock following disposal. This moisture could, in turn, cause corrosion of steel drums and iron-based materials within the waste containers. Hydrogen gas will be generated by this reaction [6]. Cellulosics, rubbers, and plastics could undergo microbial degradation, producing additional gases within the repository [7]. The CCA PA calculations predicted gas pressures at the repository horizon could reach lithostatic pressure of 14.8 MPa within the regulatory period [8].

Fig. 1 presents a schematic of waste evolution over the regulatory period. This schematic was based on several assumptions regarding future processes. The volume of brine in a disposal room was assumed sufficient to generate steel corrosion. Possible sources of brine to the repository include seepage from the host rock, upward flow from a punctured brine reservoir below the repository, and downward flow of brackish groundwater via a plugged exploratory borehole [5]. It was further assumed that the backfill material (MgO) functions only as a sink for carbon dioxide gas generated as a consequence of microbial degradation; otherwise, it was otherwise assumed inert. Creep

closure of salt into disposal rooms was assumed to cause container rupture, thus exposing waste directly to fluids present in the repository.

The modeling strategy applied to human intrusion scenarios at the WIPP incorporates conceptual models of the waste, the drilling process, and the incumbent host rock. A review of scenario development and implementation of direct releases at WIPP shows that models included the following four assumptions:

1. waste rooms and panels are hydraulically connected;
2. waste properties are analogous to a weakly consolidated, particulate material;
3. transient wellbore processes can be neglected; and
4. drilling of exploratory wells in the vicinity of WIPP will continue at present-day rates and current technology (an assumption required by 40CFR194 [1]).

These assumptions result in a bounding model of waste evolution over the regulatory period. Implementation of bounding, or conservative, assumptions was consistent with the global strategy to take a conservative approach in the modeling of WIPP performance. The logical model [8] of the repository captured the first assumption. This model represents an abstraction of the physical domain into a two-dimensional region. Although details of stratigraphy and geometry were not retained in the model, the volume and properties of each region were captured. The single panel intersected by an intrusion borehole was modeled as a homogeneous segment; the remaining panels were lumped together, with properties uniformly distributed [8].

Performance assessments for the CCA were conducted through calculation of three replicate data sets, comprising 100 vectors each. Uncertainty in conceptual models and model parameters was captured through random variation of these values within a prescribed distribution in each vector set [3]. The stochastic approach to parameter and model variation does not lend itself to simplistic analysis. However, this method fully incorporates the range of uncertainty for WIPP performance and was considered acceptable by the regulator. (Helton et al. [3] and other papers contained in this special journal issue [4,5,8,9,10,11,12] present a complete discussion of the stochastic approach and system sensitivity.) Results of the PA were presented in the CCA as sets of calculations.

The PA modeling assumptions led to the boundary conditions for the spillings model. Current practice in the vicinity of WIPP utilizes brine as the drilling mud through the salt regions [9]. Spalling was assumed to occur if repository pressure exceeds the hydrostatic pressure of a column of drilling mud, or about 8 MPa [11]. Stoelzel et al. [11] (in this issue, their Fig. 3) shows a representative drilling configuration. All direct release models for WIPP

assumed that the drill string remained in the drillhole; transport to the surface was limited to the annular volume between the edge of the drillhole and the drillbit or drill collars.

Because the waste panels were assumed to be hydraulically connected, the entire gas storage volume of the disposal area was accessible to a drillhole penetrating the repository horizon. In the petroleum industry, production of solids from a formation is generally divided into two categories: dynamic response due to a gas kick during exploratory drilling [13], and steady-state production of solids from a producing formation [14]. The CCA model for spallings assumed that the dynamic response of the system could be included in the results of an end-state model [12].

Laboratory experiments of a simulated blowout [15] conducted using damp sand as a waste surrogate material led to formulation of a mathematical model for spallings [12]. Results indicated that production of solids would cease under steady-state conditions. However, a review of relevant literature [16] shows that continuous sand production is a common problem in petroleum reservoirs producing from a weakly consolidated formation.

The CCA conceptual model of the waste was derived from assumptions that degradation processes will dominate waste evolution, and that such processes result in fine-grained particulate material. The lower bound on particle size was determined by the corrosive reactions, which are considered likely to produce particles on the order of a few tens of microns in diameter. The annular space between a drill bit and the drillhole, approximately 2.5 cm, was used to set the upper bound on particles which could be transported to the surface. Waste particle size in CCA calculations varied from 40 μm to 2.5 cm. [12].

3. Peer review of the CCA model

Federal regulations governing the WIPP specify that the conceptual models in the CCA must undergo peer review [1]. A Conceptual Model Peer Review Panel (CMPRP) was convened to ensure that the conceptual models used in the WIPP PA reasonably represented possible future states of the disposal system [4]. A team of peer review panels covered a total of 24 conceptual models used in the CCA. The conceptual model for spallings was found to be without “an adequate basis for determining that the Spallings model was either reasonable or conservative” [17].

Principal concerns of the CMPRP related to an apparent mismatch between the mathematical model of spallings and the experimental results [4,17]. Blowout experiments resulted in limited ejection of solids from the experimental apparatus. Although the damp, fine-grained sands used in the experiments were uncemented, parameter fitting exercises determined that the empirical factor for capillary forces was exactly zero, in spite of the presence of

moisture. This result, which was difficult to interpret within the confines of the assumed mathematical model, led to uncertainty regarding the fundamental assumptions of the model. The finding of zero influence due to capillary forces contradicted independent experimental and field results [14,16] which indicate that capillary forces do influence solids production in a flowing well.

The CMPRP was also concerned about the assumed physical properties of the degraded waste, particularly with regard to the selected value for waste cementation. A constant value of 1 psi (6895 Pa) was assumed to represent the lower bound for waste strength. This parameter value was selected absent any experimental data on the characteristics or cohesive nature of degraded waste materials. The laboratory experiments using uncemented, damp sand as an analog material for degraded waste represented the sole source of data used to validate the model. Predicted releases using the CCA model were sensitive to variation in the waste cementation parameter, as shown in Fig. 2.

Failure to address the mathematical discrepancies of the model, and the lack of data on a parameter clearly shown significant to results, led the CMPRP to conclude that direct release quantities due to spillings given in the CCA could not be justified. The CMPRP [17] stated, "The waste [had] not been adequately characterized and the understanding of its physical properties in its decayed state [had] not been adequately developed to support the Spallings model." The panel suggested, however, that a quantitative evaluation of the transient processes that occur during a gas blowout event could provide a basis for accepting the CCA spillings releases. To address the panel's concerns, the DOE initiated additional technical studies.

Experiments and analyses conducted following submittal of the CCA focused on three objectives. The first objective was rigorous evaluation of waste character. The second was to conduct experiments, analyses, and analog comparisons that would result in a mechanistically based conceptual model for spall, and that incorporated appropriate physical properties for the waste. The third objective was to demonstrate that, despite some technical concerns, the quantitative volumes for spalling presented to the CMPRP were, in fact, reasonable. The means employed to accomplish these objectives are presented in the following sections.

4. Waste evolution and character – A new perspective

Waste character at the time of a hypothetical drilling intrusion governs the volume of material available for release to the surface. This fundamental component in the spillings model was rigorously evaluated from the

perspectives of geomechanics, chemistry, and hydrology. In addition to a qualitative description of waste evolution, suitable surrogates were developed so that mechanical properties could be experimentally derived.

Changes within the first 100 years following disposal will be dominated by the ability of the incumbent host rock to creep into the disposal areas, thereby compacting the waste. Room closure during these early years will proceed at a rate sufficient to compact the waste rooms from the original height of 4 m to approximately 2 m [18]. Additional processes, including hydration of MgO backfill, and the presence of even small quantities of moisture will lead to a degree of cementation of some waste constituents. The corrosion of ferrous metals, aluminum, copper, and lead, and microbially induced destruction of cellulosic materials may lead to gas generation and a decrease in grain size of the initial waste constituents. Timing and rates of waste degradation, compaction, and cementation processes influence the evolution of the underground setting [19].

Considerable uncertainty exists in the degree of corrosion that might precede a spall event. As described by Helton et al. [3] the predicted fraction of iron uncorroded in the waste areas for 100 realizations for undisturbed conditions varied from 40% to 100%. This result showed that at most 60% of the available iron could be corroded under undisturbed conditions. When a borehole intrusion occurs that also penetrates a Castile reservoir underlying the repository (i.e., the E1 intrusion described by Larson [5]) a greater volume of brine could flow into the repository leading to corrosion of all of the iron available in the disturbed panel. However, for E1 scenarios, repository pressures following the intrusion event rarely exceeded 8 MPa, which was too low for a spall event. The most probable conditions for a spall event coincide with scenarios in which less than 60% of the iron was corroded.

Uncertainty in the degree of waste degradation led to formulation of various degradation scenarios [20]. Upon consideration of PA results, four degradation scenarios were proposed. These scenarios assumed partial to complete degradation of the initial waste inventory presented in Table 1. Two scenarios incorporated MgO backfill in the surrogate materials, and two scenarios neglected these effects. Waste surrogate specimens were selected for scenarios that did not include cementation effects due to salt precipitation or other chemical reactions within the waste. This was consistent with the assumption that the backfill acts only as a sink for carbon dioxide gas and was otherwise inert. A comprehensive description of surrogate material development and testing is found in Hansen et al. [19] and in Hansen and Mellegard [21].

Maintaining an approach consistent with the CCA conceptual model of the waste, samples selected for derivation of material properties testing focused on maximally degraded surrogates. This approach ensured that any

cementation effects would represent the lower bound of waste strength and cohesion. As noted by Papenguth and Myers [20], these surrogates were not considered representative of the average waste condition. Specimens prepared represented the most extreme degradation scenarios for the waste. Table 2 summarizes surrogate materials. Surrogates were mixed and compacted in a test machine. Because more than 50% of metals in the waste inventory will be present at the time of a spalling event, the waste will consist of a heterogeneous mixture of partially degraded inventory interspersed with pockets of finer-grained material similar to the waste surrogate specimens. Detailed characterization of the average strength of the blocky material present in the underground represents an enormously difficult task. However, use of the experimental values derived from the waste surrogates was easily defended as a lower bound of waste strength. A large suite of mechanical and hydrological properties tests were completed, and results are summarized in Hansen and Mellegard [21]. The tensile strength of saturated waste surrogates was on the order of 10 psi (68,950 Pa), more than ten times stronger than the generic waste strength of 1 psi assumed for the CCA. Measured permeability and porosity of the waste surrogates were 10^{-15} m^2 and 0.2, respectively. These values differed from those assumed for the CCA, in which a constant permeability of approximately 10^{-13} m^2 was assumed. Porosity of the waste reduces from approximately 0.85 at the time of disposal to as low as about 0.2 due to compaction by salt creep processes. Because CCA models assumed that salt creep slows when repository pressure rises, a porosity of 0.6 was predicted in the waste areas for a high-pressure scenario (i.e., greater than 14 MPa [8]). Although these values for permeability and porosity differed from those derived from waste surrogate experiments, they were considered consistent with expected conditions in the repository. As previously discussed, development of surrogates focused on fully degraded materials, although intrusion into a pressurized panel correlates to a panel containing a significant percentage of undegraded material. Thus, the surrogates represented those areas of extensively degraded waste. The remainder of the panel should consist of compacted waste containers interspersed with pockets of densely packed degraded material and backfill, with a bulk porosity on the order of 0.5 to 0.6. The mechanistic model developed for calculations and presented to the CMPPR assumed waste permeability would be on the order of 10^{-13} m^2 and porosity would be within the range of 0.5 to 0.6.

Having defined a set of baseline properties for the waste, a means to calculate the response of the repository to a drilling intrusion was required to fulfill the second objective of these studies. In accordance with CMPPR recommendations, this response was based on a mechanistic approach to the spillings process.

5. Systems analysis approach – The mechanistically based conceptual model

Development of the mechanistically based conceptual model was conducted in a systematic manner: (1) Waste characteristics associated with requisite underground conditions were determined. (2) Conditions necessary for spall to occur were assessed. (3) Alternative calculation methods were used to estimate system response during a drilling intrusion. (4) A rigorous evaluation of analog situations was undertaken to support validation of computed results. The final step in the analysis was a comparison of releases predicted in the CCA to failed volumes estimated using the new model.

The mechanistic model can be divided logically into three elements: motion of the column of drilling mud, gas flow within and from the repository, and variation of stresses in the waste. All three elements were dynamically coupled through the flowing bottomhole pressure. Fig. 4 depicts the mechanisms and equations used to calculate the response of the system following penetration by a drillbit. This section provides a review of the conceptual models and summary of results. Details are found in Section 3 of Hansen, et al. [19].

Scoping calculations demonstrated that ejection of the drill string was not likely. It therefore was assumed that the geometry of the wellbore system consisted of the annular area between the drill bit and drillhole. A simplified equation of motion of the mud column was based on transient pipe flow for the annular region. The equation of motion for the mud column calculated slug flow since no mixing was assumed between repository gases and the drill mud of the fluids, and considered the pressure differential down the mud column, viscous drag from the annular walls, and the hydrostatic weight of the mud.

Gas flow within and from the repository was calculated using two semi-analytical methods. These methods solve the one-dimensional (spherically symmetrical) compressible flow equations in two ways. The first method calculates gas flow as a series of steady states using solutions developed by Chan et al. [22] for one-dimensional isothermal gas flow. The second method implements a numerical solution for the one-dimensional transient gas flow equations.

Consistent with CCA assumptions, the fluid flow calculations assumed that the flowing gas was hydrogen, and assumed ideal gas behavior. The bottomhole pressure in each scenario was calculated by equating mass flow from the repository with that up the borehole, taking account of the mud flow out of the hole.

The calculation of total stress in the waste as depicted in Fig. 4 was based on the static response of a hollow elastic sphere [23] that is subject to both mechanical loading and pore pressure effects as follows:

$$\sigma_r' = \sigma_{sr} + \sigma_o \left[1 - \left(\frac{r_w}{r_n} \right)^n \right] + p_w \left(\frac{r_w}{r_n} \right)^n - \beta p(r) \quad (1)$$

$$\sigma_\theta' = \sigma_{s\theta} + \sigma_o \left[1 + \frac{1}{(1-n)} \left(\frac{r_w}{r_n} \right)^n \right] - \frac{p_w}{(n-1)} \left(\frac{r_w}{r_n} \right)^n - \beta p(r) \quad (2)$$

A compressive stress was assumed to be positive. The pore pressure stresses are given by:

$$\sigma_{sr} = (n-1)\beta \left(\frac{1-2\nu}{1-\nu} \right) \frac{1}{r^n} \int_{r_w}^r p' r^{n-1} dr \quad (3)$$

$$\sigma_{s\theta} = -\beta \left(\frac{1-2\nu}{1-\nu} \right) \frac{1}{r^n} \int_{r_w}^r p' r^{n-1} dr - p' \quad (4)$$

where:

σ_r' = radial stress

σ_θ' = tangential stress

σ_{sr} = radial mechanical stress

$\sigma_{s\theta}$ = tangential mechanical stress

p_w = bottomhole pressure

σ_o = far-field pressure

r_w = far-field radius

r_n = radius of sphere or cylinder

ν = Poisson's ratio

β = Biot coefficient

The coefficient n is 2 for cylindrical geometry and 3 for spherical geometry. Calculations used for spallings evaluation used a hemispherical geometry. The inner sphere was subjected to the bottomhole pressure. The outer surface was subject to the far-field pressure, which was lithostatic pressure at the time of the intrusion. A tensile failure criterion was assumed, whereby waste material experiences material failure when tensile stresses exceed a specified strength parameter. The nature of failure was not addressed in the model, nor was transport of solid material to the surface. These processes require additional theoretical and computational capability. Instead, it was

assumed adequate to compare the volume of waste material likely to experience tensile failure to the solids releases predicted by the steady-state CCA model.

Calculated results are most easily summarized through evaluation of the effective radius of waste material assumed to fail in tension. An example is shown in Fig. 5. This plot depicts the transient radius of a failure zone for a repository gas pressure of 14.5 MPa, and a tensile strength of 10 psi (68,950 Pa) using the fully transient gas flow equations to calculate pore pressure gradients. Plots of the pore pressure and stress gradient calculations using the quasi-static method are depicted in Fig. 6.

A summary of the volume of waste material likely to experience tensile failure during a spillings event is depicted in Fig. 7. This plot was based on several assumptions. Principal among these was that the tensile strength of the material was bounded by the experimental results on fine-grained waste surrogates. The response of the waste to tensile failure was assumed to result in particulate solids, which were transported immediately to the surface. Driller response during a gas kick was neglected; no control of the well was assumed. The ability of the flowing gas to transport solids to the surface was also not considered in this analysis. Releases predicted in the CCA [2] do not rely on these processes. For consistency, driller control and solids transport were ignored in the mechanistically based model.

Confidence in the volume of material that could be spalled was obtained through comparison with industrial analogs. The closest analog to the WIPP spillings scenario is a technology used to enhance gas production from coal seams [13]. This technique entails overpressurization of the coal seam, followed by a sudden release of gas pressure, thereby producing large seepage forces. Production of material from the formation is carefully monitored, and the final cavity size is measured. Conditions present in the coal seam cavitation technology are similar to those implemented in the mechanistically based model for spillings releases at WIPP. Comparison of the coal seam cavity size and results presented in Fig. 5, as described in Hansen et al. [19], established that calculations using the mechanistically based approach were reasonable.

6. Comparison of results with CCA model

Results derived from the mechanistically based model showed that for repository gas pressures below 14 MPa, the tensile failure radius predicted was only minimally larger than the radius of the intruding drillstring. This meant that a summation of all releases predicted using the mechanistically based model would be smaller than the summation derived when using the end-state model [12]. Values calculated using the end-state model ranged from

0.25 to 4 m³ [12]. For the mechanistically based model, the volume assumed to fail in tension when repository pressure exceeded 14MPa was within this range. If model assumptions are modified to include plastic deformation leading to formation of stable arches, energy available to transport solid waste to the surface, driller control and processes leading to a more realistic conceptual model of the waste, additional reduction in predicted spillings release volumes are expected.

In terms of compliance with EPA regulations, a comparison of the potential spillings release volumes calculated by the mechanistically based methods to those predicted in the CCA also required consideration of the probability of specific conditions required for a spillings release. For example, the probability that gas pressures in the waste could exceed 14 MPa was about 1% [19] (Appendix E, referenced document). Using the probabilistic approach [3], it is clear that the cumulative releases due to spillings predicted using the mechanistically based model would be much smaller than those presented in the CCA.

Experimental results for surrogate waste properties, presentation of computed volumes using the mechanistically based approach, and analog information were presented to the CMPPR in April, 1997. On the basis of these results, the panel concluded that the “predicted volumes presented in the WIPP CCA are reasonable” [24].

7. Perspectives on spillings releases in the CCA

The conceptual model for spillings presented for peer review, and included in the WIPP CCA, was considered adequate by its authors because of the conservatism inherent in the model for waste evolution. The simple model of waste as a granular material eliminated the need for complex analyses and experiments regarding transient processes within the disposal area. Defensibility of the conceptual model was straightforward, and numerical implementation was easily accomplished. Experimental results of a simulated spalling event indicated that releases were self-limiting. Taken together, these arguments would lead to the conclusion that the spillings model was acceptably simple, yet conservative. However, a review of the literature [16] on sand production in oil wells would have revealed a weakness in the overall argument. Industry experience indicates that solids production is not always self-limiting for a weakly consolidated formation. While the conceptual model of waste as a granular material remains conservative, a project review of the consequences of this conservative assumption would have pointed out the overall model weakness prior to the peer review process. This weakness of the CCA spalling model was detected during peer review, and additional experimental evidence was generated indicating that direct releases based on a more realistic concept of the waste form would not exceed the values predicted using the end-state model.

Consideration of peer review concerns led to reevaluation of the fundamental models of waste character and the mechanics of an inadvertent drilling intrusion into WIPP. In response to these concerns the project assumed that characterization of waste form and evolution represented a feasible exercise. This characterization followed directly from known physical processes regarding waste degradation. Inclusion of realistic chemical and physical processes in the degradation pathways resulted in development of expected waste evolution scenarios. This approach successfully eliminated the scenario that waste will degrade to a granular, non-cohesive medium.

The mechanistically based model for the spallings process addressed the peer review panel's concern that the fundamental physics of the event must also be evaluated. Calculation of system response is an important task; convincing arguments were made on the basis of experimental data, analog information, and quantification of the processes included in the mechanistically based model. These activities consume significant resources within the program, and inherently rely on waste properties derived using bounding models of the waste. Development of an experimental program to evaluate properties of waste surrogates based on various degradation pathways would substantially improve defensibility of the modeling approach. This approach would also reduce the burden associated with development and validation of models that capture the complex physical processes of a spallings release.

A retrospective review of the WIPP conceptual model for spallings leads to several observations regarding model development. (1) Experimental data is a critical component in the defense of models. In the absence of such data, reasoned arguments should be made on the basis of the expected processes. (2) Failure to follow a seemingly conservative assumption to its logical conclusion can prevent weaknesses and invalid assumptions associated with a model from being identified. (3) Complex analyses should be based on realistic, rather than conservative assumptions. This final observation also requires an honest assessment of the uncertainty associated with the selected approach and assessment of the consequences of this uncertainty.

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Table 1
Initial waste concentrations

Waste Category	Inventory (wt%)
Iron-based metal, alloys	14
Steel container material	12
Aluminum-based metal, alloys	1
Other metal, alloys	6
Other inorganic materials	3
Vitrified	5
Cellulosics	4
Rubber	1
Plastics	3
Plastic container/liner material	2
Solidified inorganic material (including cement)	4
Solidified organic material (not including cement)	0
Solidification cement	4
Soils	4
MgO backfill	37

Table 2
Materials selected for waste surrogate testing

Waste Category	Example Waste Simulants
Iron-based metals, alloys; steel container materials	Strips of steel sheet metal, small nails (cut up), scraps of steel or iron
Corroded iron-based material, alloys; steel container materials	Scrapings from rusted steel or iron; supplement with Fe(III)O.OH (goethite or limonite rock samples) crushed sand-to-silt particles
Corroded non-ferrous metals and alloys	As above for corroded iron-based metal, etc.
Other inorganic materials, vitrified	Broken labware, broken glassware
Cellulosics + rubber; plastic; plastic container/liner material	Equal masses of (a) finely shredded paper, snipped cotton balls, sawdust, shredded plastic grocery bags, O-rings, rubber gloves, rubber bands, polyethylene sheet and bottles (all comminuted with a blender or other means) + (b) peat (no vermiculite)
Solidification cement	Broken hydrated concrete and mortar, crumbled sheet rock
Soils	Natural soil
MgO backfill	Commercial pellets

Fig. 1. Artist's schematic of waste evolution over the regulatory period.

Fig. 2. Sensitivity of predicted releases using the CCA model to assumed values of waste cementation.

$$\frac{mdv}{dt} = F_p - F_f - F_w$$

$$p = \rho R_0 T$$

$$p = \frac{M_0 + M(t)}{V(t)}$$

$$\frac{\partial p}{\partial t} = \frac{k}{2\phi\mu} \nabla^2 (p^2)$$

Fig. 3. Schematic of processes included in quasi-static and transient models for the mechanistically-based spallings model.

$$\hat{\sigma}_r = \sigma_r - \beta p = [\sigma_r]_{HS} + [\sigma_r]_P - \beta p$$

$$\hat{\sigma}_T = \sigma_T - \beta p = [\sigma_T]_{HS} + [\sigma_T]_P - \beta p$$

Fig. 4. Conceptual model for stress calculations in the waste. Based on Thompson's derivations [21] (Appendix B of referenced document).

Fig. 5. Calculated radius of waste material which experiences tensile stresses in excess of 68,950 Pa (10 psi) for an initial repository gas pressure of 14.5 MPa using the fully transient gas flow equations and a linear elastic stress model.

Fig. 6. Calculated transient total stress and pore pressure for repository gas pressure of 14.5 MPa using the quasi-steady state solution for gas flow [22].

Fig. 7. Summary plot of spalling volumes, using the mechanistically based model.