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Measurement and monitoring of radioactivity for disposal and repository applications

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Summary. — Compliance monitoring is used to evaluate and confirm the adequacy of assumptions, data, parameterizations, and analyses used to demonstrate performance of a given geologic repository site. Repository performance demonstration is accomplished via a performance assessment methodology. Performance assessment provides a reasonable expectation of long-term repository performance with quantified uncertainty. In this paper, the linkage between compliance monitoring and performance assessment is explored. The U.S. Waste Isolation Pilot Plant and the suspended Yucca Mountain site are used to illustrate the discussion.

1. – Introduction

Compliance monitoring is an important tool used to validate that assumptions, parameters, and analyses used to demonstrate repository performance remain valid in ensuing years after licensing, as well as during the operational period. A site characterization program typically takes place prior to licensing of a repository. Results and findings from such a program yield expected parameter and process representations used to support the safety case of the facility. As the facility matures, new information may lead to a re-assessment and adjustment of parameters, models, etc. captured in the performance assessment (PA) used to demonstrate safe containment of radionuclides. A compliance monitoring program ensures that models, parameters, and assumptions are appropriately updated in light of new information.

There are two key aspects of a successful compliance monitoring program [1]:

- Selection of parameter/processes to be measured or monitored;
- Specification of conditions for which the regulatory authority is notified if monitored information differs from expectation.

Monitoring for performance confirmation evolves as the repository design concept matures and advances and as regulations mature.

We now utilize the example of the U.S. Waste Isolation Pilot Plant (WIPP) to provide a specific example of an ongoing compliance monitoring program and the links it has to performance assessment.

2. – The Waste Isolation Pilot Plant

The Waste Isolation Pilot Plant, 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 calculations performed by Sandia National Laboratories. 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. A compliance monitoring program ensures that observed processes and parameters for the facility and surrounding region are aligned with those implemented in the PA. 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 to support the repository recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999. A representation of the WIPP and surrounding geology is shown in fig. 1.

3. – WIPP Performance Assessment

Disposal standards for the WIPP invoke a PA demonstration that potential cumulative releases of radionuclides to the accessible environment over a 10,000-year period after disposal are less than specified limits based on the nature of the materials disposed. The PA is used to determine the effects of all significant processes and events that may affect the disposal system, consider the associated uncertainties of the processes and events, and estimate the probable cumulative releases of radionuclides. The PA analyses supporting this determination are quantitative and consider uncertainties caused by all significant processes and events that may affect the disposal system, including future inadvertent human intrusion into the repository. A quantitative PA is conducted using a series of coupled computer models in which epistemic parameter uncertainties are addressed by a stratified Monte Carlo sampling procedure on selected input parameters, and uncertainties related to future intrusion events are addressed using simple random sampling [6]. The foundations of WIPP PA are a thorough understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. At a fundamental level, the PA answers three questions about the repository system:

- What can happen after permanent closure?

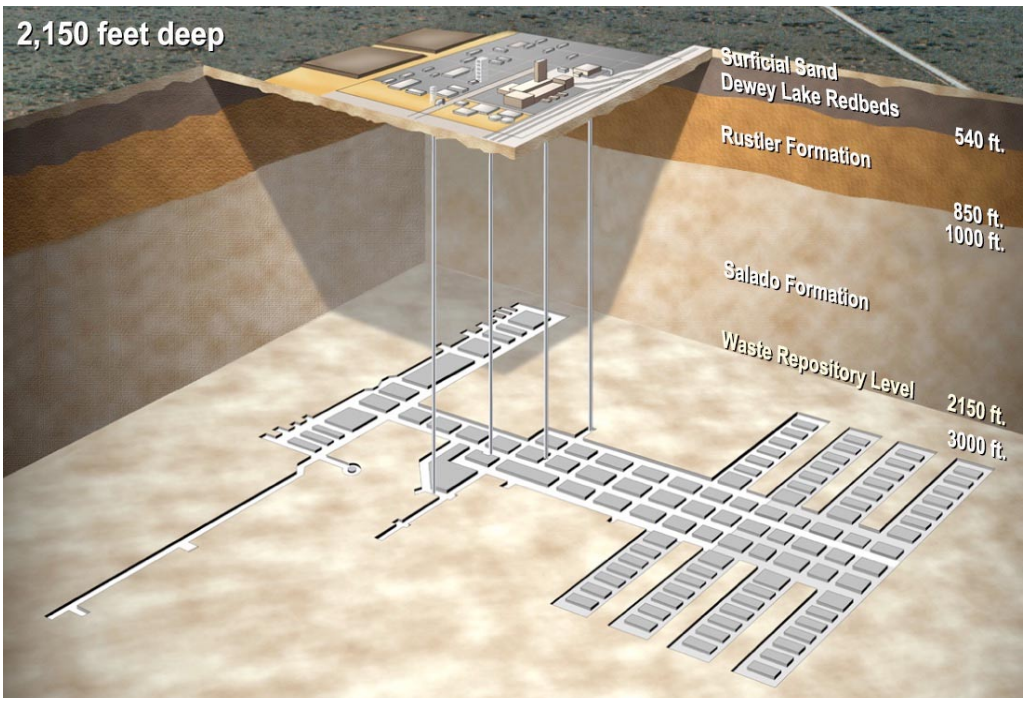

Fig. 1. – The Waste Isolation Pilot Plant

- How likely is it to happen?
- What can result if it does happen?

It also answers one question about the analysis:

- What level of confidence can be placed on the estimate of repository performance?

All features, events, and processes (FEPs) that could occur during the regulatory time frame and may affect the repository are identified and evaluated. The WIPP PA methodology includes a process that compiles a comprehensive list of the FEPs that are relevant to disposal system performance. Those FEPs determined by screening analysis to have the potential to affect performance are represented in scenarios and quantitative calculations using a system of linked computer models.

The screening criteria used for WIPP FEPs are centered around probability, consequence, and regulation. WIPP FEPs are screened according to [7]:

- Probability: If a FEP has a probability of occurring less than 10^{-4} in 10,000 years it does not have to be included in PA (*e.g.*, meteorite impact)
- Consequence: If a FEP is beneficial to performance, is not relevant to WIPP, or has an insignificant consequence to the disposal system, it does not have to be included in PA (*e.g.*, lakes, oceans, tides, floods). If a FEP is related to the WIPP disposal system and/or impacts the repository, it must be accounted for in PA (*e.g.*, chemical effects of corrosion).

- Regulation: Certain FEPs are either screened in or out by regulation (*e.g.*, mining, resource extraction following drilling).

An evaluation of undisturbed repository performance, which is defined to exclude human intrusion and unlikely disruptive natural events, is required by regulation. Evaluations of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years. Disposal system behavior is dominated by the coupled processes of rock deformation surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which they occur is generally affected by the others. The WIPP PA is also required by the performance standards to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources by humans. Human intrusion by drilling may cause releases from the disposal system through five mechanisms:

1) Cuttings, which include material intersected by the rotary drilling bit.

2) Cavings, which include material eroded from the borehole wall during drilling.

3) Spallings, which include solid material carried into the borehole during rapid depressurization of the waste disposal region.

4) Direct brine releases, which include contaminated brine that may flow to the surface during drilling.

5) Long-term brine releases, which include the contaminated brine that may flow through a borehole after it is abandoned.

The first four mechanisms immediately follow an intrusion event and are collectively referred to as direct releases. The accessible environment boundary for these releases is the ground surface. The fifth mechanism, actinide transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. The accessible environment boundary for these releases is the lateral subsurface limit of the controlled area. A schematic illustrating the direct and long-term release mechanisms for the WIPP is shown in fig. 2.

3˙1. *The WIPP Compliance Monitoring Program.* – Federal requirements for the WIPP facility specify that the disposal system must be monitored to detect substantial and detrimental deviation from expected disposal system performance. The WIPP Compliance Monitoring Program (CMP) consists of pre-closure and post-closure monitoring activities. Techniques used to support these activities are carefully chosen so as to not jeopardize isolation of the waste. The monitoring program is conducted until the U.S. DOE and the federal regulator agree there are no significant concerns to be addressed by further monitoring. The long-term performance expectations for the disposal system are derived from conceptual models, scenarios, and assumptions implemented in the WIPP performance assessment. The CMP recognizes that ten parameters important to estimations of repository performance are to be monitored [5]. These parameters are:

1) Creep closure and stresses

2) Extent of brittle deformation

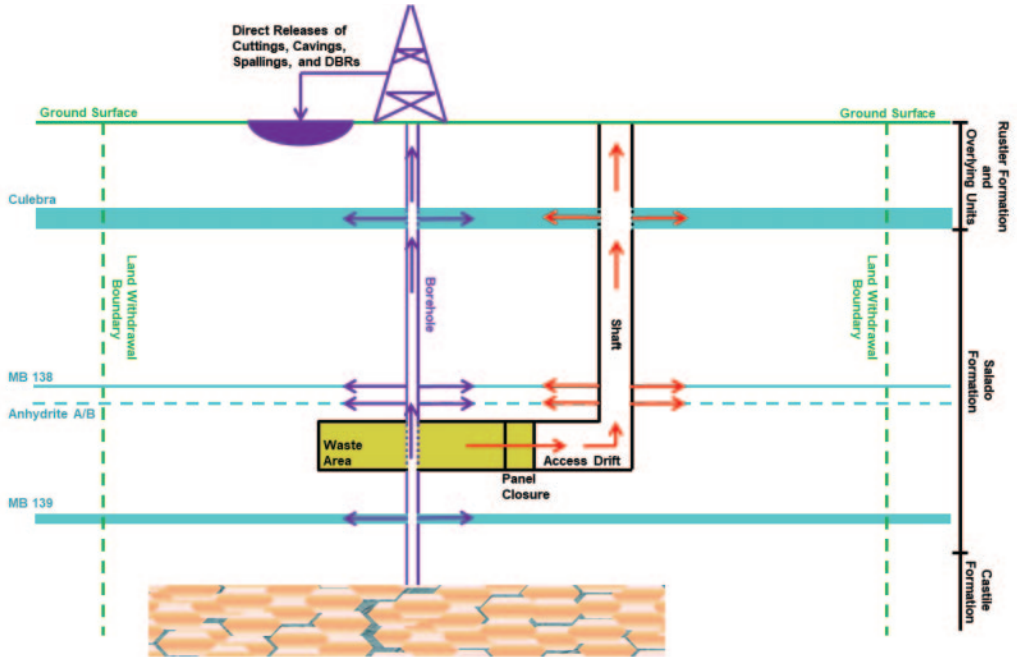

Fig. 2. – WIPP Direct and Long-term Release Mechanisms

3) Initiation of brittle deformation
4) Displacement of deformation features
5) Change in Culebra Dolomite Member groundwater composition
6) Change in Culebra groundwater flow
7) Drilling rate
8) Probability of encountering a Castile Formation brine reservoir
9) Subsidence
10) Waste activity

The data used to assess the ten monitoring parameters of the CMP are generated by five individual monitoring programs. The CMP links individual monitoring parameters and monitoring programs to related WIPP PA parameters and FEPS. The CMP also specifies the frequency of data collection for each of the parameters (see Table MON-1 of [5]). Each monitoring program focuses on the collection of field data. Results from each monitoring program are documented individually in annual reports. Assessment results of the ten monitored parameters are documented and reported in compliance monitoring parameter assessment reports [4]. If any of the data, parameters, or observations are not consistent with expectations, the WIPP CMP process requires that concerns be addressed, and recommendations be developed. Results from monitoring programs are generated on an ongoing basis throughout the operational period of the repository.

Compliance monitoring data are provided to the cognizant individuals and organizations within the WIPP project and evaluated for their significance. The evaluation results and data summaries are reported to the federal regulator.

The five individual monitoring programs are:

- The Geomechanical Monitoring Program
- The Groundwater Monitoring Program
- The Delaware Basin Drilling Surveillance Program
- Subsidence Monitoring Program
- Waste Inventory Monitoring

Data collected as part of the Geomechanical Monitoring Program are used to validate the WIPP design, track short-term and long-term geotechnical performance behavior of underground openings, and support routine safety and stability evaluations of excavations. From an operational point of view, geomechanical data are used to identify areas of potential instability and allow corrective action to be taken in a timely manner. For underground opening behavior, in situ data are used to model long-term disposal system performance in the WIPP PA. A complementary Geosciences Program documents existing geologic conditions and characteristics and monitors for changes resulting from excavation. The Geosciences Program implements field activities such as geologic mapping of the facility and near-surface stratigraphic horizons, core logging, and geophysical surveys. These activities generate data used in monitoring the repository and in rock mechanics studies. Information from the Geosciences Program is used to document the existing geologic conditions and characteristics and to monitor for changes resulting from excavations. Activities associated with this program include geologic and fracture mapping, seismic monitoring and evaluation, and other activities performed as needed. These activities characterize, demonstrate the continuity of, and document the geology at the site.

Groundwater collection data from numerous wells at or near the WIPP facility is carried out under the Groundwater Monitoring Program. The Culebra Dolomite Member of the Rustler Formation is the focus of this monitoring program. The Culebra has been extensively studied and found to be the most likely hydrologic pathway to the accessible environment for any potential human-intrusion-caused release scenario. The Groundwater Monitoring Program addresses requirements for sample collection, groundwater surface elevation monitoring, groundwater flow direction monitoring, data management, and reporting of groundwater monitoring data. It also identifies analytical parameters selected to assess groundwater quality. Water level data are collected to assess changes in Culebra groundwater flow. Water level measurements are tracked over time from wells distributed across the WIPP area to monitor potentiometric surface and groundwater flow directions. If changes in water level(s) occur, the cause is investigated, and any potential impact on parameters and models used to assess the long-term performance of the repository is evaluated.

Significant oil and natural gas resources are located in the Delaware Basin of West Texas and Southeast New Mexico. The Delaware Basin underlies the WIPP. The Delaware Basin Drilling Surveillance Program provides active surveillance of drilling activities within the Delaware Basin. The WIPP PA includes the impacts of drilling on the performance of the disposal system. The number of deep boreholes drilled per square

kilometer is a parameter used in PA calculations for inadvertent intrusion scenarios. This parameter is based on actual drilling rates within the Delaware Basin in the previous 100 years. The results of the Delaware Basin Drilling Surveillance Program are used to detect any substantial deviations from the assumptions used in WIPP PA. The collection of information about resource exploration and exploitation activities and practices in the Delaware Basin provides information used to determine if the drilling scenarios, assumptions, and probabilities used in the WIPP performance assessment continue to be valid for each 5-year recertification of the WIPP disposal system.

Activities in the Subsidence Monitoring Program measure vertical movement of the land surface. Subsidence monitoring involves measurement of the vertical height difference between two or more markers placed on the ground surface a known distance apart. A leveling survey is used to detect vertical movement over time. Subsidence monitoring is conducted to detect substantial and detrimental deviations from expected repository performance by comparing actual subsidence to predicted subsidence.

Waste activity parameter information is collected in the Waste Inventory Monitoring Program. Information describing waste activity parameters is measured or estimated by generator sites through waste characterization activities. Radionuclide inventory data and material parameter weights for every container of waste placed in the WIPP underground repository are collected in a database at the time waste is certified for shipment to the WIPP facility. Reports are then generated to tabulate key waste parameters for waste that has been emplaced in the repository. Total waste material parameter weights and curie content are tracked for 10 radionuclides (Am-241, Pu-238, Pu-239, Pu-240, Pu-242, U-233, U-234, U-238, Sr-90, Cs-137). Tracked waste activities are used to describe the emplaced inventory in the WIPP performance assessment.

There is a very strong link between the models, parameters, and FEPS used to demonstrate performance of the WIPP disposal system and the WIPP Compliance Monitoring Program.

4. – Yucca Mountain

The Yucca Mountain site was proposed as a deep geological repository for spent nuclear fuel (SNF) from U.S. commercial nuclear power plants and other U.S. high-level radioactive waste (HLW). In support of the licensing application for the site, over a decade was spent developing the Yucca Mountain performance confirmation program. It was included as part of the Yucca Mountain License Application to the U.S Nuclear Regulatory Commission (NRC) in June 2008 [3]. A motion to withdraw the Yucca Mountain License Application was submitted by the U.S. DOE in March 2010. The adjudicatory proceeding associated with the Yucca Mountain construction authorization application remains suspended. Yucca Mountain is shown in fig. 3.

4˙1. *The Yucca Mountain performance confirmation program.* – Development of the Yucca Mountain performance confirmation program began during site characterization. Information from site characterization provided the basis for understanding the capability of natural and engineered barriers to delay flow and transport and for evaluating system performance. The understanding of barrier capabilities developed during site characterization provided the basis for determination of monitoring activities.

Monitoring envisioned to support Yucca Mountain performance confirmation was tightly linked to the performance assessment used to demonstrate safe geologic disposal of SNF and HLW in the proposed facility. The monitoring program was designed to

Fig. 3. – The Yucca Mountain Site.

confirm the adequacy of assumptions, data, and analyses used to demonstrate effective isolation of waste materials in the safety case [2]. The Yucca Mountain performance confirmation program had two objectives. The first objective was to provide information used to confirm that subsurface conditions encountered and changes in those conditions during construction and waste emplacement operations remained within the expectations of the license application. This included monitoring of subsurface conditions and testing to confirm geotechnical and design assumptions. Plans for in situ monitoring, as well as field and laboratory tests, were included. Second, the program provided information to confirm that natural and engineered barriers functioned as expected. The program was developed with the intent to evaluate information supporting compliance demonstrations of post-closure performance objectives for individual protection and groundwater protection and considered pre-closure aspects of repository performance.

Specifically, the Yucca Mountain performance confirmation program was developed to:

- Provide baseline information and analysis of that information on parameters and natural processes pertaining to the geologic setting that may be changed by site characterization, construction, or operational activities.
- Monitor engineered systems and components intended to operate as barriers after permanent closure to ensure that they function as assumed in the performance assessment.

- Monitor and analyze changes from baseline conditions that could affect repository design or performance.
- Compare measurements and observations with design bases and assumptions to identify significant differences that can be used by performance assessment to evaluate the significance of these differences to repository performance.
- Provide information for determining if modifications to the design or construction methods are warranted, consistent with design control processes to ensure proper safety evaluation and configuration management of necessary changes.
- Report significant differences between expected results and monitoring and testing information to the federal regulator, along with an evaluation of the effect of those differences on repository design or performance. Such evaluations potentially included recommended changes to construction methods, design, or performance analysis approaches.
- Confirm the bases relied upon for retrieval of waste.
- Provide information to update performance assessment prior to permanent closure.

The guiding principles above provided a feedback mechanism between the overall monitoring program and the performance assessment used in the safety case for the facility. Twenty monitoring activities were identified for Yucca Mountain performance confirmation using the guiding principles above. Some were selected as being most relevant to confirming pre-closure and post-closure performance, based on existing technical information and total system performance assessment results. Others were chosen to meet specific regulatory requirements. The twenty monitoring activities envisioned to support performance confirmation were:

1) Precipitation Monitoring
2) Seepage Monitoring
3) Subsurface water and rock testing
4) Unsaturated zone testing
5) Saturated zone monitoring
6) Saturated zone fault testing
7) Saturated zone alluvium testing
8) Drift Inspection
9) Thermally accelerated drift near-field monitoring
10) Dust buildup monitoring
11) Subsurface mapping
12) Thermally accelerated drift in-drift environment modeling
13) Seismicity monitoring

14) Construction effect monitoring

15) Thermally accelerated drift thermal-mechanical modeling

16) Seal and backfill testing

17) Waste package monitoring

18) Corrosion Testing

19) Corrosion testing of thermally accelerated drift samples

20) Waste form testing

Detailed descriptions of these performance confirmation monitoring activities can be found in [3].

5. – Conclusion

Compliance monitoring is fundamentally necessary to confirm adequacy of assumptions, models, and parameters used to demonstrate performance of a given site and repository. It provides a means of ensuring that data, parameters, and models used to represent the disposal system remain valid as the site matures. Performance assessment provides a quantified demonstration of repository regulatory compliance with quantified uncertainty. A FEPs analysis guides modeling of the repository in the performance assessment. As the facility matures, new information may lead to a re-assessment and adjustment of parameters, models, etc. captured in the performance assessment. A compliance monitoring program ensures that models, parameters, and assumptions are appropriately updated in light of new information. Compliance monitoring is an essential and ongoing component of the U.S. WIPP compliance recertification application process. It was also an essential component of the Yucca Mountain license application.

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REFERENCES

[1] Hansen F. D., Repository Performance Confirmation (2011) Sandia National Laboratories, Albuquerque, NM. SAND2011-6277.

[2] U.S. Department of Energy, Yucca Mountain Repository License Application Safety Analysis Report, Chapt. 2: Repository Safety after Permanent Closure (2008) Las Vegas, NV. DOE/RW-0573, Rev. 0.

[3] U.S. Department of Energy, Yucca Mountain Repository License Application Safety Analysis Report, Chapt. 4: Performance Confirmation Program (2008) Las Vegas, NV. DOE/RW-0573, Rev. 0.

[4] U.S. Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2019 for the Waste Isolation Pilot Plant: Appendix DATA-2019 Monitoring Data and Reports (2019) Carlsbad, NM. DOE/WIPP-19-3609, Rev. 0.

[5] U.S. Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2019 for the Waste Isolation Pilot Plant: Appendix MON-2019 WIPP Monitoring Programs (2019) Carlsbad, NM. DOE/WIPP-19-3609, Rev. 0.
[6] U.S. Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2019 for the Waste Isolation Pilot Plant: Appendix PA-2019 Performance Assessment (2019) Carlsbad, NM. DOE/WIPP-19-3609, Rev. 0.
[7] U.S. Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2019 for the Waste Isolation Pilot Plant: Scope of Performance Assessment (40 CFR 194.32) (2019) Carlsbad, NM. DOE/WIPP-19-3609, Rev. 0.