REGULATORY PERSPECTIVES ON CLIMATE CHANGE AND ADAPTATION FOR GEOLOGIC DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE

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ABSTRACT

Increasing emissions of carbon dioxide and other greenhouse gases into the atmosphere from the burning of fossil fuels have contributed to global atmospheric warming. Based on current projections, additional warming is expected to occur in the future, leading to further melting of polar ice sheets, rising sea levels, and changes in global and regional weather patterns. Climate experts worldwide generally agree that, even with the most rigorous emissions reductions, climate will continue to change due to the anthropogenic greenhouse gas emissions. This report highlights future scenarios and likely impacts of climate change on potential geologic repositories in the United States over two time periods: the preclosure, operational timeframe and the postclosure, waste isolation performance timeframe. Climate change during the preclosure period is expected to be influenced mainly by the current regime of anthropogenic greenhouse gas emissions, subsequently returning to the natural, glacial–interglacial cycles likely to dominate the later portions of the postclosure period. Licensing reviews for potential geologic repositories could consider the increased vulnerability during the preclosure period to flooding and other weather-induced damages, and disruption of support utilities that could increase the potential for accidents and operational failures. Potential impacts during the postclosure period would be driven mainly by infiltration and deep percolation, sea-level changes, and glaciation, which may lead to changes in subsurface mechanical, hydrologic, and chemical properties and processes. Given these potential future impacts to safety and performance of geologic repositories, key considerations for climate adaptation in nuclear facility designs and plans are identified in terms of infrastructure resilience and barrier robustness. Several climatic factors considered for geologic disposal include (i) a warming (transient) climate over the period of operation of facilities; (ii) a change in the intensity and frequency of extreme weather events; (iii) responses to global climate change that may vary by region across the country; (iv) a potential extension of the duration of the current interglacial period due to greenhouse gas emissions, followed by a return of the influences of the Milankovitch cycles as the dominant drivers of climate change.

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1 INTRODUCTION

This report primarily focuses on the regulatory consideration of global warming and its associated impacts on regional climate change. The majority of the scientific community over the past 5 years has reached a consensus that the Earth is warming primarily as a result of emissions of carbon dioxide and other greenhouse gases from human activities (IPCC, 2007a; Karl, et al., 2009). Worldwide impacts of global warming include changing weather patterns, melting ice sheets, rising sea levels, and coastal land erosion, which already are affecting natural and built systems. Impacts from climate change can be diminished by substantially reducing the amount of greenhouse gases released into the atmosphere, thereby mitigating the primary causes of climate change. Even with these reductions, however, global warming still is expected to occur (IPCC, 2007c; Van Vuuren, et al., 2008). Concurrent with the scientific community's consensus on global warming is an improving capability to delineate regional variations in weather and climate associated with global warming.

Global warming, and its continued evolution on short time scales, may have potential implications for U.S. Nuclear Regulatory Commission (NRC) regulatory activities for geologic disposal. With climate change occurring over the operational period of facilities, evolving weather and climatic inputs can be considered in assessments of disposal facility designs and plans. Aspects of both climate and weather may impact assessments; climate is taken as a spatial and temporal average of weather conditions or events. Climatic responses to global warming vary with the region. Recent improvements in climate and weather modeling help to delineate scenarios for all regions of the United States. For longer timeframes, such as the postclosure period, safety assessments have used climate change scenarios based on the Milankovitch cycles, as supported by paleoclimatic data. The term "natural climate cycles," as used in this report, includes orbital geometry-based climate cycles (Milankovitch cycles), rather than the more general meaning that would also include solar output variation and volcanic eruptions that perturb greenhouse gas and aerosol levels. Internal climate processes, such as the influence of changing atmospheric and oceanic currents, also influence climate change, though the contribution of some of these processes is not well constrained. Incorporating anthropogenically influenced global warming into climate scenarios for postclosure assessments of geologic disposal may (i) change the flux and chemistry of water reaching a repository for the initial hundreds to thousands of years and (ii) delay the onset of the next glacial period.

To be prepared for analyzing and reviewing safety cases and license applications for these facilities, NRC staff needs to stay abreast of the scientific community's understanding of the current trend of climate change and its potential impacts. Section 2 presents an overview of observed global climatic changes and projected potential future climate changes for regions of the United States. Also in Section 2, potential impacts of future climate scenarios to geologic disposal systems are discussed. Section 3 addresses potential regulatory insights incorporating current predictions of climate change.

2 FUTURE SCENARIOS AND POTENTIAL IMPACTS

This section considers future climate scenarios and potential impacts over two periods: the short-term, operational timeframe and the long-term, waste isolation performance timeframe. Assessment of potential climate impacts to the repository would be determined by the locations and types of activities conducted during these timeframes.

Ongoing and future global warming climate scenarios described in Section 2.1 reflect scientific consensus of two extensive panel projects: an international panel on the global climate, and a national panel organized within the U.S. federal government and focused on regional predictions. Potential impacts discussed in Section 2.2 are identified by associating projected climate phenomena with facilities, infrastructure, and operational activities anticipated at a potential repository site, and the expected future state of the repository after final closure. For both timeframes, Section 2.2 highlights potential impacts of climate change on a geologic repository that may be sited in different regions of the country. However, this evaluation does not consider the likelihood or feasibility of actually siting a geologic repository in any one of these regions. Potential impacts discussed in Section 2.2 do not consider implementation of adaptation measures by nuclear facility operators or potential licensees to adjust designs, planning, and operations to the projected future climate scenarios. Factoring in adaptation measures is addressed in the regulatory insights discussed in Section 3.

2.1 Future Climate Scenarios

Advances in climate modeling over the past decade demonstrated the linkage between greenhouse gases and observations of global warming (IPCC, 2007b). Nesting of the global models with smaller scale models has improved understanding of regional climate changes and their connection to global climate changes (Karl, et al., 2009). The reliability of these climate models, when including the input of greenhouse gas emissions, has contributed to the scientific community's consensus of a primary anthropogenic influence on global warming. Greenhouse gases, which include carbon dioxide, methane, nitrous oxide, halocarbons, ozone, and water vapor, reflect longwave radiation from the Earth's surface, thus trapping the heat. The warming influence of carbon dioxide emissions is more than the cumulative effect of all other greenhouse gases, thus leading to the common focus on carbon dioxide levels. Paleoclimatic data support the link between high levels of greenhouse gases in the atmosphere and warmer global climate conditions. Current and projected greenhouse gas levels haven't occurred in the past 650,000 years (IPCC, 2007b). Paleoclimatic records also support the apparent fast rate of global warming currently occurring.

2.1.1 Global Projections

The most recent, comprehensive resource for global climate change issues is the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In separate report volumes, three IPCC working groups examined the science, vulnerabilities and impacts, and mitigation of future climate change attributable to both natural variability and human activity (IPCC, 2007b,c,d). Increasing emissions of carbon dioxide, methane, and other greenhouse gases into the atmosphere from the burning of fossil fuels are primary contributors to global atmospheric warming. From pre-Industrial-Revolution-era levels of about 280 parts per million by volume (ppm), when carbon dioxide released by natural processes almost exactly balanced the amount absorbed by plants and other "sinks" on Earth's surface, the concentration of carbon dioxide in the atmosphere has risen to approximately 390 ppm today (NAS, 2008). Instrumental records, data reconstructions, and state-of-the-art climate model simulations have demonstrated that trends in global atmospheric warming in the last few decades of the 20th century cannot be explained without including human-related increases in greenhouse gases (IPCC, 2007b).

Atmospheric radiative forcings imposed by greenhouse gas emissions have contributed to surface temperatures rising by an average of 0.8 °C [1.4 °F] in the past 100 years. Climate projections anticipate an additional warming of 1.1–6.4 °C [2.0–11.5 °F] during the 21st century, with land areas and higher latitudes experiencing the greatest warming (NAS, 2010). Global atmospheric warming is closely associated with thermal expansion of the oceans and melting of glaciers and polar ice sheets, all of which contribute to rising sea levels. The average rate of sea-level rise during the 20th century was 0.12–0.22 cm/yr [0.05–0.09 in/yr] (IPCC, 2007b). Global sea levels are projected to rise by an average of 0.18–0.59 m [0.6–1.9 ft] by the year 2100 solely due to thermal expansion of the oceans. This projection excludes the effects of climate-carbon cycle feedbacks and contributions from melting ice sheets, glaciers, and ice caps. Because thermal expansion of the oceans is projected to continue for many centuries after greenhouse gas concentrations may have stabilized at or above present levels, long-term sea-level rise may exceed 4 m [13 ft]. However, the magnitude of sea-level rise observed for a given coastline also depends on changes in land surface elevation, or isostatic changes; a subsiding coastal land mass will experience a greater relative sea-level rise than a coastline undergoing uplift.

Other processes associated with global warming include increases in the frequency of intense, heavy precipitation; tropical cyclone activity; and intense heat waves. Although the severity of these extreme weather events would vary among the continents and regions of the world, their altered frequencies, combined with sea-level rise, are expected to produce adverse impacts on natural and built systems. The most significant impacts would include higher incidences of wildfires; early snowmelt and contraction of snow cover area; increases in thaw depth over most permafrost regions; and more areas exposed to droughts, flooding, coastal land erosion, and associated infrastructure damage. Individually and collectively, these potential impacts indicate risks to a broad range of natural and built systems.

2.1.2 National Issues and Regional Changes

Projections of future climates in the United States are derived mainly from studies conducted under the U.S. Global Change Research Program (USGCRP), formerly called the U.S. Climate Change Science Program. USGCRP is a multiagency program established to coordinate and integrate federal research on changes in the global environment and their implications for society. USGCRP's most recent comprehensive study, the second National Climate Assessment, projected future climate changes and evaluated potential impacts to geographical regions, and societal and environmental sectors nationwide (Karl, et al., 2009). This national assessment was based on 21 Synthesis and Assessment Products that addressed key scientific issues relevant to national climate policy (NSTC, 2008). Projections of future climate change considered low and high greenhouse gas emissions scenarios derived from IPCC's Special Report on Emissions Scenarios (IPCC, 2000); however, these scenarios did not assume that all sectors of industry and society would adopt climate change mitigation and adaptation policies. Additional data inputs included government statistics and peer-reviewed research results from the transportation and energy sectors. Overall, the assessment concluded that lower emissions result in less climate change and thus reduced impacts.

Table 2-1 summarizes climate changes projected to occur over the 21st century for eight regions delineated in USGCRP's second National Climate Assessment. The immediate impacts of the

Table 2-1. Projected Occurrence and Direction of Changes in Weather-, Climate-, and Water-Related Conditions Across Regions of the United States*

Phenomenon	Regions†							
	NE	SE	MW	GP	SW	NW	AK	Coasts
Average annual temperature	▲	▲	▲	▲	▲	▲	▲	▲
Number of hot days	▲	▲	▲	▲				
‡Earlier spring snowmelt	✓					✓		
Length of ice-free /frost-free and summer growing seasons	▲		▲				▲	
‡Sea-level rise	✓	✓				✓		✓
Rainfall frequency & intensity	▲		▲	▲	▲			
Precipitation (Annual)	▲		▲				▲	
Precipitation (Winter)			▲			▲		
Precipitation (Spring)			▲					
Precipitation (Summer)						▼		
Drought frequency, duration, and intensity	▲	▲		▲	▲		▲	
Risk of flooding	▲		▲		▲	▲		▲
‡More precipitation occurring as rain than as snow	✓					✓		
‡Drier overall				✓ (South)	✓		✓	
‡Wetter overall				✓ (North)				
Ice coverage							▼	
Hurricane intensity		▲						▲
Coastal storm surge intensity	▲	▲				▲	▲	▲
Lake water levels and areas			▼				▼	
‡Permafrost thawing							✓	

*Direction of change: ▲(increase); ▼(decrease)

†Regions defined by USGCRP (Karl, T.R., J.M. Melillo, and T.C. Peterson, eds. "Global Climate Change Impacts in the United States." New York City, New York: Cambridge University Press. 2009). The Pacific and Caribbean islands are not included in this table, because of their relatively small areal extent.

[NE] Northeast – ME, NH, VT, MA, CT, RI, NY, PA, WV, MD, DE, NJ
[SE] Southeast – VA, KY, NC, TN, SC, GA, AL, MS, FL, AR, LA
[MW] Midwest – MN, IA, MO, WI, IL, MI, IN, OH
[GP] Great Plains – MT, WY, ND, SD, NE, KS, OK, TX
[SW] Southwest – CA, NV, UT, CO, AZ, NM
[NW] Northwest – WA, OR, ID
[AK] Alaska
Coasts–ocean coasts of the continental United States

‡Climate change phenomenon indicated by occurrence only (✓)

warming of Earth's atmosphere are described in terms of various phenomena characterizing the occurrence and direction of changes in climate-, weather-, and water-related conditions across the nation. These phenomena include increasing temperature, changes to precipitation amounts and patterns, sea-level rise, and ice cover. As a direct consequence of global warming, every region of the United States will be expected to experience increased air temperatures during the 21st century. However, the occurrence and magnitude of changes in other phenomena would vary spatially, across and within regions, and seasonally.

2.1.3 Climatic Factors Associated with Global Warming

Several climatic factors nationwide can be linked to global warming such that (i) the climate is changing on a decadal to centennial scale; (ii) the frequency and magnitude of extreme events are changing under global warming; (iii) changes to regional climate predictions vary across the country; and (iv) the duration of influence of greenhouse gases on climate, though uncertain, may delay the return to climate change dominated by the Milankovitch cycles. The potential impacts of these changes in climate on a repository system are described in Section 2.2, and their potential influence on regulatory considerations is discussed in Section 3. Comments on uncertainty for each of these four climatic factors follow.

In the near term (decades), anthropogenic influences on climate are readily swamping the slow cooling trend natural orbital geometry-based (i.e., Milankovitch) cycles predict (IPCC, 2007b). The scientific community acknowledges observed changes in climate and the expectation of continued climate change over the near term (IPCC, 2007b; Karl, et al., 2009). Past records of fast (millennial scale) global warming and large releases of carbon dioxide, referred to as hypothermal events (NAS, 2011), had reported temperature increases of 5 °C [41 °F] in tropical regions and 9 °C [48 °F] at the poles. Uncertainty in the extent of the global warming, and the impact on the hydroclimate, is closely tied to uncertainty in greenhouse gas emission levels and their residence period in the atmosphere–ocean system.

Weather events, particularly extreme events, are already considered in safety analyses. There are indications, however, that the distribution of weather events will likely shift to slightly different recurrences, and the magnitude of phenomena may also shift to more extremes in the distribution (Karl, et al., 2009). Note that changes to distributions of weather events may not necessarily be reflected in changes to climates; climate is a spatial and temporal averaging of weather conditions. Also, the uncertainty of the distribution of future weather events, which may not be adequately captured by the characteristics of past events, is exacerbated by difficulties in identifying changes in extreme tails of distributions based on short records as the climate is evolving.

Regional responses to global warming more directly factor in the internal dynamics of climate compared to the larger scale global models. Examples of the internal dynamics that may affect regional climate responses are a shift in the jet stream over the North American continent or a reduction in the oceanic currents that could alter regional and global heat transfer. Regional climate change predictions, more so than global climate predictions, are a recent advance of the climate modeling community. Regional models are nested with global climate models, and thus share and perhaps enhance uncertainties related to lack of knowledge on internal climate-driving processes. With the continued emphasis by USGCRP (2011), more reliable predictions of regional climates can be expected in the future.

Estimates of the duration of anthropogenic influence on climate are not well constrained, ranging from thousands to tens of thousands of years (NAS, 2011), or 5,000 to 50,000 years (IPCC, 2007b). Due to greenhouse gas emissions, the current interglacial period is projected to be extended (i.e., a delay is expected in the onset of the next global glacial period as analysis of the Milankovitch cycles would have predicted without elevated greenhouse gas levels). Based on interpretations of the glacial onsets and Milankovitch cycles, the Earth should be in a cooling period, with the next full glacial period occurring in 30,000 years, and a stadial (cool period within an interglacial period) becoming more well developed in the next 10,000 years (IPCC, 2007b). Two methods have been used to assess the duration of anthropogenic influence on climate: (i) analysis of paleodata indicative of high greenhouse gas levels with concordant information on climate change and (ii) climate models that incorporate the carbon cycle. Records of past rapid global warming events with increases in carbon dioxide levels comparable to current projections suggest that global warming may persist for 20,000 to 40,000 years. The anthropogenic perturbation of greenhouse gas levels may persist for more than 100,00 years based on carbon cycle models if the total amount of carbon emitted is large (NAS, 2011). However, it is not clear what greenhouse gas levels are needed to drive climate over the natural cycle. As the influence of greenhouse gases dissipates, over the longer time scales, the Milankovitch cycle will begin to dominate the global climate. In the Eocene, without the influence of anthropogenic greenhouse gases, the duration of interglacials has varied (IPCC, 2007b) in two patterns. From 2.5 to 1 mya, full glacial cycles averaged approximately 41,000 years. For the past 800,000 years, full glacial cycles averaged approximately 100,000 years.

2.2 Potential Impacts of Climate Change

This section considers potential impacts of climate change over two periods: the short-term, operational timeframe and the long-term, waste isolation performance timeframe. Assessment of potential climate impacts to the repository would be determined by the locations and types of activities conducted during these timeframes. These potential impacts do not consider implementation of adaptation measures by nuclear facility operators or potential licensees (e.g., changes in design, construction, or operations) to adjust to projected future climate scenarios.

Climate change reflected in anthropogenic-related global warming has the potential to affect repository activities and conditions during the preclosure and postclosure periods. During construction and prior to final closure of a geologic waste repository, the surface operational facilities (e.g., aging, waste handling, and packaging facilities) and the utilities that support these facilities could be exposed to an evolving set of climate change phenomena. After final closure, climate change at the Earth's surface may affect repository conditions, though the perturbations may be dampened at the depth of the repository to an extent that depends on the properties of the overlying rock formations. Potential impacts are identified by associating projected climate phenomena with facilities, infrastructure, and operational activities anticipated at the potential repository site, and the expected future state of the repository after final closure.

2.2.1 Operational Timeframe

The expected activities during the operational timeframe include construction of the repository surface and subsurface infrastructure; receiving, staging, aging, packaging, and emplacing of the waste; dismantling and decommissioning of the surface facilities; and final closure of the repository. The impacts of climate change throughout the operational period could, for example, require consideration of heavy storm runoff, flooding, and other extreme weather events that may alter the characteristics of the repository site or disrupt utilities (for example, power and water), all of which may increase the risk of accidents during repository operations.

USGCRP's second National Climate Assessment evaluated regional climate change impacts to seven broad sectors: water resources, energy supply and use, transportation, agriculture, ecosystems, human health, and society (Karl, et al., 2009). Of these sectors, water resources, energy supply and use, and transportation are most closely related to construction and operation of a potential geologic disposal facility. Potential impacts from climate change will vary by region depending on the projected occurrence and direction of changes in climatic and hydrologic processes, as indicated in Table 2-1. As the following summaries indicate, many of these impacts are interdependent.

During repository operations, raw water supply would be needed to support various cooling systems (such as fuel handling pools and air conditioning), fire suppression systems, and human consumption. Regions projected to receive less precipitation combined with increased evaporation would generate less runoff and groundwater recharge. These conditions could affect the selection or plan for obtaining the water supply to support repository site operations. For example, in the Great Plains region, projected increases in precipitation are not likely to be sufficient to offset decreasing water availability due to increasing evaporation caused by rising temperatures, or for many parts of the Southeast and Southwest where water shortages may be expected due to projected drought conditions related to the current trend of global warming (Karl, et al., 2009).

The largest increases in precipitation intensity are projected to occur in regions with the highest increases in average annual precipitation, notably the Northeast and Midwest (Karl, et al., 2009). Heavy, intense downpours would increase the frequency and potential severity of flooding events. If more winter and spring precipitation occurs as rain than snow, there would be increased risks of sediment and debris flows, landslides, and slope failures due to additional runoff and infiltration, which may result in structural damage to surface facilities, road closures, and costly repairs and reconstruction. Coastal regions are likely to experience rising sea levels that could inundate surface infrastructure and utilities. In addition, impacts from wave damage and storm surges are projected to increase.

Electrical power, power infrastructure, and the nation’s transportation system may all be affected by the impacts of global warming. Generally, it is reasonable to assume that societal adaptation measures will be sufficient to maintain electrical power, power infrastructure, and the nation’s transportation at the same functional levels that exist today. NRC should be cognizant of the relation between climate change and changes to the following three outside systems:

- Virtually every proposed repository operation would run on electrical power during the operational period. Projected temperature increases due to global warming are very likely to increase peak demand for electricity in most regions (Karl, et al., 2009). Moreover, this energy demand is inextricably linked to water consumption. For example, as discussed earlier, higher temperatures in the Southwest would increase water demand, while reduced precipitation and increased evaporation would reduce water availability. Under these conditions, additional energy would be required to pump water from deeper aquifers or transport water from more distant sources, potentially raising the cost of repository operations.

- Power plants, oil refineries, transmission and distribution facilities, and other electrical energy infrastructure located in coastal regions could be at risk of damage from climate change phenomena (Karl, et al., 2009). The East Coast and Gulf Coast are particularly vulnerable to projected sea-level rise because the land surface is relatively flat and sinking in many places. The Gulf Coast is also home to the nation’s oil and gas industry, with a large concentration of offshore drilling rigs, refineries, pipelines, and a significant proportion of imports transported through this region. Sea-level rise, combined with land subsidence and intense coastal storm activity, would render existing and potential future energy infrastructure prone to frequent inundation or damage. For other inland production and delivery systems, hurricanes and other extreme storm events may damage transformer stations and transmission lines, causing potentially costly interruptions to electrical power supply.

- Climate change poses risks of damage and disruptions to the nation's transportation system, which in turn affects many sectors of commerce and industry. Geologic repository facilities are expected to rely heavily on the nationwide network of roads, railways, and land-based transportation infrastructure for deliveries to the site. The projected increases in frequency and intensity of hurricanes and rainstorms would lead to rivers flooding more often with the potential to inundate and erode nearby railway and roadway embankments. Also, transportation through coastal regions would be significantly challenged by sea-level rise and increased land erosion in these areas. In particular, much of the Gulf Coast's transportation infrastructure, which exists on low-lying, subsiding land, faces the risk of extended service disruptions due to sea-level rise, high waves, and coastal land erosion.

If no societal adaptation measures were taken, the nation's electrical power grid, energy transmission infracture, and transportation system could be adversely impacted by future climate changes associated with greenhouse gas emissions and global warming. NRC expects that societal adaptation measures will maintain these systems at the same functional levels that exist today. NRC should remain cognizant of changes that may negatively affect the safety case and address concerns as information becomes available anytime during the licensing and operation periods.

2.2.2 Waste Isolation Performance Timeframe

Unlike the operational timeframe, a geologic repository would be in a passive state during the waste isolation performance timeframe, with few or no surface facilities. This period represents the postclosure timeframe during which the waste would be isolated from humans and the environment by encapsulation in engineered containers emplaced in deep rock formations. Over this period, Earth's climate is likely to evolve both naturally and because of radiative forcing attributable to anthropogenic greenhouse gas emissions. Potential impacts of climate change on the geologic repository would depend on the extent that climate-related ground surface phenomena would penetrate the overlying geologic formations and the engineered waste containment features. Climate change would likely affect sea-level changes, infiltration and deep percolation, and glaciation.

Current trends in global warming, which are closely associated with thermal expansion of the oceans and melting of polar ice sheets, are likely to result in rising sea levels. Increases in local water depth due to sea-level rise would amplify the height of coastal waves generated from the stronger winds expected to accompany more intense storms (Hooker, et al., 2008). As a result, sea-level rise could induce land erosion during storms in coastal regions. The rate of erosion would depend on the rate of relative sea-level rise, local topography, rock type, and coastline orientation relative to the predominant wave direction. Erosion due to global warming may be reduced at inland locations, away from the influence of rising sea levels.

During the early periods of the waste isolation timeframe, repository performance could be influenced by current trends in global warming. Beyond these periods, current research on the evolution of greenhouse gas emissions scenarios does not support reliable projections of global warming and climatic conditions. Alternative hypotheses supporting the future evolution of Earth's climate are available based on past evidence indicating the existence of a natural cycle (the Milankovitch cycle), which in the recent past is in an approximately 100,000-year cycle of colder, glacial climate followed by warmer, interglacial climate (IPCC, 2007b; Karl, et al., 2009; SKB, 2007; Walter, 2005). The following discussion of potential climate change impacts associated with infiltration, deep percolation, and glaciation during the waste isolation performance timeframe assumes this natural cycle.

The Earth is presently in an interglacial climatic phase. Consensus within the climate science community indicates that global warming induced by anthropogenic greenhouse gas emissions may delay, but is not likely to prevent, the transition to the next glacial climatic period. As the Earth transitions from the present interglacial phase into the next glacial climatic period, many regions of the United States are expected to experience a cooler, wetter climate, which would mean higher precipitation and reduced evaporation (NAS, 1995). As a result, rates of infiltration and aquifer recharge are likely to increase, which might raise the groundwater table, thereby increasing the rate of water movement in the saturated zone. Under these flow conditions, more water would reach the repository and possibly alter the chemical properties of water contacting the waste containers and the waste form itself, which could increase the rates of radionuclide release into the groundwater. Furthermore, the geochemical transformation and transport of released radionuclides would be affected by interactions between the increased groundwater advective flow and geochemical and hydrodynamic processes, such as sorption, mineral precipitation, dissolution, matrix diffusion, and dispersive mixing. These processes and interactions are already included in repository performance assessment models currently in use worldwide. However, because of lack of complete knowledge of the future evolution of these interactions and spatial heterogeneity of geologic conditions in general, the impacts of climate change on radionuclide travel times and concentrations in groundwater are subject to uncertainty. Such uncertainties could be considered to enhance development of risk insights from repository performance assessment model results.

During the waste isolation performance timeframe, the global climate regime is likely to pass through several glacial–interglacial climatic cycles (NAS, 1995). There is much uncertainty about how long global warming would extend the current interglacial climatic period. Models assuming various levels of greenhouse gas emissions indicate the next glacial maximum may not occur for the next 50,000 to 500,000 years (Loutre and Berger, 2000; Texier, et al., 2003; Archer and Ganopolski, 2005). Regardless of when the next glacial maximum might occur, many parts of North America and Europe would be expected to experience a sequence of temperate, permafrost, and glacial climatic conditions and then return back to temperate conditions (SKB, 2007). This cycle of conditions may cause changes in rock stresses and the groundwater flow regime mainly due to the loading and unloading of thick ice sheets over land surfaces (McMurry, et al., 2003). Also, repository performance may be modified by changes in the subsurface mechanical, hydrologic, and chemical properties and processes. As a result, potential impacts may include development and rejuvenation of fractures; regional changes in groundwater flow patterns; and modification of redox conditions by introduction of low salinity, possibly oxidizing water from ice melting.

The foregoing discussions indicate the key issues for addressing anthropogenic-induced climate change are determining what climate change phenomena are possible and describing how these phenomena may affect long-term repository safety. Advances in climate modeling over the past decade have improved regional climate projections and their connection to global climate changes. Using climate models that incorporate anthropogenic influences to supplement climate projections, which are currently based on paleoclimatic records and the Milankovitch cycle, may contribute to reducing the uncertainty of future projections of climatic phenomena. System performance assessment has proved effective in synthesizing these uncertainties and obtaining insights into the potential vulnerability of geologic repositories to impacts from climate change.

3 REGULATORY INSIGHTS FOR CLIMATE ADAPTATION

In licensing geologic waste repository facilities, NRC staff must ensure that applicants' proposed facility designs and operational safety measures provide adequate protection for the public and the environment. Incorporating climate adaptation into these evaluations could involve reviewing projected changes in intensity and frequency of extreme weather events, droughts, sea-level rise, and changes in related parameter distributions. For both preclosure and postclosure, the primary regulatory consideration for global warming is the development of future climate scenarios to use for performance assessments. Features of future climate scenarios include the climate domains, sequences, timings, and durations that can be used to examine the performance of the repository system.

Most of the society's current efforts to address future climate change have focused on mitigation through reduction of greenhouse gas emissions. However, climate experts worldwide agree that, even with the most rigorous emissions reductions, adaptation measures across all sectors of industry and society will be needed to adjust to already changing climatic conditions (IPCC, 2007c; Van Vuuren, et al., 2008). Historically, societies have managed the impacts of weather events and climate change. Societal adaptations, as used in IPCC (2007c) for example, refer to activities outside the control of NRC or the licensee (e.g., state governments and non-nuclear industries). Whereas NRC should be cognizant of societal mitigation and adaptation measures, identification of any specific future measures would necessarily be considered speculative. It is reasonable to assume that societal adaptation measures would be sufficient to maintain the key infrastructure systems (e.g., electrical and water distribution and transportation) of the United States to ensure the same functional levels as exist today.

Analogous to societal adaptation measures, nuclear facility operators and potential licensees can take measures to adapt to global warming and the associated change in climatic factors. In this context, climate adaptation refers to a licensee's response to evolving climatic conditions. Implementing effective adaptation measures would build resilience into systems and reduce their vulnerability to climate change impacts. Examples of these measures include integrating climate change considerations into facility design standards and revising construction codes accordingly, siting or relocating critical infrastructure to low- or no-impact areas, and erecting physical barriers to protect vulnerable systems from exposure to climate change phenomena. NRC would consider the adequacy of proposed climate adaptation measures by nuclear facility operators and potential licensees consistent with its regulatory authority.

Section 3.1 identifies regulatory considerations pertaining to future climate scenarios that incorporate global warming, and adaptation of geologic disposal systems to potential impacts from that climate change. Section 3.2 describes relevant activities and guidance in several other NRC offices pertaining to greenhouse gases and climate change.

3.1 Regulatory Considerations for Geologic Disposal Systems

As discussed in Section 2, climate change may affect geologic repositories in the short term, during the operational (or preclosure) period and the long term, and during the waste isolation (or postclosure) period. Climate-related review areas for a potential geologic repository license application should be prioritized based on proximity of the proposed repository site to probable regions of exposure to significant climate change phenomena. Geographical location would indicate the climate phenomena that might influence short- and long-term evolution of the repository, and hence the range of applicable adaptation measures by the nuclear facility operator or potential licensee. For example, a repository located far inland from the coastline is not likely to be threatened by sea-level rise, whereas if the repository is located in an arctic region, long-term impacts from glaciation could be the primary determinant of climate adaptation measures. NRC staff guidance could consider climatic attributes of geographical regions across the nation.

Review of a license application for a potential geologic disposal facility would involve both safety and environmental aspects. Consistent with the NRC mission to protect public health and safety, and the environment, these aspects of a potential license application review both involve public and occupational safety. Using projections of future climate scenarios and potential impacts, such as those described in Section 2, the safety evaluation, as appropriate, could examine possible climate change impacts that could affect either operational or postclosure performance. In addition to addressing possible climate change impacts to a potential geologic disposal facility, the environmental review would evaluate potential cumulative impacts on environmental resources. USGCRP's second National Climate Assessment evaluated regional climate change impacts under seven broad sectors: water resources, energy supply and use, transportation, agriculture, ecosystems, human health, and society (Karl, et al., 2009). These sectors align with the review areas addressed under the National Environmental Policy Act (NEPA) when examining impacts associated with proposed federal actions. In accordance with NEPA, NRC has incorporated these review areas into staff guidance in NUREG–1748 (NRC, 2003).

The NRC regulatory framework needs to continue to be informed by up-to-date developments in global and national climate change research programs. IPCC and USGCRP should be the primary resources for projections of global and regional climate change. Some aspects of the IPCC program of activities leading to the Fifth Assessment Report, due in the 2013–2014 timeframe, align with the NRC risk-informed and performance-based regulatory program structure. To achieve better integration among the three IPCC working groups, several cross-cutting issues have been incorporated into planning and scoping of climate evaluations for the Fifth Assessment Report (IPCC, 2011). These include addressing increasing concerns for the impacts of low-probability, high-consequence events, and interests in risk assessment and risk management as viable approaches to adaptation planning. Because IPCC recognizes that these issues are understood differently across its working groups and component disciplines, guidance documents are being developed for consistent use of climate scenarios and treatment of uncertainties and risks. As NRC develops guidance for incorporating climate change into licensing application reviews for potential geologic repositories, NRC staff should remain well informed of the methodologies IPCC and other global and national climate research programs are considering for addressing the uncertainties and risks associated with climate adaptation.

In the United States, USGCRP plans to adopt a regional approach to the third National Climate Assessment, due in 2013 (USGCRP, 2011). Presently, through the Regional Climate Centers (RCC) program, the National Oceanic and Atmospheric Administration (NOAA) is engaging federal and state agencies with academic and research institutions nationwide in timely production and delivery of useful climate data, information, and knowledge for decision makers and other users at the local, state, regional, and national levels (NOAA, 2011). Climate data and regional projections from the USGCRP and RCC programs may be used to support NRC rulemaking and licensing reviews for potential geologic waste disposal systems.

In reviewing a potential geologic repository license application, the safety evaluation involves examining the applicant's climate projections for potential impacts to the repository operations and designs. To support this evaluation, understanding the regional distributions and trends that describe extreme weather events, sea-level rise, and glaciation provides a more comprehensive linkage between climate projections and proposed adaptation strategies. While IPCC and USGCRP advance regional climate research programs, NRC staff should continue to monitor the outcomes of these studies for insights that could support site-specific safety evaluations for potential geologic repositories.

3.2 Other NRC Activities Related to Greenhouse Gases Emission and Climate Change

NRC considered the effects of global warming and changing climate in the environmental impact statement (EIS) guidance for evaluation of new reactors (NRC, 2010). The basis for climate projections was the IPCC (IPCC, 2007a,b) and USGRP (Karl, et al., 2009) scientific panel reports. Explicit in the EIS guidance is the premise that climate over the period of operation of facilities should not be considered constant, but rather changing in accordance with projections that consider the influence of greenhouse gas emissions.

The NRC Office of New Reactors (NRO) updated its EIS guidance in NUREG–1555 to address climate change and greenhouse gas emissions (NRC, 2010). This EIS supplemental guidance document, and the updated guidance for staff (NRC, 2011a), reference both the CEQ (2010) draft recommendations for addressing climate change and the relevant Commission Order CLI 09-21. The CEQ (2010) draft guidance distributed to the heads of federal agencies and departments requests that the effects of climate change and greenhouse gas emissions be considered in the NEPA context. In this guidance, the Council on Environmental Quality advised federal agencies to consider the following in scoping their NEPA analyses: (i) the greenhouse gas emissions of a proposed action and alternative actions and (ii) the relationship of climate change effects to a proposed action or alternatives. In the NRO framework, climate change and greenhouse gas emissions are treated in separate sections of the staff EIS guidance in NUREG–1555 (NRC, 2011b):

- “Climate change is to be addressed in Chapter 2 as a changing affected environment under the discussion of climate; thereafter, it is to be considered in particular resource areas (air and water resources, ecological resources, and human health areas) as part of the cumulative impacts analysis (reflecting past, present and reasonably foreseeable effects) in Chapter 7 for the proposed site and in Chapter 9 for the alternative sites.”

- “Carbon dioxide and other greenhouse gas emissions are to be considered as direct, indirect or related impacts on air quality (along with criteria pollutants) in Chapter 4 (Building Impacts), Chapter 5 (Operational Impacts), Chapter 6 (Fuel Cycle and Decommissioning), Chapter 7 (Cumulative Impacts at the Proposed Site), and Chapter 9 (Alternative Energy Sources and Cumulative Impacts at the Alternative Sites).”

The relevant part of NRO guidance for geological disposal—the portion in Chapter 2 of the EIS guidance—is that the affected environment should incorporate future climate scenarios that reflect climate change as influenced by greenhouse gas emissions. The NRO update (NRC, 2010) of NUREG–1555 indicated that the IPCC and USGRP climate projections and conclusions pertaining to the effects of greenhouse gas emissions represented reliable source information because, as stated by the U.S. Environmental Protection Agency, the climate projections were “well vetted by both by the climate change research community and the U.S. government.”

Two other NRC activities have factored in greenhouse gas emissions and impacts of global warming, albeit in a manner that should be considered examples rather than guidance. For the first activity, the NRC Office of Nuclear Reactor Regulation (NRR) considers greenhouse gas emissions and climate change in its environmental reviews, though it does not have separate guidance documents. As appropriate for the site considered in the environment review [the Seabrook facility, for example (NRC, 2011c)], NRC staff considered sea level rise, increased incidence of extreme storm events, and the cumulative impact of greenhouse gas emissions associated with the facility on global warming. For the second activity, in response to a public comment related to sea level rise due to global warming for the Waste Confidence decision (75 FR 81037, 12/23/2010), NRC maintained that (i) slow onset would allow for a response to sea level rise and (ii) storm surge would hit first, but that current regulations already dealt with floods and extreme events. For the extreme events portion of the comment, the NRC staff indicated that analyses need only account for changing event frequencies and magnitudes.

NRC staff guidance for incorporating climate change into safety and environmental reviews is an evolving topic still undergoing consideration within NRC and the larger NEPA community. The development of EIS guidance by NRO is a prominent effort among those by other NRC offices to incorporate the advances in climate projections over the past decade. Therefore, for consistency across the agency, NRC staff involved with developing regulatory insights for climate change and greenhouse gas emissions for geologic disposal systems should remain cognizant of activities within and outside the agency regarding approaches for addressing global warming.

4 CONCLUSIONS

The scientific community consensus is that climate change is already happening, and additional changes can be expected for all plausible future greenhouse gas emissions scenarios. The impacts being observed presently indicate that changes to future planning and management of natural and built systems may be needed to address changes in climate.

For safe geologic disposal of radioactive waste, climate adaptation strategies should consider processes and event sequences that could connect projected future climate phenomena with potential radiological exposures to humans and the environment. Although the magnitudes and rates of change for climate phenomena are not known, their immediate and potential long-term impacts on future geologic waste repositories can be evaluated to provide insights on performance. Therefore, within the present NRC regulatory framework, future climate scenarios that incorporate features of the current global warming climate could be developed to examine repository safety. Four aspects of global warming could be considered in the future climate scenarios: (i) the current climate is transient over the scale of preclosure operations; (ii) the frequency and intensity of extreme weather events may be changing; (iii) smaller scale climate models allow for more reliable predictions of regional climate responses to global warming; and (iv) global warming driven by greenhouse gas emissions may extend the current interglacial period, thus delaying the onset of the next glacial period.

Climate parameter distributions need to be reassessed as the global and national climate research programs publish new information on climate-related hazards and risks. The primary research and scientific consensus programs are the IPCC and the USGRP. Furthermore, uncertainties surrounding potential future impacts and needed adaptation measures should be considered in developing NRC staff guidance for licensing potential geologic repositories.

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