# New LLW Facilities Project – Stage 2

# Position Paper on Climate Change and its Impacts

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## Executive summary

E1. Owing to the long timescales for decay of some radioactivity and the high degree of containment afforded by the engineering, the environmental safety case for the proposed New LLW Facilities at Dounreay needs to consider the evolution of the facilities over thousands of years. During this time, considerable changes in climate are expected. The climate changes naturally as a result of astronomical forces, as illustrated by the many cycles of glaciation and inter-glacial periods over the last million years. Imposed on this natural change is climate change from global warming, a consequence of the emissions of greenhouse gases into the atmosphere. Global warming may cause melting of ice sheets and thermal expansion of the oceans leading to increased sea levels, which may change the coastline of Scotland through marine inundation and erosion of the land. Although the rates and magnitudes of these future changes are not known with certainty, the long-term effects of sea-level rise and coastal erosion are of concern when assessing the performance of the proposed facilities at Dounreay.

E2. This position paper presents a review of climate change, which was undertaken to bring the project up to date with the latest scientific literature, and to support the siting process and the safety assessment of the proposed facilities. The approach has been to update and re-assess the previous UKAEA position of 2006 developed by Morgan and Wilmot [1], using information from a number of recent open-file sources, including the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2007, a review of coastal evolution studies at Dounreay produced by the British Geological Survey in 2007, and the UK Climate Impacts Programme (UKCIP02).

E3. This paper contains descriptions of global climate changes, focusing on future global sea-level changes; past and future sea-level changes at Dounreay; possible impacts of waves, storm surges and tsunamis at Dounreay; coastal erosion at Dounreay; the possible impacts of sea-level rise and long-term coastal erosion at Dounreay, with a consideration of the implications for siting the proposed facilities; the climate change assumptions embraced by the Run 2 performance assessment (PA) calculations; and some Run 2 PA results to illustrate the low radiological consequences of the proposed facilities to potentially exposed groups.

E4. The main findings on future sea-level changes are:

(i) Climate change models are immature; and therefore predictions of sea-level change carry large uncertainties in magnitudes and timings. Climate change model results vary widely depending on the assumptions for future greenhouse gas emissions scenarios.

(ii) A reasonable *upper* estimate for the relative sea-level rise at Dounreay is around 12 m above Ordnance Datum, which is based on an assumption that both the Greenland Ice Sheet and the West Antarctic Ice Sheet will disappear entirely over several thousands of years.

(iii) If extended global warming were to occur, sea level could stand high for tens of thousands of years before global cooling takes place once again. Current estimates for the onset of global cooling and future large-scale re-glaciation are 50,000-100,000 years from now. Large-scale re-glaciation – as in past glacial cycles – would lead to sea level dropping to around 120 m below the present-day level at the next glacial maximum, currently thought to be about 180,000 years from now.

E5. The main findings on coastal erosion are:

(i) There is a paucity of information on current and near-past erosion rates in the Dounreay area.

(ii) It is difficult to extrapolate short-term data to the long term. The potential effects of future sea-level rise on long-term coastal erosion rates are uncertain.

(iii) A reasonable *upper* estimate of the long-term average coastal erosion rate at Dounreay is 10 mm/yr for the period when sea level remains high.

E6. The main conclusions of this study are:

(i) A siting objective for the proposed facilities, known as the “red line”, was set 100 m inland of the 20 m topographical contour [1]. The “red line” is a reasonable spatial bound for avoiding disruption by erosion or inundation of the proposed facilities for at least 10,000 years.

(ii) By around 10,000 years from now the average alpha-radioactivity level in the vaults will have declined to levels similar to background, i.e. current levels measured in soils in the vicinity of the Dounreay site.

(iii) The proposed facilities are unlikely to be inundated, except if coastal erosion were to result in exposure of the facilities in a recessed cliff-line.

(iv) If coastal erosion were to occur at up to 10 mm/yr, it would take at least 22,000 years to start eroding the proposed facilities.

(v) Run 2 PA calculations indicate that low radiological dose rates would arise to all potentially exposed groups before and during erosion of the facilities, irrespective of erosion rates.

## Introduction

1. Selecting a preferred location for the proposed New LLW Facilities requires a set of assumptions about what might happen in the long term [1]. This involves an understanding of the possible future impacts of climate change in terms of sea-level rise and coastal erosion at Dounreay. The large uncertainties that surround these possible future impacts are taken into account in the performance assessments (PAs) for the long-term behaviour of the proposed facilities by considering a number of different scenarios. As Morgan and Wilmot [1] reported, the long-term evolution of the coastline at Dounreay was considered as part of the PA studies conducted during Stage 1 of the New LLW Facilities Project [e.g., 2, 3]. These studies recognised the uncertainties associated with specifying climate change, sea-level rise and coastal erosion, and treated these uncertainties by considering a set of PA scenarios encompassing different assumptions (Table 1 from [1]).

**Table 1: Run 1 Performance Assessment scenarios.**

| Scenario | Timescale for Coastal Erosion (years after present) | Maximum Sea Level Rise (m) | Maximum Coastal Erosion |
|---|---|---|---|
| Normal Evolution | 10,000 | 2 | Erosion concentrated in geos, no substantial inlets. |
| Extended Global Warming | 10,000 | 5 | 55 mm/yr.<br>550 m total. |
| Ice Sheet Collapse | 25,000 | 9.5 | 55 mm/yr for the first 5,000 years, and<br>30 mm/yr for the next 20,000 years.<br>875 m total. |

2. The coastal erosion rate of 55 mm/yr was regarded as a pessimistic maximum average rate. The value was based on data presented by Hutchinson and Millar [4]. A less pessimistic maximum average erosion rate of 10 mm/yr over 10,000 years (i.e., 100 m of cliff retreat) was subsequently assumed and adopted as a constraint for siting the proposed facilities [1]. In addition, it was assumed that locating the facilities above the 20 m topographical contour would prevent inundation over the period of interest [1]. Assuming cliff retreat 100 m inland from the 20 m contour provided a conservative “red line” that was used as a constraint for siting the proposed facilities (Figure 5 in [1]).

3. This paper provides an updated position on the impacts of possible future sea-level rise including coastal erosion at Dounreay, by taking into account commentary on the Morgan and Wilmot paper [1] by the British Geological Survey (BGS) [5] and the latest literature on climate change.

4. In addition, this position paper presents revised climate-change assumptions for use in assessing the performance of the proposed facilities. The results of some relevant PA runs, carried out under Stage 2 of the Project, are also presented. These modelling runs use climate change assumptions as bounding

limits, and the results show that any radiological consequences arising from climate change and coastal erosion would be very low.

5. This position paper is structured into sections and sub-sections covering the following topics:
   - (i) Global climate changes, with a focus on future global sea-level rises.
   - (ii) Sea-level changes at Dounreay, with a brief description of past sea levels followed by a consideration of future changes.
   - (iii) Possible impacts of waves, storm surges and tsunamis on sea levels at Dounreay.
   - (iv) Coastal erosion, with descriptions of the controlling factors followed by a consideration of estimations of short-term and long-term erosion rates at Dounreay.
   - (v) A summary of the possible climate-change impacts at Dounreay with respect to sea-level rise and coastal erosion, and a consideration of the implications of these impacts for siting the proposed facilities.
   - (vi) Climate change assumptions embraced by the Run 2 PA calculations.
   - (vii) Some Run 2 PA results to illustrate the low radiological consequences of the climate change assumptions for the future environment of the proposed facilities.

## Global climate changes

6. The report from Working Group I of the Intergovernmental Panel on Climate Change (IPCC) [6] examines the science of climate change as part of the IPCC’s Fourth Assessment Report. Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity.

7. Emissions of the greenhouse gases carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), into the atmosphere from the burning of fossil fuels will have a profound combined long-term warming effect on global climate [6]. The increase in $CO_2$ abundance since the late 1950s can be compared with data from analysis of the composition of air enclosed in bubbles in ice cores from Greenland and Antarctica. $CO_2$ abundances were significantly lower during the last Ice Age than over the last 10 kyr of the Holocene. From 10 kyr before present (BP) up to the year 1750, $CO_2$ abundances stayed within the range 280 ± 20 parts per million by volume (ppm). During the industrial era, $CO_2$ abundance rose roughly exponentially to 379 ppm in 2005. Pre-industrial variations of atmospheric greenhouse gas concentrations observed during the last 10 kyr were small compared to industrial era greenhouse gas increases, and were most likely due to natural processes. It is 90 to 99% probable, i.e. very likely, that the current atmospheric concentrations of $CO_2$ and $CH_4$ exceed by far the natural range of the last 650 kyr. Over the same period, Antarctic temperatures and $CO_2$ concentrations co-varied, indicating a close relationship between climate and the atmospheric carbon cycle.

8. It is likely, i.e. 66 to 90% probable, that earlier periods were warmer, as they were characterised by atmospheric $CO_2$ concentrations higher than those

currently measured. This appeared to be the case for climate states in the Pliocene that occurred for about two million years from about 5 Ma to 3 Ma ago, and for the warm event that lasted for about a hundred thousand years during the Palaeocene-Eocene Thermal Maximum (PETM) 55 Ma BP [6]. The estimated magnitude of carbon release for the PETM is of the order of 1 to $2 \times 10^{12}$ tonnes of carbon, a similar magnitude to that associated with greenhouse gas releases forecast for the coming century [6]. Moreover, the period of recovery through natural carbon sequestration processes was estimated to have been about 100 kyr, which is similar to that forecast for the future if greenhouse gas emissions continue at current levels [e.g. 7].

9. Climate models indicate that at the Last Glacial Maximum (LGM), about 21 kyr BP, the global temperature was 3°C to 5°C cooler than the present due to changes in greenhouse gas forcing and ice sheet conditions. Including the effects of atmospheric dust content and vegetation changes gives an additional 1°C to 2°C global cooling, although scientific understanding of these effects is very low [6]. According to Fairbanks [8], global sea level at the LGM was about 125 m below today's level. However, more recent estimates cluster around 120 m below the present-day level [6].

10. According to Oppenheimer [9], prior to the LGM during the last interglacial period about 120,000 kyr BP, there is evidence to suggest that global sea levels were at least 6 m higher than they are today, due in part to possible complete melting of the West Antarctic Ice Sheet (WAIS). However, the consensus view now suggests that the sea level stood 4-6 m higher during the last interglacial period [6].

11. Global mean sea level has been rising recently; from 1961 to 2003, the average rate of sea-level rise was 1.8 ± 0.5 mm/yr. For the 20th century, the average rate was 1.7 ± 0.5 mm/yr [6]. Sea-level change is spatially highly non-uniform, and in some regions rates are up to several times the global mean rise, while in other regions sea level is falling. The magnitude of sea-level rise for a given coastline depends on the changes in global sea-level (eustatic sea level) and the changes in the height of the land (isostatic changes). The net result of these changes is the relative sea-level rise that would be witnessed by an observer on the beach. A subsiding coastal land mass will have a greater relative sea-level rise than for a coastline undergoing uplift.

12. The recent rise in global mean sea level has been accompanied by considerable decadal variability. For the period 1993 to 2003, the rate of sea-level rise is estimated from observations with satellite altimetry as 3.1 ± 0.7 mm/yr, significantly higher than the average rate. For this period, the contributions from thermal expansion and ice melting were 1.6 ± 0.5 mm/yr and about 1.2 mm/yr, respectively. The tide gauge record indicates that similar large rates have occurred in previous 10-year periods since 1950. It is not known whether the higher rate in 1993 to 2003 is due to decadal variability or an increase in the longer-term trend [6].

13. Simulations for the 20th Century by the latest state-of-the-art climate models have demonstrated that recent trends in ocean heating, the melting of glaciers and sea-ice, and ecosystem shifts cannot be explained without including human-related increases in greenhouse gases [6]. Some of the main model-based predictions from [6] include the following:
    - (i) A best estimate global temperature rise by the end of the century of between 1.8°C and 4°C, with a possible temperature rise by the end of the century of between 1.1°C and 6.4°C.
    - (ii) A best estimate global sea-level rise of between 0.18 m and 0.59 m by the 2090s.
    - (iii) Arctic summer sea ice is likely to disappear in the second half of the century.

14. Model-based predictions of global temperature and sea-level rises are entirely dependent on what assumptions are made for future emission rates of the greenhouse gases. Predicted global temperature and sea-level rises are quoted as ranges to account for uncertainties in the greenhouse gas emissions scenarios. Low emissions scenarios lead to low estimates of global temperature and sea-level rise, whereas high emissions scenarios result in high estimates of these parameters. Current understanding of some important effects driving sea-level rise is known to be limited, and so the IPCC report [6] does not make an assessment of an upper bound for sea-level rise. Model-based projections of global average sea-level rise by the 2090s indicate a best estimate range between 0.18 m and 0.59 m, but the projections include neither the uncertainties in climate-carbon cycle feedbacks nor the full effects of changes in ice-sheet flow. Therefore, the upper value of this range (0.59 m) is not to be considered as an upper bound for sea-level rise.

15. Thermal expansion of the oceans will continue for many centuries after greenhouse gas concentrations have been stabilised at or above present levels, causing an eventual sea-level rise much larger than that projected for the 21st century [6]. Estimates of long-term equilibrium global average sea level rise above pre-industrial levels due to thermal expansion only range from 0.4 to 3.7 m, depending on the gas emissions scenario and the resultant temperature rise [6]. Long-term thermal expansion is projected to produce 0.2 to 0.6 m of sea-level rise per degree Celsius of global average warming above pre-industrial temperatures (2 – 6.1°C, depending on gas emissions scenario) [6]. For most greenhouse gas stabilisation levels, thermal equilibrium would be approached after a few centuries. In addition, contraction of the Greenland Ice Sheet is projected to continue to contribute to sea-level rise after 2100, even if $CO_2$ emissions were to cease. Current global model studies provide medium confidence that partial deglaciation of the Greenland Ice Sheet, with some possible ice losses too from the WAIS, would occur over a period ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more [6].

16. Complete melting of the Greenland Ice Sheet and the WAIS would lead to a contribution to sea-level rise of up to 7 m and about 5 m, respectively [6].

This would require that global average warming was sustained for millennia in excess of 1.9 to 4.6ºC relative to pre-industrial values. According to Vaughan *et al*. [10], complete deglaciation of the Amundsen Sea Embayment (ASE) ice sheet would take millennia at the present rates of ice sheet thinning. The ASE ice sheet occupies about a third of the WAIS area.

17. Computations by the United States Geological Survey indicate that the present Antarctic and Greenland ice sheets contain enough water to increase global sea level by nearly 80 m if they were all to melt [11].

18. Finally, according to [6], key uncertainties remain in the climate simulation models. Even though a great deal is known about glacial-interglacial variations in climate and greenhouse gas concentrations, a comprehensive mechanistic explanation of these variations has yet to be found. Similarly, the mechanisms of abrupt climate change (for example, in ocean circulation and drought frequency) are not well understood. Neither the rates nor the processes by which ice sheets grew and disintegrated in the past are known well [e.g. 12].

## Sea-level changes at Dounreay

19. In this section, past and future sea-level changes at Dounreay are described, with a consideration of the possible impacts of isostatic uplift, waves, storm surges and tsunamis.

### *Past sea-level changes*

20. A recent investigation by BGS concluded that it is very likely that much of the coastal zone lying below the 20 m topographical contour in the Dounreay area was inundated by the sea during the last 15,000-20,000 years, when deglaciation of the Main Late Devensian ice sheet occurred. It is probable that this inundation was relatively short-lived, as distinct shoreline features are restricted to the mouths of valleys, which were infilled with loosely consolidated sediments that could be easily re-worked by the sea [13].

21. Other sea-level changes around the coast of Scotland may have occurred during the past 20,000 years in response to rapid but relatively short-lived climate events. These are Heinrich and Dansgaard-Oeschger events that occur during glacial periods. They appear to show spatial coherence over a wide region and have timescales of decades. They caused abrupt changes in climate that were well in excess of the variability seen over the last 8,000 years. A robust case has been made for a link between these events and major reorganisations of the ocean currents in the North Atlantic [14, 15, 16]. Dansgaard-Oeschger and Heinrich events were reasonably regular during the last Ice Age, and would have caused unpredictable effects on the climate state through disruption of the Gulf Stream [17].

*Isostatic uplift*

22. Isostatic uplift has been occurring in Scotland for the past 13,000 years or so in response to the removal of the ice sheet loading that was present during the Ice Age. Central Scotland was covered by about 1 km of ice [18]. There is currently more isostatic uplift in central Scotland, where the ice sheets were thicker, than at the north coast [18]. The isostatic uplift rate is expected to remain constant for the next several hundred years [19].

23. The pattern of relative sea-level change in Scotland is complex, because of the variations in isostatic uplift. In the Firth of Forth, for example, post-glacial beach deposits are found well above present sea-level. Along the northern coast of Scotland, however, relative sea-level has been below the present level for much of the post-glacial period. A calculated sea-level curve for the Wick River Valley, for example, suggests a rapid rise in relative sea level between 7,200 years BP and 6,200 years BP, and then a more gradual rise, interrupted with minor falls, during the last 6,000 years. The final phase of sea-level rise started between about 1,200 and 900 years BP, and is continuing to the present day, reaching an elevation of about 2.40 m above Ordnance Datum (AOD) in the lower Wick River valley (the highest elevation of Mean High Water Spring Tides), which is coincident with the present-day surface level of modern saltings in the area [13].

24. BGS studies [13] of accretion rates of saltmarsh deposits at Bettyhill (Figure 1) indicated that stable environmental conditions have existed over a considerable period at the mouth of Strath Naver. In particular, the analysis showed that the upper 13 cm of material had accumulated over the last 130 years, suggesting that the saltmarsh sediment accretion rate has averaged 1 mm/yr, and has kept pace with recent relative sea-level rise [13]. On the basis of this analysis, the BGS argued [13] that there is no evidence of current crustal uplift or subsidence at the Strath Naver site. The BGS conclusion is not inconsistent with the work of Shennan and Horton [20], who estimated an isostatic uplift of between 0 mm/yr and 0.5 mm/yr along the northern coast of Scotland. The BGS also argued that isostatic uplift may have ceased at Dounreay (about 28 km east of Bettyhill) [13].

25. There is anecdotal evidence from long-time residents in the Dounreay vicinity that areas of the sea bed that are now exposed were not almost 80 years ago, suggesting a rate of isostatic rebound for the Dounreay site that exceeds recent eustatic sea-level rise [1].

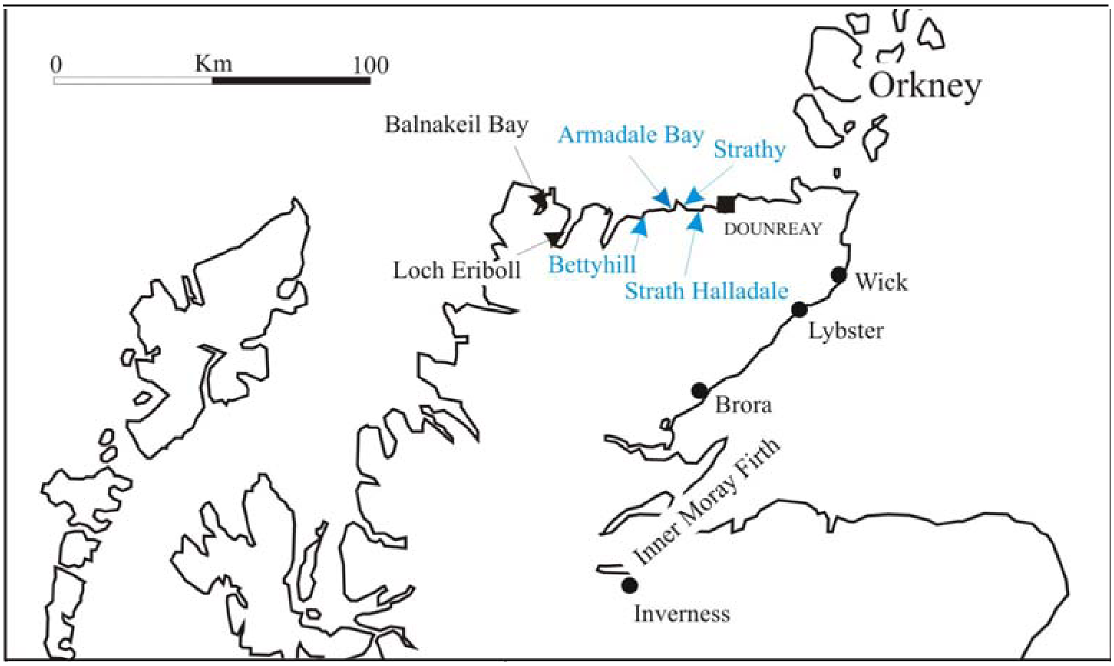

**Figure 1: Northern Scotland, showing sites (named in blue) investigated by BGS. From [13].**

*Sea-level changes up to 2300*

26. The UK Climate Impacts Programme (UKCIP02) is funded by DEFRA and is carried out jointly by the Tyndall and Hadley Centres. UKCIP02 created a set of four emissions scenarios to predict how climate might change in the UK over the next century, and used high-resolution climate models to estimate ranges of sea-level rise around the UK [21]. Taking into account eustatic sea-level rise and assuming an isostatic uplift of 0.7 mm/yr, UKCIP02 predicted a +1 cm (low emissions scenario) to +61 cm (high emissions scenario) relative sea-level rise for the 2080s in NE Scotland [21]. This range reflects the uncertainty in the emissions scenarios assumed in the modelling. For comparison, the IPCC range for global sea-level rise by the end of the century is between +18 cm and +59 cm, depending on the assumed emissions scenario [6]. For high-emissions scenarios, the effect of isostatic uplift, which is relatively small at Dounreay, becomes negligible, and relative sea-level rise will approximate to eustatic sea-level rise.

27. Like the IPCC estimates, the UKCIP02 projections for sea-level change are only for approximately the next 80-100 years. By extrapolating the projected rates of sea-level rise beyond 2100 for a further two hundred years, a reasonable estimate for three hundred years of sea-level rise was made by Nirex [22]. This was considered justified given the range of uncertainty involved in the projections. For the UK, this approach applied to IPCC and UKCIP02 projections suggested a *minimum* of 1.5 m to 2 m sea-level rise around much of the coastline by 2300. This sea level rise will be determined largely by the thermal expansion of sea water. However, melting of the

Greenland Ice Sheet and the WAIS could accelerate on this timescale, and could add significantly to these projected increases [10, 22].

### *Waves and storm surges*

28. In addition to long-term changes in relative sea level brought about by changes in global ice volumes, thermal expansion of the oceans and isostatic responses, there will be short-term increases in sea level and the influence of the sea brought about by events such as waves and storm surges.

29. Coastal wave height is a function both of local water depth and of the strength of offshore waves [21]. Breaker heights along the Dounreay coastline of up to 14.5 m AOD have been estimated by Hutchinson [23]. However, such large waves would break some distance from the coastline (500-600 m), and therefore much of the potential for mechanical action would have been reduced by the time the waves reached the coastline [23]. In contrast to some high-energy coasts in Scotland [24], no cliff-top storm deposits are present near the proposed position of the facilities. The influence of large waves at Dounreay is evidenced by wave-clawed rock ledges, exposed through the superficial deposits, on the cliffs in front of the existing LLW Pits at heights of 14.4 m AOD [23]. Furthermore, the influence of storm events has also been observed in front of Landfill 42 where sections of geotextile matting were eroded by wave clawing up to heights of 9.5-10.5 m AOD [25].

30. According to Scottish Natural Heritage, Dounreay could experience a storm surge greater than 3.44 m relative to mean sea-level within 100 years [19].

### *Tsunamis*

31. In addition, there may be potential short-term effects from tsunami events [26]. The Second Storegga Slide occurred about 7,100 yr BP, and resulted in associated surges of up to 4.3 m AOD (recorded at Strath Halladale - see Figure 1) [27]. A previous report suggested that the full extent of this inundation may have been up to 10-20 m [28].

32. Should one occur, a tsunami of up to 20 m could reach the proposed facilities after erosion of the cliff or with increased sea level. A large tsunami could, in theory, cause superficial erosive damage to the top of the cap, but is unlikely to have a significant effect on the wastes inside the vaults. It is considered that the sea water from the wave would quickly drain away.

33. The run-up (the height reached by the wave) of a tsunami can be related to the magnitude of the initiating earthquake. The Second Storegga Slide may have been caused by a large magnitude seismic event during glacial rebound of the crust, following the last glaciation. McEwen [29] reported that the magnitude of the earthquake which initiated the Second Storegga Slide has been estimated to be compatible with predictions of the upper bound of seismic risk for the North Sea based on historic seismicity data. The implication is that future Storegga Slides of similar magnitude to the second one may not occur

until after the next glaciation. Glacial advances comparable to the last glaciation are unlikely to occur in the next 100,000 years [e.g. 30].

34. A tsunami sufficiently large to disrupt the proposed facilities (i.e. with a run-up >20 m) is unlikely until after the next glaciation, when large earthquakes related to crustal uplift might occur again to trigger off-shore sediment slides. A tsunami of sufficient magnitude to affect the performance of the proposed facilities at Dounreay is unlikely to occur in the timeframe of concern.

*Climate and sea-level changes beyond 2300*

35. Beyond the next 300 years, uncertainties in the driving mechanisms of climate change (e.g., rates of release of greenhouse gases) and in the responses of the Greenland and Antarctic ice sheets to global warming mean that there are large uncertainties concerning the rate and magnitude of sea-level rise at Dounreay and how long higher sea levels would persist.

36. Following melting of some of the ice sheets, it is assumed that, eventually, the amounts of greenhouse gases in the atmosphere will start to decline. Astronomical forces will then re-assert themselves to cause a period of global cooling, with re-growth of continental ice sheets and a decrease in eustatic sea level.

37. Modelling natural $CO_2$ variations with no anthropogenic influences results in a prediction that the next glacial maximum will not occur until around 100 kyr after present (AP), with cooling commencing at around 50 kyr AP [7]. Factoring in fossil fuel contributions along with natural $CO_2$ variations gives modelling results that indicate a prolonged interglacial period, with the next glacial maximum occurring at 178 kyr AP [30]. Models that assume more extreme greenhouse gas emissions scenarios suggest that the current interglacial period may last for at least 500 kyr [31].

*Summary position on climate and sea-level changes beyond 2300*

38. It is not known if all sea ice and land ice, particularly that in Antarctica, will completely melt as a result of global warming [e.g. 10]. If it were to occur, most of Britain would be inundated by a sea-level rise of about 80 m [11], and UK society would be totally changed from what it is today. Disregarding scenarios of extreme sea-level rise, a best *upper* estimate of around 12 m AOD can be made for the relative sea-level rise at Dounreay, based on an assumption that both the Greenland Ice Sheet and the WAIS will disappear entirely over several thousands of years [6]. The timing of this sea-level rise is dependent on future gas emissions and the consequent rates of ice-sheet depletions. A pessimistic assumption is that this level of increase will occur over the next few millennia up to 10 kyr AP, when the relative sea level would reach a maximum of +12 m AOD. In view of the large uncertainties over the long-term fates and impacts of the greenhouse gases, this upper estimate of 12 m of sea-level rise is considered sufficiently pessimistic that it could take

into account any sea-level rise from long-term thermal expansion of the oceans.

39. The proposed facilities are expected to be located between 24 m and 29 m AOD and at approximately 220 m from the nearest cliffs, which are about 15 m high. Therefore, a relative sea level of 12 m AOD would not overtop these cliffs during calm seas, except possibly during a storm surge which could add around 3.4 m to the sea level. The cliffs will retreat inland by erosion, and might even become higher with respect to relative sea level. Although a sea level of 12 m AOD combined with an additional 3.4 m of storm surge could provide 14.5 m-high waves (as at present) that could splash inland at elevations higher than 29 m AOD, the sea water would quickly drain away. Such storm events are considered ephemeral compared to marine inundation, although they will contribute to coastal erosion (see paragraph 29). It is considered, therefore, that the proposed facilities are unlikely to be inundated by rising sea levels.

40. Climate modelling of the northern hemisphere by Loutre and Berger [7] suggests that it will take 50 kyr to recover from the impacts of global warming. However, other modelling results indicate that this recovery period could be more than ten times longer (>500 kyr) if high greenhouse gas emissions scenarios persist [31]. With such large uncertainties in long-term climate change modelling, it could be assumed that cooling in the northern hemisphere will not start to take place until after 50 kyr AP, and possibly not until after 100 kyr AP. Therefore, the relative sea level at Dounreay could remain at 12 m AOD for an extended period of between 40 kyr and possibly more than 90 kyr. It could also reasonably be assumed that during this period there is no significant isostatic uplift.

41. The cooling period is likewise highly uncertain, and is assumed to occur from some stage after 50 to 100 kyr AP, until a glacial maximum is established at around 180 kyr AP [30]. During this cooling period, relative sea level at Dounreay is assumed to fall gradually from a peak of +12 m AOD towards its present level and then further to a minimum level coinciding with the next glacial maximum at about 180 kyr AP. At this stage, global sea levels may have fallen to as low as 120 m below the present-day sea level [6].

## Coastal erosion

### *Generic background*

42. Although marine inundation is the most obvious consequence to be expected from sea-level rise, coastal erosion leading to significant coastal retreat is also a potential threat to current land use. Coastal erosion occurs particularly during storms when high-energy waves are generated. If storms become more frequent and more intense due to global warming, there will be greater erosion resulting from storm events. Stronger winds predicted in future climate scenarios, allied with higher sea levels, will increase the strength and height of storm surges, which have high erosive power. In addition, mean coastal wave

heights are likely to increase in future climate scenarios as coastal wave height is controlled by local water depth (which will increase as sea levels rise) and the strength of offshore winds (which are predicted to increase). Therefore the increased energy in coastal waves will be transmitted to the shoreline, resulting in increased erosion [21]. The vulnerability of a coast to erosion is partly determined by the characteristics of that coast, and will therefore vary depending on the region under consideration. Some important characteristics that influence the rate of coastal erosion include the rate of relative sea-level rise, lithology (the type of rock present), bedding plane geometry, topography, and the orientation of the coast relative to the predominant wave direction.

43. During periods when relative sea level is falling, rates of coastal erosion are likely to be low. This is because coastal landforms, such as cliffs and sand dunes, would be reached less and less often by storm tides.

44. Topographic features such as wave-cut platforms and beach slopes would tend to protect the coastline. In general, the rate of lateral erosion ($\delta X/\delta t$) of a coastline is directly proportional to the rate of downward erosion ($\delta Z/\delta t$), or lowering, of a shore platform [32]. A simple expression connects these two parameters [33], as follows:

$$\frac{\delta X}{\delta t} = \left(\frac{\delta Z}{\delta t}\right) \Big/ I$$

where $I$ is the gradient of the shore platform.

*Estimation of coastal erosion rates*

45. It is important to distinguish between short-term coastal erosion rates and future long-term rates. Short-term observations of erosion rates may not be indicative of long-term rates, especially when other mechanisms of lateral erosion may occur in the long term, for example, as a result of sea-level rise.

46. Auton *et al*. [5] undertook a desk review of different methods of measuring coastal evolution and erosion rates for Dounreay. These included:
(i) Profiling between erosion pins installed in a cliff face can be used to estimate cliff retreat over timescales of a few decades [e.g. 33].
(ii) Lichenometry can be used to date portions of a cliff line and shore platform, and offers the opportunity to establish zones where negligible erosion has occurred during the last few hundred years [5].
(iii) Recent advances in GIS and 3-D computer modelling packages and modern field surveying equipment, such as dGPS and laser scanning, provide a more rigorous approach to monitoring bulk rates of coastal erosion [5].
(iv) Sequential (every 5 years) targeted laser scanning of cliffs, slots, notches and foreshore platforms, allows highly accurate quantitative measurement of both vertical and lateral erosion by a single technique. This, together with programmes of erosion-pin monitoring, on-site and laboratory geotechnical testing, targeted to cover the range of rock types known to be present across each scanning site, can give objective geo-referenced measurements. Such data would enable 3-D erosion

rate monitoring and also the construction of 4-D bulk rock mass assessment models of coastal evolution that accurately reflect changes during the monitoring period [5].

47. However, extrapolating current erosion rate measurement and erosion rates inferred from the recent past to the long-term future may not be reliable. This is because of the uncertainty of the effects of sea-level rise on coastal erosion.

*Coastal erosion at Dounreay*

48. The cliffs at Dounreay are composed of sedimentary rocks belonging to the middle Old Red Sandstone. These Devonian flagstones are strongly jointed and dip seawards at about 10°. The cliffs range from 10-m to 15-m high along the length of the Dounreay Site, and are capped by up to a few metres of glacial till and fill (superficials). The site is exposed to strong marine attack, mostly from the northwest. Along most of the Caithness coastline the sea bed plunges steeply to depths of over 35 m within 1500 m of the cliff line so there is probably little dissipation of wave energy before it reaches the coastal zone. However, wave energy is reduced to some extent by offshore reefs, which strike at 065°-070°N, i.e., roughly parallel with the coast, with saw-tooth profiles. Each reef is formed of a 4-m to 7-m-high landward-facing scarp, and a seaward slope inclined at about 10°. These have been breached in places along major joints, resulting in zones of enhanced coastal erosion (termed sub-geos) on the wave-cut shore platform [33]. Where faulting or jointing has weakened the rocks in the cliffs, geos or inlets have been cut back by marine erosion [33]. Blocky slabs that are monitored on the Dounreay coastline can become undermined by wave action and can be turned out suddenly under the influence of gravity. Were such events being monitored, it would result in a large calculated short-term erosion rate that could be misleading if used to estimate average long-term rates.

49. Wave height is one of the major factors influencing coastal erosion [e.g. 21, 24]. Greatest wave activity occurs in February/March and October/November. Maximum wave heights are likely to be reached in February, and may be as high as 20 m [33].

50. The superficials on top of the flagstones are eroded more uniformly and more rapidly than the flagstones, due to their unconsolidated nature. The lateral rate of erosion of the cliffs therefore depends on the elevation of the transition from the flagstones to the superficials (rockhead level) relative to the sea and wave levels. Erosion of superficials only occurs if the rockhead level is below the base of the cliff. Rockhead level will change as recession progresses, thus affecting the erosion mechanisms and in turn, cliff recession rates. The threshold rockhead level varies as function of the morphology of the cliff and surrounding area, the geology and with changing sea and wave levels. Average rates of erosion of the superficials range from about 50 mm/yr to 210 mm/yr, depending on the rockhead level in the cliff face [33].

51. At the present time, the rockhead level is such that erosion of the flagstones, not the superficials, governs the lateral erosion rate of the Dounreay cliffs [4]. The intrinsic average recession rate of the more resistant flagstone layers, consisting of massive, cemented, low-porosity beds, is low, less than 0.05 mm/yr [33].

52. The main control on the long-term erosion rate of the cliffs at Dounreay is the rate of slot deepening in the more porous, less competent flagstone interbeds [33]. These are fissile, thinly-bedded sandstones, siltstones, shales and impure limestones, the erosion of which proceeds chiefly by the erosion of finer-grained layers. This mechanism causes the development of horizontal slots, both by groundwater seepage and wave action, that deepen until slabs of the remaining, more competent rock become loose or fall down by cantilever failure [33]. Storm waves are capable of removing blocks of considerable weight (around a tonne or more) at Dounreay [33].

53. Hutchinson *et al*. [33] made what they termed "*rough estimates*" of the rate of slot deepening within the local cliffs at Dounreay. These estimates were based on the depths of weathered hollows, or tafoni, on the underside of two selected slot roofs. The depths (D in cm) of the tafoni were assumed to have been related to the time of erosion (t in years) by the following empirically derived equation: $D = 20.3(1 - e^{-0.005t})$ [33]. This equation was derived for cliff-faces of tuffaceous conglomerate in Japan [34], a rock that may not compare well with a fine-grained flagstone if the conglomerate contains minerals that are more susceptible to chemical weathering or if it has pebble-sized clasts that can be easily eroded. In the case of the Japanese conglomerate, the tafoni developed relatively quickly. Use of the equation for the flagstones at Dounreay may result in derived erosion times that are too short. The time estimates of about 40 years that were derived from this equation, and used to calculate slot deepening rates of 9 mm/yr and 41 mm/yr for the two overhangs [33], may be under-estimates, implying that the slot deepening rates are maximum values only. Nevertheless, Hutchinson *et al*. [33] used these two estimates of flagstone slot deepening rates to assume future rates of cliff recession of 10 mm/yr (optimistic) and 50 mm/yr (pessimistic)[1] for the Shaft area.

54. An additional conservatism was introduced by Hutchinson *et al*. [33] by assuming a 10% compound *per century* increase in the extrapolated erosion rate to account for a rise in mean sea level, assumed to be initially 5 mm/yr. Although Hutchinson *et al*. [33] considered that the rise in sea level would not significantly affect hard-rock erosion rates, the compound increase in rates of erosion was applied because the coastline by the Shaft has relatively thick superficial deposits. The focus of the work by Hutchinson *et al*. [33] was to provide a worst case scenario for marine inundation of the Shaft in the medium-term, and the conservatism of the approach was therefore considered appropriate.

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[1] *N.B*. The previous use of a 55 mm/yr pessimistic rate (see Table 1) was based on a misreading of erosion rate data presented in [4].

55. The uncertainties in the estimation process for lateral erosion rates of the cliffs near the Shaft are large, and give rise to highly cautious rate values [33]. The limitations in the methodologies used to estimate lateral erosion rates at Dounreay [33] have been commented on earlier by Auton *et al*. [5], who recommended that a more modern survey be performed to obtain better rate estimates.

56. Anecdotal evidence from local fishermen highlights the conservatism of the estimates of cliff erosion made by Hutchinson *et al*. [33]. An overhang and slot, just below high-water, was used as a shelter from the rain by a local fisherman, Johnny Bain, over 80 years ago [1, 35]. The overhang can still only just accommodate one person sheltering from the elements, despite a prediction, based on the pessimistic recession rate of 50 mm/yr from Hutchinson *et al.* [33], suggesting a potential increase in slot depth of 4.0 m. Furthermore, the majority of the inscription that Mr. Bain made at the time can still be read.

57. Hutchinson *et al*. [33] provided a rate for post-glacial penetration of geos close to the Dounreay site, based on archaeological evidence. A broch at Green Tullochs is partially penetrated by a narrow geo, Geo Croiche. Taking an archaeologically acceptable date for the broch of around 2,000 yr BP, an average rate of lengthening of the geo of 2-9 mm/yr can be estimated [1]. However, there are a number of uncertainties associated with applying estimations of geo lengthening to long-term cliff erosion: a geo may not be facing the predominant direction of incoming waves; a geo is a coastal expression of a fault zone, and the material present in a fault may not be representative of the main rock mass in the cliffs; and groundwater discharge from a geo will be higher than from the main body of the cliff, due to faulting, thus accelerating erosion and geo lengthening.

58. Information on erosion rates can also be derived from studies elsewhere, although there will be significant uncertainties in the application of such rates because of differences in lithology, coastal morphology and the frequency and magnitude of the storms that are the principal causes of erosion. Hutchinson *et al*. [33] considered “The Stacks” on the east coast of Caithness, where near-vertical cliffs of generally massive Devonian sandstones and associated offshore stacks are capped with a glacial diamict. The strata forming the stacks must have been more or less continuous with those in the main cliff at the time the diamict was deposited. Therefore, the 15-m separation of the main stack from the cliff is post-glacial, and the average rate of widening can be estimated to have been about 3 mm/yr, or 1.5 mm/yr on each face [33].

59. A world-wide review of lateral sea-cliff erosion is presented by Sunamura [36], who provided order of magnitude estimates of lateral erosion rates, averaged over periods of 10-100 years. The rates for granitic rocks and limestones are given respectively as 1 mm/yr and 1 to 10 mm/yr. Assuming a flagstone lithology has an erosion resistance between that for granite and that for limestone, a cautious upper average rate for flagstones is considered to be 10 mm/yr.

*Summary position on coastal erosion at Dounreay*

60. Uncertainties are introduced when historical erosion rates are extended into the future. In particular, there is an inherent difficulty in extrapolating short-term (years) and small-scale (mm) processes and measurements to predict long-term (thousands of years) and large-scale (landform) changes. Reliance on short-term data can lead to an emphasis on extreme events and an over-estimate of rates of change in the long term [e.g. 37].

61. Without any changes in relative sea level, it would be expected that erosion rates along coastlines such as that at Dounreay would decrease with time as the wave-cut platform fronting the cliff becomes wider and is more able to dissipate the power of waves and storms [e.g. 38]. With a rising relative sea level, there may not be an opportunity for this type of equilibrium to be established, in which case coastal erosion would be expected to continue. Bearing this in mind, and taking into account the above discussion, it seems reasonable to assume a value of 10 mm/yr as a *maximum* average rate of long-term coastal erosion at Dounreay. However, with so much uncertainty encompassed by this upper estimate of the average rate of long-term coastal erosion, there is as much potential for a slower average rate to occur in the far future at Dounreay, for example as low as 1 mm/yr. This would lead to no marine erosion of the proposed facilities for a period of over 200,000 years, during which time global cooling would most likely have occurred and led to glaciation of the site.

62. Assuming an upper average erosion rate of 10 mm/yr and a continually rising sea level, it would take at least 22,000 years to erode 220 m of the cliffs at Dounreay, the approximate distance between the cliff-line and the expected location of the proposed New Facilities.

## Summary and implications for siting of the proposed facilities

63. Wider issues than climate change impacts at Dounreay need to be considered when making decisions on a preferred siting of the proposed facilities. Two of these issues are:
    (i) The views of local and other stakeholders.
    (ii) Radioactive decay of the LLW inventory, which will lead to a significant decrease in total radioactivity level in only a few hundred years after closure [39].

64. What remains in terms of radioactivity in the waste form would be mostly due to the presence of long-lived radionuclides of the actinide elements, the average alpha-activity of which would drop after around 10,000 years to the levels currently observed in Dounreay soils (Figure 2). The average alpha-radioactivity in the waste form would fall to 0.4 Bq/g after approximately 20,000 years (Figure 2). It is expected that degradation processes will largely homogenise the wastes in each vault after a few thousand years, thus smoothing out any high-activity clumps that were originally present. None of

the alpha concentrations, originating from the proposed facilities, calculated for the solid media in the geosphere, i.e., bedrock and soils, would approach the currently observed background alpha concentrations in soils in the vicinity of the Dounreay site (Figure 2). Therefore, assumptions about marine inundation and coastal erosion of the proposed facilities may be considered relatively insignificant beyond about 10,000 years AP, when the average alpha-radioactivity level in the waste form will have dropped to levels similar to background (Figure 2).

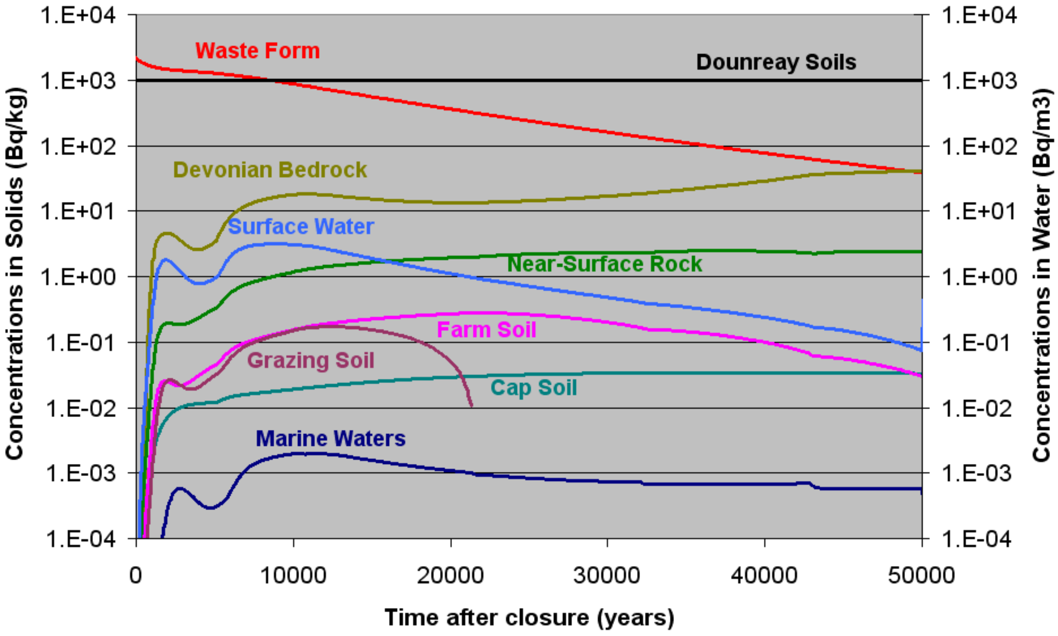

**Figure 2: Total average alpha radioactivity concentrations originating from the proposed New Facilities (solids – Bq/kg; waters – Bq/m$^3$) in the main Run 2 PA media. Average background alpha concentration in Dounreay soils (Bq/kg) is shown for comparison. From [39].**

65. The above discussion of the potential impacts of sea-level rise has concluded that the proposed facilities are unlikely to be inundated, except if coastal erosion were to lead to exposure of the facilities in a recessed cliff-line.

66. The above re-assessment of the erosion rates has concluded that a value of 10 mm/yr is a reasonable *maximum* average rate of long-term coastal erosion at Dounreay. Assuming this rate, it would take at least 22,000 years to erode the cliff-line 220 m inland to the planned position of the proposed facilities.

67. The “red line” presented in Figure 5 of [1] is drawn 100 m inland from the 20 m topographical contour, and has been used to help constrain the siting of the proposed facilities. On the basis of this position paper’s re-assessment of sea-level rise and coastal erosion at Dounreay, the “red line” is considered to be an appropriate spatial criterion to ensure that the proposed facilities will be secure from coastal erosion for at least 10,000 years.

## Climate change assumptions

68. No regional simulations of climate evolution over the assessment timescale of the Run 2 PA have been published for Northern Scotland. However, SKB has discussed the evolution of the climate over the next 100,000 years in Sweden [40]. The reference evolution of climate-related conditions in the main scenario of SR-Can uses a model reconstruction of the Weichselian glaciation, the best-known glacial cycle [40]. This defines a scientifically reasonable starting point for the analysis of future potential climate impacts on repository performance and safety [40]. Although this approach of projecting a past glacial cycle into the future has its merits (e.g., there is no need to consider different greenhouse gas emissions scenarios in climate change models and the concomitant uncertainties), it is not the approach taken for performance assessment of the proposed facilities [1]. Instead, account is taken of (a) the results of climate change models that predict the timing and magnitude of sea-level change, and (b) estimates of coastal erosion rates [2, 3, and Table 1].

69. Table 2 summarises the climate change assumptions that have emerged from the re-assessments made in this paper for use in the Run 2 PA. Climate change impacts are considered up to the next glacial maximum, assumed to occur at around 180 kyr AP. The Dounreay landscape would be expected to be glaciated several millennia before the next glacial maximum is reached.

70. As discussed above, there is much uncertainty surrounding the period of extended global warming and the subsequent period of global cooling, and this is captured in the climate change assumptions (Table 2). This uncertainty translates into a possible range of maximum cumulative cliff-line erosion distances between <500 m and <1,000 m.

## Performance assessment assumptions and results

71. For the purposes of a performance assessment, key uncertainties regarding the effects of climate change are the rate and extent of coastal erosion during global warming, and the extent of any subsequent sea-level fall. Scenarios used in the Run 2 PA have been developed to recognise and encompass the uncertainties associated with specifying climate change, sea-level change and coastal erosion in the long term [39].

72. Some Run 2 scenarios (Undisturbed Performance and Disturbed Performance scenarios) and associated PA results are briefly described below. The PA results demonstrate that the calculated radiological consequences to the potentially exposed groups (PEGs) from the proposed facilities are extremely low [39]. Note that the Crofter PEG is considered the key PEG under both scenarios.

**Table 2: Climate change assumptions.**

| Periods of Climate Change (years AP) | Sea-Level Change (m AOD) | Maximum Coastal Erosion at Dounreay | Commentary on Levels of Confidence |
|---|---|---|---|
| 0 - 10,000 (Collapse of the Greenland Ice Sheet and the West Antarctic Ice Sheet) | 0 to +12 | <10 mm/yr, or <100 m. | Sea-level rise depends on the gas emissions scenario; a cautious position is adopted. Medium confidence that the erosion rate is a reasonable maximum. |
| 10,000 – 50,000 (Extended global warming)<br>OR<br>10,000 – 100,000 (Extended global warming) | +12 (constant)<br><br>+12 (constant) | <10 mm/yr, or <400 m. <500 m of cumulative erosion.<br>OR<br><10 mm/yr, or <900 m. <1,000 m of cumulative erosion. | Low confidence in the sea-level position, the extent of global warming, and the rate of erosion.<br>The proposed facilities may become eroded after about 20 kyr AP, regardless of the assumed period of extended global warming. |
| 50,000 – 180,000<br>OR<br>100,000 – 180,000 (Cooling to the next glacial maximum at 180 kyr AP) | +12 to –120 | No marine erosion of the land. Land re-emergence occurs. | Medium confidence that no coastal erosion by the sea will occur.<br>High confidence that the land and the facilities will be eroded by glacial ice before 180 kyr AP. |

73. The Run 2 Undisturbed Performance scenario considers how the disposal system will evolve, allowing for uncertainty in performance of the different disposal system barriers, but excluding any events whose occurrence bypasses or destroys one or more of the disposal system barriers. Coastal erosion processes are assumed to take place during the Undisturbed Performance scenario as sea level rises, reducing the extent of rock between the proposed facilities and the coast. Erosion results in dispersion of material from the cliff face onto the foreshore and into the sea [39]. However, erosion is assumed not to extend as far inland as the proposed facilities. The calculated annual dose-time curve for the Crofter PEG and a Foreshore User (the Angler PEG in the Run 2 PA [39]) are shown in Figure 3, assuming an average erosion rate of 1 mm/yr.

74. It is possible that an extended period of high sea level and/or an increase in erosion rates could lead to erosion of the proposed facilities. This has been modelled as a Disturbed Performance scenario by assuming the same processes that are operating today continue until the facilities are eroded onto the foreshore and subsequently into the sea. Again, erosion is assumed to

result in dispersion of material from the cliff face onto the foreshore and into the sea, but this time including the wastes from the proposed facilities [39]. Uncertainty in the erosion rates has been considered by undertaking two calculations, with the shorter time accounting for the maximum pessimistic erosion rate provided in Hutchinson *et al*. [33] (50 mm/year), and the longer time accounting for erosion continuing at the maximum rate assumed in [1] and confirmed in this paper (10 mm/year). The same PEGs considered in the Undisturbed Performance scenario have been used. The calculated annual dose results for the two Disturbed Performance scenario calculations are shown in Figure 3. The calculations cease once erosion has completely eroded the facilities; after 40,000 years for an assumed average erosion rate of 10 mm/year, and 10,000 years for an assumed rapid average erosion rate of 50 mm /year.

75. The peak calculated annual doses for the key Crofter PEG result mainly from ingestion of foodstuffs from livestock cattle. Calculated annual doses to this PEG decrease as a result of erosion and the reduction in the area of contaminated ground that is assumed suitable for livestock farming between the facilities and the coast. The faster the erosion, the lower the calculated annual doses to the Crofter PEG become.

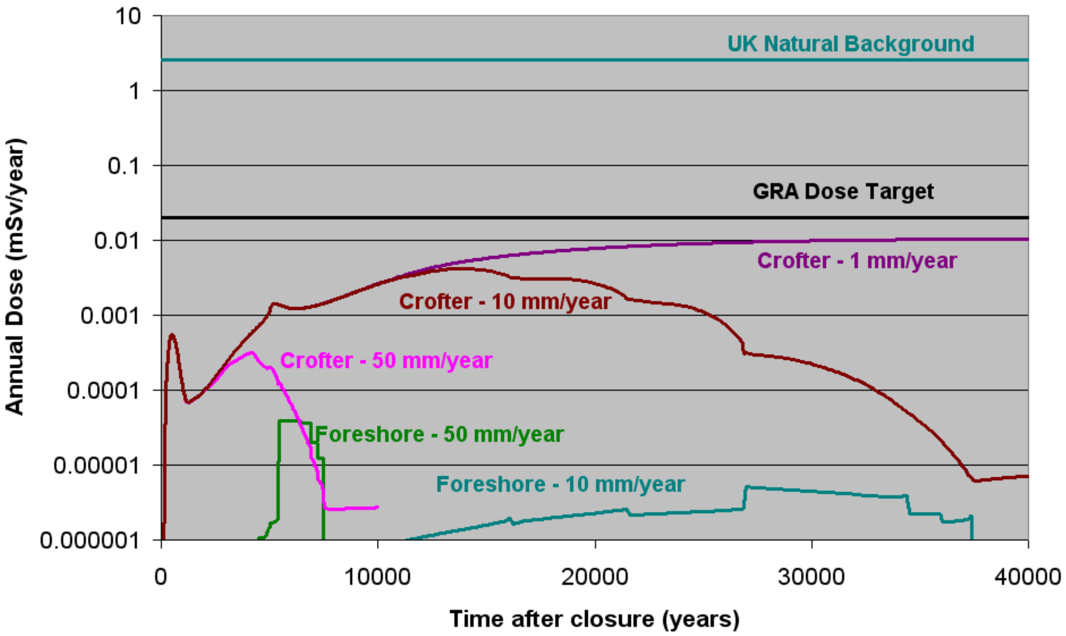

**Figure 3: Comparison of Run 2 PA calculated annual doses to the key Crofter PEG for three alternative stylisations of coastal erosion. Also shown are the calculated annual doses to a Foreshore User (the Run 2 PA Angler PEG). Erosion at 1 mm/yr does not reach the facilities over the timescales shown. Erosion at 10 mm/yr breaches the facilities over tens of thousands of years. Erosion at 50 mm/yr breaches the facilities in thousands of years. After [39].**

76. The peak calculated annual doses for the Foreshore User PEG result mainly from external irradiation from exposure to material eroded onto the foreshore.

The sooner this occurs after closure, the higher the activity in the eroded material (waste once the facilities are breached) and the higher the calculated doses (Figure 3). However, the eroded material is expected to have a low residence time on the foreshore, and the calculated annual doses are very low.

77. Low calculated annual doses to the Foreshore User PEG (Figure 3) are to be expected when it is considered that, after a few thousand years, the average alpha-radioactivity level in waste being eroded from the facilities would be similar to the natural background levels currently observed in soils in the vicinity of the Dounreay site (Figure 2).

78. When the facilities have been completely eroded and the waste material has all been removed by the sea, the annual doses are expected to decline sharply. There remains a residual calculated dose to the Crofter PEG from consumption of molluscs. The concentrations of radioactivity in the coastal waters supporting the molluscs are maintained at a low level by exchange with the marine sediments that have received input from the material eroded onto the foreshore. However, the calculated doses are several orders of magnitude below the regulatory dose target [41] (see Figure 3).

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