Miljöorganisationernas kärnavfallsgranskning, MKG

Underlag för kompletteringskrav rörande permafrostdjup

Prof em Matti Saarnisto, Helsingfors Maj 2012

Evaluation of permafrost depth simulations in SKB report TR-11-01

To Whom It May Concern

In the SKB report TR-11-01 entitled "Long-term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark" there is the following statement on page 28:

"For glacial and in particular permafrost climate conditions the temperature at repository depth will decrease, but will always be above 0°C."

The director of the Swedish NGO Office for Nuclear Waste Review (MKG) Dr. Johan Swahn asked me to evaluate this statement in an e-mail letter dated 18 April 2012 together with an evaluation of studies indicating permafrost depth during the previous glaciations. According to the SKB reports, the maximum possible depth of permafrost at Forsmark has been -270 m, whereas the minimum depth of the repository for spent nuclear fuel would be -457 metres.

In October 2007, I was asked by the Radiation and Nuclear Safety Authority of Finland (STUK) to evaluate the Posiva Report 2006-5 entitled "Expected Evolution of a Spent Nuclear Fuel Repository at Olkiluoto" with special emphasis on the climate scenarios described in it (relevance, uncertainties) and the way how permafrost formation was dealt with (with relevant parameters) as well as the basis of selection of parameters used and their numerical values. The reason for the request by STUK was my lecture at the University of Helsinki in September 2007 where I explained current discoveries of the stages of the last, Weichselian glaciations. The results were the outcome of the extensive EU-funded QUEEN (Quaternary Environment of the Eurasian North) research programme of the European Science Foundation. I was responsible for the Finnish part of the programme and the Swedish participants were from the universities of Lund and Stockholm. In 2010 the extensive summary paper of QUEEN was globally the most cited publication in its field of the past ten years (Svendsen et al. 2004).

According to the above investigation and together with several other current studies, southern Finland and south-central Sweden, thus also Olkiluoto and Forsmark, were ice-free, periglacial permafrost territory for tens of thousands years during the Weichselian glaciations. In my lecture, I estimated that deep permafrost was formed during the ice-free periods and I suggested the possibility that it penetrated to the planned depth of the Olkiluoto repository. After the lecture, a geologist from STUK told me that STUK is worried about permafrost at Olkiluoto and soon afterwards STUK requested opinion on the above-mentioned Posiva report, which was unknown to me.

I was also asked to give my opinion of the Posiva plan to store spent nuclear fuel at Olkiluoto in the Commerce Committee and Environment Committee of the Finnish Parliament in May/June 2010. In the latter hearing representatives of STUK and the Geological Survey of Finland GTK were asked for their opinion of my evaluation of the Posiva report including the permafrost depth. They both agreed saying that my findings should be taken seriously. GTK has consulted Posiva for decades.

When I became acquainted with the Posiva report I no longer wondered why STUK was worried. How it would be possible that during the future glaciations permafrost will penetrate in Olkiluoto only to -182 metres 60,000 years after the present (AP), as it penetrated to the depth of 800 metres in Whiteshell, Manitoba, Canada during the last, Wisconsin glaciation, using the same mathematical model and in similar geological conditions? This was the crucial question of the 30-page report, which I wrote to STUK in January 2008.

The unpublished report is kept in the archives of STUK[*]. The Whiteshell case will be treated in more detail below.

The last, Weichselian, glaciation that followed the Eem interglacial 120,000 years ago was the model glaciation in the Posiva Olkiluoto case, as it is in the Forsmark case. The glaciations/stadial-interstadial history and their chronology are reasonable well established especially in Scandinavia although open for revisions because the stratigraphic record is never complete in glaciated terrain. The glaciation histories of Forsmark and Olkiluoto are nearly identical. This also applies to the maximum thickness of the continental ice sheet to more than 2,500 m, the submergence of the sites by the Baltic basin waters and glacial isostacy. These similarities are also shown in the SKB and Posiva reports. In addition, both localities are situated in Precambrian crystalline terrain and thus the thermal conductivity properties of the granitoid rocks are comparable. This all means that their permafrost history should be more or less the same.

The Weichselian temperature fluctuations are known in detail on the basis of the Greenland ice core studies (Johnsen et al. 2001), but quantitative temperature and precipitation estimates outside Greenland are challenging. This also applies to the Forsmark Weichselian temperatures. In the permafrost modelling, the Greenland GRIP core temperature record was utilized, which is a common practice. However, in my mind, temperature values that are too high were chosen at Forsmark, which has resulted in permafrost depths that are too low. The Greenland ice core temperatures used in simulations fluctuated greatly, deviating ca. -8° C from the present and merely -11° C during the coldest stages just over 70,000 and 20,000 years ago (SKB report p. 440). In Greenland, the same data, however, shows greater deviations from present temperatures: c. 15° C and more than 25°C, respectively. In the SKB report, according to the authors of the report, the greatest uncertainties in permafrost simulations are "the air temperature curve reconstructed for the Forsmark site for the last glacial cycle, which is estimated to be uncertain by ±6° C". If the uncertainty in climate parameters is incorporated in permafrost simulations, permafrost will reach a maximum depth of 410 m (SKB report p. 447). With all known uncertainties and using their extreme values favourable for permafrost growth, the permafrost will reach a maximum depth of -463 metres at Forsmark, which is, however, considered unrealistic and therefore the possibility of freezing of groundwater at the depository depth is excluded. In any case, this simulated extreme value is more or less the same as the planned minimum depth of the depository -457 m.

The chosen Forsmark temperatures were compared in the SKB Climate report with the pollen-based Weichselian interstadial temperatures from Sokli, Finnish Lapland (SKB Climate report p. 309-312). The Sokli data, however, should be used critically, because the chronology of the studied sequence is highly uncertain. Somewhat surprisingly, the SKB report does not mention the temperature modelling by Siegert et al. (2001) and Siegert and Dowdeswell (2004), which is based on the QUEEN data and published in the same volume as the Weichselian ice-sheet history by Svendsen et al. (2004), which is known to the authors (also by Hubberten et al. 2004, in the same volume).

Siegert et al. (2001) used a numerical ice-sheet model linked to a simple climate model to reconstruct the Scandinavian-Barents-Kara Sea Ice Sheet as constrained by the geologically mapped ice margins of the ESF-QUEEN Project (Svendsen et al. 2004). Siegert and Marsiat (2001) explain the modelling as follows: "An inverse procedure was employed in which the ice-sheet model's climate inputs (mean annual precipitation and air temperature) were adjusted until a fit between the model results and the geological evidence was established ". The climatic conditions during the Last Glacial Maximum (LGM) ca. 18-20 ka BP were extremely cold, -22° C in Southwestern Finland, according to the ice-sheet modelling and a sophisticated atmospheric general circulation model (AGCM) produces still colder temperatures between – 35° and -40° C, similar to present Greenland interior temperatures.

The cold LGM climate is also confirmed by palaeobotanical evidence from NW Russia immediately outside the LGM margin. Based on (albeit limited) pollen data, Tarasov et al. (1999) calculated that the winter and summer temperatures in this region were depressed by as much as 20°-29° C and 5°-

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[*] The review is available from STUK by request as Matti Saarnisto, "Evaluation report on the POSIVA Report 2006-5 Expected Evolution of a Spent Nuclear Fuel Repository at Olkiluoto", January 2008. Act reference number 67/410/07.

11°C, respectively. Cold Weichselian climate has been modelled in several studies, see e.g. Kageyama et al. (2001), Ramstein et al. (2007), Renssen & Vandenberghe (2002) & Roche et al. (2007).

On the basis of the above, including the Greenland Grip data, the Weichselian climate was extremely cold before the first glaciation, which covered Forsmark over 60,000 years ago for nearly 10,000 years. Forsmark was not covered by continental ice between 55,000 and more than 20,000 years ago, when the glaciation spread to its maximum Weichselian position, the Last Glacial Maximum LGM , which was reached 18,000 -20,000 years ago. The deglaciation of Forsmark took place c. 11,000 years ago.

Starting 55,000 years ago the climate was periglacial; it was getting colder and permafrost formed. The rapid growth of the glaciation to its maximum position, 1000 kilometres in 10,000 years, in the eastern sector of the Scandinavian ice sheet implies a cold climate, which was at its coldest during the Weichselian glaciations. This was also the case during the previous 100,000-year long glacial cycles, as shown by the Antarctic Vostok ice core. The climate was coldest at the end of the glacial cycle and thus also permafrost should be deepest in periglacial areas at that time (Figure 1).

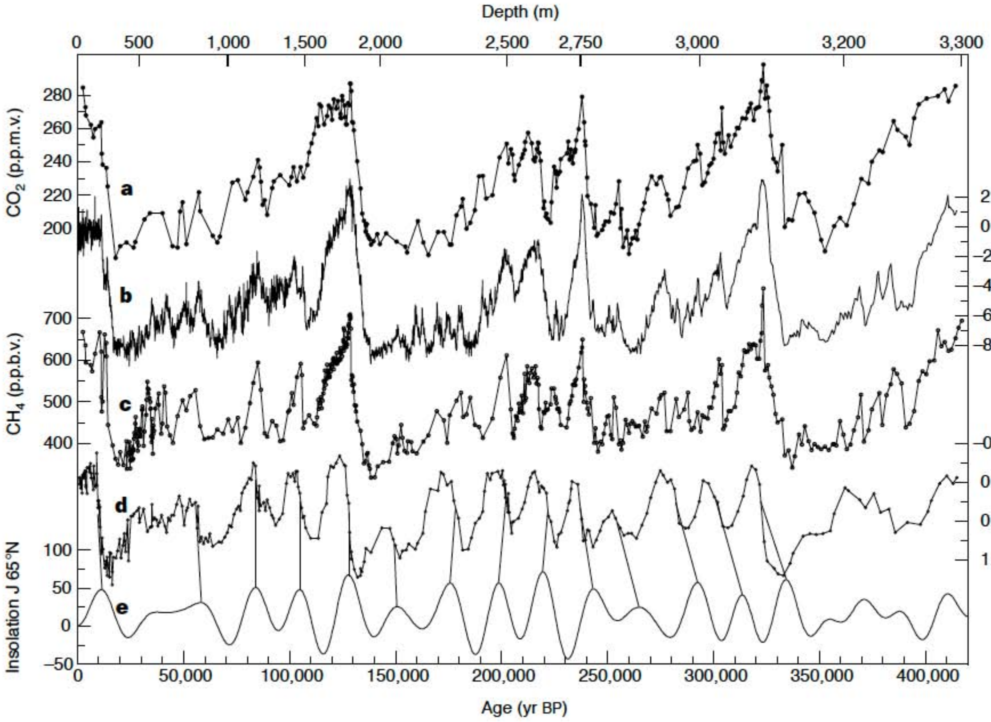

Figure 1 Petit, J.R et al. 1999 (figure 3).

On the basis of the above, it is surprising that the permafrost modelling at Forsmark has produced deepest permafrost at -230 m only 60,000 after present (AP), thus comparable to the time before the first Weichselian glaciations at Forsmark more than 60,000 years ago. The extreme cold period before 60,000 years ago lasted less than 10,000 years compared with the 30,000-year long periglacial time before the last glacial, when temperatures were extremely low for several thousand years: 32,000 - 25,000 years ago before the ice advance. In the Forsmark simulations, the permafrost will reach only more than 150 m during the coming late-glacial ca. 95,000 AP. Thus, this is in conflict with the geological data, which shows that the climate was coldest before the last ice advance to its last glacial maximum position.

In the permafrost modelling in Olkiluoto, the deepest permafrost -182 m will be reached already 65-70,000 years after the present, like at Forsmark, whereas the permafrost depth 95,000 AP, comparable to the time before LGM, would be merely 100 metres, suggesting milder periglacial conditions than 65,000 to 70,000 AP. At Forsmark the simulations are based on somewhat different model than at Olkiluoto. The postulated long submergence of Forsmark by the Baltic basin waters is now included in the simulation, but the temperature parameters should be questioned, because permafrost is present at the bottom of shelf seas in the Siberian coast, thus pointing to bottom temperatures colder than the +4° C used in the Forsmark simulations. The permafrost simulations that have resulted in nearly identical permafrost depths in both cases have been performed by Hartikainen and his colleagues (SKB Permafrost simulations report by Hartikainen & Kouhia, Posiva Report 2006-5 and Hartikainen 2006).

Hartikainen and his colleagues were also responsible for the Whiteshell permafrost modelling in Alberta, Canada. The extensive international modelling programme DECOVALEX was performed for modelling permafrost depths in glaciated terrains in Northern Hemisphere middle latitudes (e.g Hartikainen 2004, Aalto & Hartikainen 2004, Boulton & Hartikainen 2004, Chan et al.2005). The study was performed in the Whiteshell study area, which is situated on the Canadian Shield in Manitoba. The glacial and temperature history of the Whiteshell area during the last, i.e. Wisconsin, glaciation is surprisingly similar to that of the Olkiluoto area (Figure 2): the site was glaciated for a short time at about 60,000 and between 22,500 and 11,000 years ago with a maximum ice sheet thickness reaching 2,500 metres.

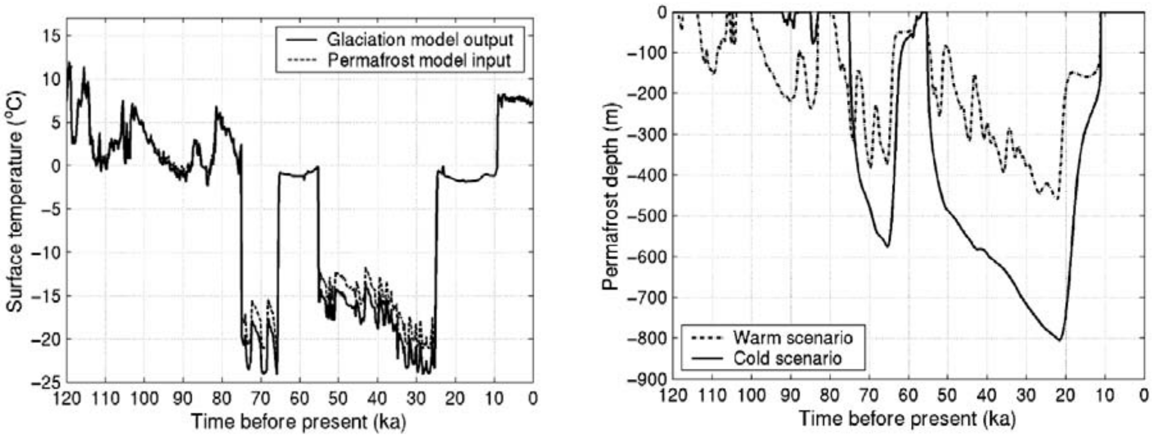

Fig. 10. Modelled ground surface temperature at Whiteshell through the last glacial cycle [7,8].

Fig. 13. Modelled permafrost depth through the last glacial cycle.

Figure 2. Chan et al. 2005.

At Whiteshell, the climate during the Early Wisconsin glaciation before 80,000 BP fluctuated between interstadial and stadial as in N Europe and the modelled surface air temperatures were lowest at -20°-25° C between 35,000 and 22,500 BP. Similar temperatures were also constructed for Olkiluoto before LGM, as described above. The existing water bodies were omitted in the modelling procedure, as in Olkiluoto, and rock properties similar to the Aspö site in Sweden were used in simulations. The modelling results in a permafrost depth of 800 metres before the ice advances towards the LGM position. The melting of permafrost takes place when the Whiteshell site was under the continental ice 22,500 -11,000 BP (Boulton et al. 2004). The glacial temperatures correspond to the modelling estimates of the QUEEN project for the Scandinavian ice sheet as mentioned above.

The Whiteshell studies or the related publications are not mentioned in the SKB report and I could not find references to them in the SKB Forsmark permafrost simulations report by Hartikainen et al. That is surprising. It is tempting to refer to a paper related to the Whiteshell permafrost studies, whose first author is G. Boulton (Boulton et al. 2004), one of the world's leading glacial geologists: “The value of the models can be tested only through their capacity to simulate the known climate and glacial history in the past”.

Using the so-called PMIP model-data comparison (Kageyama et al. 2001) and Greenland temperature history, Forsström (2005) has modelled the Eurasian Ice Sheet's dynamics during the last glaciation. On the basis of her results and combined with geothermal heat data, Forsström concludes that at LGM the ground surface temperature beneath the glacier was -12° C at Outokumpu, Eastern Finland, and that during the melting of the glacier after LGM the surface temperature increased linearly towards 0° C. The same modelling also results in below-freezing temperatures of -4° C at the depth of -500 metres, thus well below the planned depository depth at Olkiluoto -420 m.

The above results show that the LGM ice sheet was cold- based in southern Finland. Lundqvist (2007) has suggested on the basis of the configuration of glacial landforms, that the ice sheet was cold-based until the deglaciation of the Bothnian Sea ca. 11,000 years ago, i.e. until the Forsmark site became ice-free. Contrary to the above information, the LGM glaciation is warm-based in the SKB report model thus again reflecting too high temperatures in modelling exercise, which has lead to permafrost depths that are too low.

The following two examples from glacial and periglacial environments contribute to an understanding of the permafrost depth during the future glaciations comparable to the last, Weichselian, glaciations. The example from Antarctica was not known to me when I evaluated the above Posiva report, whereas the studies from the Lupin cold mine in Canada were treated in my report. Both show considerably deeper permafrost than simulated for Forsmark and Olkiluoto.

Geophysical and geodetic studies of bedrock, permafrost and continental ice in Queen Maud Land, Antarctica have been conducted by Ruotoistenmäki and Lehtimäki (2009). Their study has relevance also for the permafrost effects on a spent nuclear fuel repository. In Figure 3 a simplified model is given of permafrost effects on a repository. Ruotoistenmäki and Lehtimäki write: “When predicting the effects of future ice ages on the nuclear waste disposal depositories it is important to study sites where present day permafrost characteristics in bedrock below continental ice are well known. The method described here gives a rapid method for measuring the geometry and conductivity of permafrost giving thus background material for modelling permafrost behaviour. If, e.g. in Fennoscandia, the average annual temperature during the future ice age will be close to -15º C, as predicted, it can be assumed that permafrost and underlying pulse of saline waters will reach depths of ca. 800 m. However, the intensity of saline water pulse in e.g. Finland will apparently be different due to different composition and structure of bedrock (basaltic in Basen- Fossilryggen and mainly crystalline in Finland). Moreover, even in areas where continental ice and permafrost have already melted, the deep layers of saline waters can still give indications of the geometry of the ancient permafrost, as depicted in Figure 6”, Figure 6 is reproduced as figure 3 in this report.

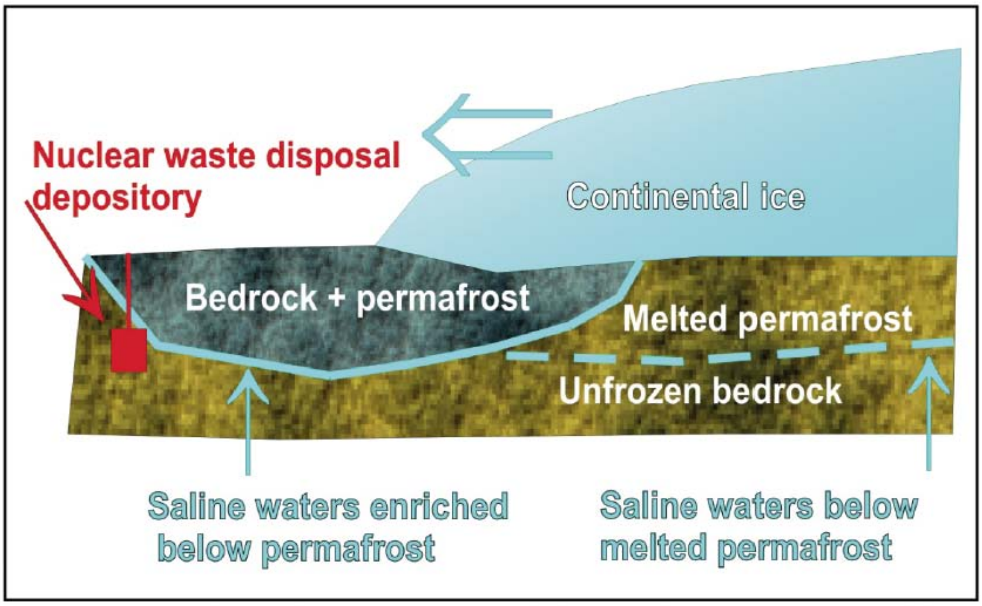

Fig. 6. Model of permafrost effects on nuclear waste repository.

Figure 3. Ruotoistenmäki & Lehtimäki 2009.

Permafrost depths were empirically studied in the Lupin gold mine, NW Canada by Ruskeeniemi et al. (2002, 2004). They found that permafrost penetrates to the depth of 540 metres where the temperature was 0° C. They also conclude that permafrost has reached its present depth only during the past 5,000 years when the climate has cooled to the present -12° C annual temperature. The early postglacial temperatures were several degrees centigrade higher but in any case clearly below 0° C. The old permafrost had melted due to geothermal heat between 28,000 and 9,000 BP when the Lupin site was covered by the continental ice sheet or a body of water. As soon as the site emerged, the permafrost started to develop, i.e. 9000 a BP and with an accelerated speed during the past 5,000 years. The temperature history and available time at Lupin are very similar to Forsmark and Olkiluoto before the ice advance 20 ka BP. The rock parameters are obviously, however, different, as the rock type is quartzite at Lupin with very high hydraulic conductivity in subvertical structures. In Forsmark and Olkiluoto the rocks are granitoids (and basalt in Basen-Fossilryggen, Antarctica).

Conclusions

In the SKB report, according to its authors, the greatest uncertainties in permafrost simulations are “the air temperature curve reconstructed for the Forsmark site for the last glacial cycle, which is estimated to be uncertain by ±6 C”. This conclusion is obvious.

The temperatures chosen from the Greenland GRIP core data in permafrost simulation are too low, and therefore permafrost depths that are too low were obtained. Contrary to the past glaciation history, showing coldest climate at the end of a glacial cycle, chosen temperatures were coldest in the middle of the glacial cycle, and thus simulated permafrost was the deepest. However, the long periglacial, ice-free period of up to 30,000 years leading to the rapid expansion of the ice sheet to the last glacial maximum LGM is the period when permafrost penetration is deepest. According to the SKB report, in Forsmark (and according to the Posiva report in Olkiluoto) the permafrost depth during this period is, however, is lower than earlier, - 150+ m at Forsmark and -100 m. at Olkiluoto. The suggested maximum depths ca. 60,000 AP would be -230 m and -182 m, respectively.

It is interesting to note that generally in the permafrost simulation performed by Hartikainen et al. there is a tendency to somewhat deeper permafrost at Forsmark in comparison with Olkiluoto, although similar climate parameters have been available. Perhaps this shows the improvement of the model. In extreme simulation, the permafrost reaches -450 m at Forsmark, which is the planned repository depth, but this has been considered unrealistic (SKB Permafrost simulations report p. 97). The sensitivity of the permafrost depth to temperature and time is illustrated in the SKB Climate report Figure 3-52.

The periglacial ice-free periods when Forsmark emerged from the Baltic basin waters were long enough 75,000-65,000 and 55,000-25,000 years ago for the deep permafrost formation, deeper than the planned depository, if lower temperatures would be used in simulations. The QUEEN modelling suggests much colder temperatures during the last glacial maximum supported also by palaeobotanical evidence, which means deeper permafrost. Case studies from Antarctica and Lupin in Canada as well as modelling exercise at Whiteshell, Canada suggest much deeper permafrost also at Forsmark. A cold-based last ice sheet would also contribute to the deeper permafrost when compared to the Forsmark simulations using a warm-based ice sheet.

Dr. Ilmo Kukkonen, GTK, a leading specialist of past rock geothermal properties, and a long-time partner of Posiva, gave a lecture in June 2010 at a small meeting in Moscow, where I was also present. He simulated the permafrost depth during a glacial cycle in Finland, which resulted in 600-metre deep permafrost. I do not know the parameters that he used, but at least he knew the parameters that I proposed in my evaluation to STUK of the Posiva report entitled “Expected Evolution of a Spent Nuclear Fuel Repository at Olkiluoto”, mentioned above.

In conclusion, I disagree with the SKB statement that "For glacial and in particular permafrost climate conditions the temperature at repository depth will decrease, but will always be above 0°C."

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