Working Report 97-51e

A Response to Report "A critical review of published groundwater flow models for safety of nuclear waste disposal" (STUK-YTO-TR 130)

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December 1997

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Diary code ENE4-9K-97	**Order reference**
Project title and reference code	**Report identification & Pages** ENE4/49/97 18 pages — **Date** 30.12.1997

Report title and author(s)

A RESPONSE TO REPORT "A CRITICAL REVIEW OF PUBLISHED GROUNDWATER FLOW MODELS FOR SAFETY OF NUCLEAR WASTE DISPOSAL" (STUK-YTO-TR 130)

Lasse Koskinen

Summary

This report responds to the criticism expressed against the groundwater flow modeling work done at VTT Energy. The criticism is presented in report "*A critical review of published groundwater flow models for safety of nuclear waste disposal*" (STUK-YTO-TR 130) published by the Finnish Nuclear Safety Authority. The main approach applied in the reviewed works is the equivalent porous medium approach. Undoubtedly, this modeling approach is based on a number of simplifying assumptions, partly in order to facilitate computations in practice and partly due to lack of more detailed data from the preliminary site investigations. The weaknesses of this approach are explained in our reports according to the normal scientific manner. On the other hand, also the rationale and advantages of the approach have been clearly described. We find the criticism largely unwarranted and misleading mainly for the following reasons:

- The criticism presents several misleading remarks on the original works. These are explicitly addressed in this report.
- The criticism fails to recognize the link between an appropriate modeling approach and the scale of the flow domain and the pertinent phenomenon. Although water flows along fractures of the crystalline hard rock on all scales, over large enough volumes the equivalent porous medium approach may be reasonable. As a token of this, the approach has performed satisfactorily in real and well documented modeling exercises.
- The criticism ignores the rationale and advantages of the modeling approach in the reviewed reports. They represent the state of the numerical and conceptual model development that was consistent with the set objectives, and the quality and quantity of the hydrogeological data of the time of the analyses.
- The criticism seems to be based on the notion that the modeling methodology was in a sort of a standstill phase. The notion is not correct. The groundwater flow modeling within nuclear waste management — as any long term scientific programme — undergoes a consistent evolution, which has not been recognized by the critic.
- Much of the criticism actually discusses inadequacies that are in reality arising from the insufficient data from the preliminary site investigations. A continuing model development consistent with the increasingly detailed data is being undertaken in the cooperation with the experts of VTT Communities and Infrastructure.
- Although the criticism suggests "alternative" approaches, it does not discuss how these would benefit the safety analysis in determining the crucial flow and transport parameters in practice, and within the schedule of the Finnish site selection programme.

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Approved by Lasse Mattila Research Manager, Nuclear Energy	**Availability statement** Published as POSIVA Work Report 97-51e

A RESPONSE TO REPORT "A CRITICAL REVIEW OF PUBLISHED GROUNDWATER FLOW MODELS FOR SAFETY OF NUCLEAR WASTE DISPOSAL" (STUK-YTO-TR 130)

ABSTRACT

This report responds to the criticism expressed against the groundwater flow modeling work done at VTT Energy. The criticism is presented in report "*A critical review of published groundwater flow models for safety of nuclear waste disposal*" (STUK-YTO-TR 130) published by the Finnish Nuclear Safety Authority (former Finnish Centre for Radiation and Nuclear Safety). The main approach applied in the reviewed works is the equivalent porous medium approach. Undoubtedly, this modeling approach is based on a number of simplifying assumptions, partly in order to facilitate computations in practice and partly due to lack of more detailed data from the preliminary site investigations. The weaknesses of this approach are explained in our reports according to the normal scientific manner. On the other hand, also the rationale and advantages of the approach have been clearly described. We find the criticism largely unwarranted and misleading mainly for the following reasons:

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- The criticism seems to be based on the notion that the modeling methodology was in a sort of a standstill phase. The notion is not correct. The groundwater flow modeling within nuclear waste management — as any long term scientific programme — undergoes a consistent evolution, which has not been recognized by the critic.
- Much of the criticism actually discusses inadequacies that are in reality arising from the insufficient data from the preliminary site investigations. A continuing model development consistent with the increasingly detailed data is being undertaken in the cooperation with the experts of VTT Communities and Infrastructure.
- Although the criticism suggests "alternative" approaches, it does not discuss how these would benefit the safety analysis in determining the crucial flow and transport parameters in practice, and within the schedule of the Finnish site selection programme.

Keywords: groundwater flow, modeling approach, porous medium, continuum, scale.

VASTINE RAPORTTIIN "A CRITICAL REVIEW OF PUBLISHED GROUNDWATER FLOW MODELS FOR SAFETY OF NUCLEAR WASTE DISPOSAL" (STUK-YTO-TR 130)

TIIVISTELMÄ

Tämä raportti on vastine VTT Energiassa tehdylle pohjaveden virtausmallinnusta kohtaan esitetylle kritiikille, jonka Säteilyturvakeskus on julkaissut raportissa "*A critical review of published groundwater flow models for safety of nuclear waste disposal*" (STUK-YTO-TR 130). Arvosteltujen mallinnustöiden keskeisin lähestymistapa on ekvivalentin huokoisen väliaineen malli. Lähestymistapa toki perustuu yksinkertaistaviin oletuksiin, jotta ongelma saataisiin käytännössä käsiteltävään muotoon. Toisaalta yksinkertaisiin oletuksiin turvauduttiin myös alustavien sijoituspaikkatutkimusten tuottaman tiedon riittämättömyyden vuoksi. Mallinnusmenetelmän heikkoudet on selostettu alkuperäisissä raporteissa tieteellisen raportoinnin edellyttämän käytännön mukaisesti. Toisaalta myös lähestymistavan perusteet ja vahvuudet on niissä tuotu selkeästi esille. Mielestämme kritiikki on pääasiassa perusteetonta ja harhaanjohtavaa seuraavista syistä:

- Kritiikki esittää useita harhaanjohtavia alkuperäisiä töitä koskevia huomautuksia, joihin vastataan tässä raportissa.

- Kritiikki ei ymmärrä tarkoituksenmukaisen mallinnusmenetelmän ja tarkasteltavan virtausalueen tai -ilmiön skaalan välistä yhteyttä. Vaikka kiteisessä kalliossa pohjavesi virtaa raoissa kaikissa skaaloissa, riittävän suurten kalliolohkojen tapauksessa ekvivalentin huokoisen väliaineen lähestymistapa voi olla hyväksyttävissä. Osoituksena tästä menetelmällä on saatu tyydyttäviä tuloksia todellisissa ja hyvin dokumentoiduissa mallinnusharjoituksissa.

- Kritiikki sivuuttaa alkuperäisissä raporteissa esitetyt mallinnusmenetelmän perustelut ja vahvuudet. Raportit edustavat aikansa numeerisen ja konseptuaalisen virtausmallinnuksen kehitysvaihetta, joka oli yhdenmukainen silloisten asetettujen tavoitteiden, ja hydrogeologisen tiedon laadun ja määrän suhteen.

- Kritiikki vaikuttaa perustuvan käsitykselle, että mallinnusmenetelmä olisi jonkinlaisessa valmiissa, pysähtyneessä tilassa. Käsitys ei pidä paikkaansa. Pohjaveden virtausmallinnus — kuten mikä tahansa pitkäaikainen tieteellinen tutkimusohjelma — kehittyy asetettujen tavoitteiden mukaisesti.

- Suuri osa kritiikin esille tuomista seikoista liittyy itse asiassa puutteisiin alustavien sijoituspaikkatutkimusten tuottamassa tiedossa. Mallinnusmenetelmää kehitetään johdonmukaisesti yhdessä VTT Yhdyskuntatekniikan asiantuntijoiden kanssa siten, että laskentatulokset perustuvat yhä laajemmalle ja seikkaperäisemmälle paikkakohtaiselle tiedolle.

- Vaikka kritiikki ehdottaa "vaihtoehtoisia" lähestymistapoja, se ei selitä, miten ne käytännössä hyödyntävät turvallisuusanalyysia virtaus- ja kulkeutumisparametrien määrittämisessä Suomen ydinjätehuollon aikataulun puitteissa.

Avainsanat: pohjaveden virtaus, mallinnusmenetelmä, huokoinen väliaine, jatkumo, skaala

CONTENTS

1 INTRODUCTION

This memorandum responds to the criticism by Laine (1997) who has expressed an opinion on the numerical groundwater flow modeling performed at VTT Energy. Laine's (1997) criticism is based on the following reports published by the Nuclear Waste Commission of the Finnish Power Companies:

- Koskinen L. & Laitinen M. 1995. "Numerical study on the effects of the alternative structure geometries on the groundwater flow at the Olkiluoto site". Report YJT-95-15.

- Koskinen L. & Meling K. 1994. "Numerical study on the effects of the alternative structure geometries on the groundwater flow at the Romuvaara site". Report YJT-94-18.

- Löfman J. & Taivassalo V. 1993. "FEFLOW 1.10 — Solving of coupled equation for flow, heat transfer and solute transport". Report YJT-93-30.

- Poteri A. & Taivassalo V. 1994. "Modeling of the fracture geometry in the preliminary site investigations for a nuclear waste repository". Report YJT-94-08.

- Taivassalo V., Koskinen L. & Meling K. 1994. "Groundwater flow analyses in preliminary site investigations — Modeling strategy and computer codes". Report YJT-94-04.

- Taivassalo V. & Mészáros F. 1994. "Simulation of the groundwater flow of the Kivetty area". Report YJT-94-03.

- Taivassalo V. & Poteri A. 1994. "Assessing the velocity of the groundwater flow in bedrock fractures". Report YJT-94-17.

The organization of this report is the following: The next section, the main part of this report, forms the reply according to flow of the pages in Laine (1997). Although the referred points of the criticism are repeated in this report, the reader is expected to have Laine's (1997) report available while reading this reply. The excerpts from (Laine 1997) are indicated inside quotation marks (" ") and are printed with *italic* typeface. Other quotations are given in a similar style but in indented paragraphs. The third section describes two real and well-documented modeling exercises, where the potential of the equivalent porous medium approach was tested against some other approaches. The fourth section introduces a plan to outline the groundwater flow modeling within next few years.

2 DETAILED COMMENTS

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"As a result, it was concluded that the obtained flow model for the specific site is only one of the many possible alternative models reproducing the values measured in the field and in the boreholes".

The "obtained flow model" was directly based on the corresponding bedrock model, which, in turn, built on the best available geological expertise on an investigation site. As a simplifying working hypothesis — to facilitate numerical simulations in practice — it was indeed assumed that to a large extent the bedrock models correctly described the reality. At least in the case of the Romuvaara area, even the most recent field observations do not essentially disagree with the main characteristics of the early conceptual models. Factually, regarding to essential flow characteristics on the site scale, the potential of this so-called deterministic approach has not been seriously challenged. Most recently published performance assessments concerning crystalline rock (SKB-91, Kristallin-I, AECL, Nirex-95, SKI SITE-94) take this approach for the large scale flow simulations; see e.g., (NEA 1997).

"Moreover, the equivalent continuum approach is a very strong simplification of the crystalline bedrock characterized by the discontinuities such as joints and fracture zones. In addition, the assumption of homogeneity and isotropy of the bedrock properties outside the major fracture zones may lead to erroneous results."

Our modeling approach is **not** a continuum model in the implied sense. VTT Energy's modeling approach makes every effort to respect all the discontinuities that have been presumed significant on the *site scale*. The number of discontinuities — each described separately with the equivalent porous medium approach — can amount to several tens of fracture zones and other flow regions. For the smaller scale flow simulations, appropriate approaches are being developed (Niemi et al. 1997; Koskinen et al. 1998).

Of course any simplifying assumption may lead to erroneous results. Therefore simulation results are compared with observations. In addition, our modeling approach has also been compared with other approaches in two real and well-documented modeling exercises (see Section 3). However, there is no and will never be any modeling method free of simplifications.

"It is proposed that, besides the present flow modeling approach, alternative approaches should be applied using as a starting point the discontinuities in the bedrock and a division of the bedrock according to fracturing into separate hydraulic units."

There is no "present flow modeling approach" in the implied sense. Question really is what is an appropriate approach to be used in the problem at hand. The equivalent porous medium[2] approach is applicable to resolve the flow field on a site scale (i.e., scale of a rock block comprising an area of several square kilometers large and a couple of kilometers deep) in practice.

Modeling approaches of a stochastic continuum and fracture network modeling are presently being applied on intermediate scale (that is up to about 1 km) and block scale (~ 50 m) (Niemi et al. 1997; Koskinen et al. 1998). Both approaches are being developed and applied consistently with the expanding body of field data.

"*Geostatistical methods, especially the indicator approach, should be used in mapping the heterogeneity of the bedrock properties in site areas. The use of geostatistical expertise is essential in determining the spatial correlation and its anisotropy for the hydraulic properties because the available data preferentially from a small number of boreholes.* "

The hydrogeologic properties of bedrock units were provided us by geologists. Some changes of the physical parameters were achieved with calibration. The methodology to determine the spatial correlation and anisotropy upon the basis of fracture networks and hydrogeologic data is being developed by the group of VTT's geostatisticians (Niemi et al. 1997). With regard to the numerical flow modeling, it undergoes a steady and consistent development in which the reviewed works have represented a natural stage.

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"*Introduction*" of (Laine 1997) is largely inaccurate and outdated, and evidently fails to communicate some basic facts about the nuclear waste management programme in Finland. For example,

- today, there are four — not three — investigation sites,
- the site selection is managed by Posiva Oy, which
- is owned by Teollisuuden Voima Oy and Imatran Voima Oy power companies, and
- the nuclear waste repository is planned to contain the spent fuel from both the Olkiluoto and Loviisa power plants,
- the site selection programme is scheduled according to predetermined milestones:
- The site for spent fuel disposal will be selected by the end of the year 2000; construction will start 2010, operation starting in 2020 will last for about 25 years.

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[2] In this respond, to maintain the consistency with the currently generally used terminology, we use the term "equivalent porous medium" approach to stand for the modeling concept that was called "equivalent continuum" approach in the reviewed reports.

Pages 17 and 18:

In essence, all of the "critical points" are already discussed in our reports — as the conventional scientific procedure stipulates. Instead, the conduct in the criticism to lump them together out of their contexts is an unscientific and unjustified treatment, which distorts the argumentation and motivation of the original texts. While the discussion on page 17 in (Laine 1997) is misleading in general, only the falsest remarks are addressed here.

"*Moreover, fitting the fracture geometry to better correspond to the obtained simulation results is questionable: the changes of the fracture geometry should be based on the geological expertise. The bedrock models are not unique but they should not be changed solely based on the simulation results.*"

We disapprove of this completely untrue expression. The reasoning for the "*changes of the fracture geometry*" can be found in the original texts as well as the motivation and content of the works studying the effect of the alternative structure geometries (Koskinen & Meling 1994; Koskinen & Laitinen 1995). The variations were mainly based on the alternative models presented by geologists. Only when they did not offer any explanation for the evident discrepancy between measured and calculated values, the modelers suggested a feature, while capable of explaining the anomaly, such that it represented the slightest possible but a realistic change in the original bedrock model.

"*(2) The argumentation concerning the applied equivalent continuum approach is not satisfactory. The fact that it is usually applied does not mean that it is an adequate approach.*"

The above statement exemplifies the abuse of the out-of-context sentences of the original texts. The approach, its limitations, and the significance and interpretation of results were — according to normal scientific practice — clearly explained in each of our reports. The following excerpt is from (Taivassalo, Koskinen & Meling 1994) page 8:

> "*When the site characterization programme was planned (Äikäs 1985), the equivalent continuum approach was the only one available. Even nowadays, in simulating groundwater flow for large areas such as an investigation area, the equivalent continuum approach is used almost exclusively. Given the prior data available, the objectives of the flow analyses and the time constraints, there were no feasible alternatives for carrying out the flow analyses in the preliminary site investigations other than the equivalent continuum approximation.*"

On the other hand, whether the approach is "adequate" can be tested to some extent with real cases as described in Section 3.

"*(3) The bedrock properties are assumed to be isotropic even if, for example, the hydraulic conductivity ruled by fracturing possesses a strong anisotropy.*"

During the preparation of the reviewed reports there was no actual quantitative information on the anisotropy of the conductivity at the investigation sites. According to Niemi (1994) the data from the preliminary site investigations were not sufficient to allow the determination of anisotropy.

"*(5) The physical phenomena such as hydraulic head is assumed to be continuous. This is however not probable. The bedrock consists of separate hydraulic systems with their own head distributions and these separate systems are connected top the surface only at a few points. (...) This makes the upper boundary condition questionable. For each of the connected fracture systems the hydraulic properties should be defined separately.*"

It is true that some problems are associated with the direct application of the water table as the top boundary condition. This has been clearly explained in the reviewed reports. Otherwise, point "*(5)*" is largely beyond comprehension. The hydraulic head is a continuous quantity (rather than "*phenomenon*") in nature. In some cases, it may vary strongly in space but this variability is due to even more remarkable variability of the conductivity, which is the first thing to be resolved in any case.

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Instead of the definitions presented by the critic, the community of nuclear waste management abides by the definitions of IAEA (1993):

> "***calibration*** *(of a model). A process carried out by comparison of* ***model*** *predictions with field observations and experimental measurements. A* ***model*** *may be calibrated by using data obtained from a particular location or for a limited range of conditions. It may then be considered valid for use in those circumstances but not necessarily in all circumstances.*
>
> ***validation*** *(of a model). A process carried out by comparison of* ***model*** *predictions with field observations and experimental measurements. A* ***model*** *is considered validated when sufficient testing has been performed to ensure an acceptable level of predictive accuracy over the range of conditions over which the* ***model*** *may be applied. (Note that the acceptable level of accuracy is judgemental and will vary depending on the specific problem or question to be addressed by the* ***model****.)*
>
> ***verification*** *(of a model). The process of showing that a mathematical* ***model****, or the corresponding computer code, behaves as intended, i.e. that it is a proper mathematical representation of the conceptual* ***model*** *and that the equations are correctly encoded and solved.*"

These definitions differ significantly from those on page 19 in Laine (1997). It is regrettable if the ignorance of some basic definitions has lead to misinterpretations.

Pages 21–23 (Section 4.1)

The geostatistical approach to infer the hydrogeologic properties of the bedrock is already being developed and subsequently applied by the modeling team of VTT Communities and Infrastructure (Niemi et al. 1997).

With regard to bedrock properties, we have relied on experts. The simple parametrization utilized in the reviewed works has had its practical merits. Obviously more elaborate treatments have their own advantages as well as disadvantages. For example, according to Rosen & Gustafson (1996), whom are referred in (Laine 1997), one major weakness (among a few) of their geostatistical approach is that

> "*There is a discrepancy among statisticians regarding Bayesian statistics, and it should be emphasized that its use is controversial.*"

Laine (1997) applied a geostatistical approach to determine the hydraulic conductivity at the Olkiluoto site:

"*As an example, the hydraulic conductivity at the Olkiluoto site was geostatistically simulated using the conditional sequential indicator simulation (...) with only one cut off (1.00E-07 m/s). There were not enough data for the proper variogram analysis (description of the spatial correlation), and the spatial correlation and its anisotropy were inferred from the assumption of the main fracture direction being to the northwest. In addition, the results of the geostatistical study done for geophysical and geological data from the Olkiluoto site (Laine 1996) was used.*"

The assumption is incorrect. The main fracture direction is not to the northwest at the Olkiluoto site (Front & Kontio 1994; Paulamäki 1996; Paulamäki et al. 1996). The conformity between the structural model of the Olkiluoto site and Figure 6 in (Laine 1997) is virtually non-existing.

Laine's (1996) work applied geostatistical methods to characterization of the heterogeneity at Olkiluoto. The *main* outcome (in the sense of "characterization" as it is given in the abstract in (Laine 1996)) is the following:

> "*..., the fracturing seems to form zones in the sparsely fracture rock mass.(...) According to these simulations, the bedrock of Olkiluoto is rather heterogeneous.*"

Indeed, one can only agree with this "result".

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"*The possibility of the use of the geological expertise, for example concerning tectonic history of the studied areas, should be reconsidered. The tectonic history means the deformations that have deformed the bedrock from the time of sedimentation and first magmatic intrusions until the present. Deformations are either plastic, such as ductile folding, or brittle such as fracturing. For the major part of the Finnish bedrock, ductile folding predominated in deeply buried formations. The latest deformations were and are mainly brittle near or at the surface. The early fold generations caused by schistosity that often controls the fracture directions. The* *deformations depend on the stresses and tensions in the rock and the rock types. Even if the description of the tectonic history does not give exact numbers for modeling, it may give the critical directions for anisotropy of the geological structures to be used in fracture modeling. In the Precambrian bedrock, an additional difficulty is folding: the directions measured for jointing are not in relation to the geographic North but to the previous tectonic features such as schistosity. The different rock types also behave differently during deformations."*

Fracture network modeling is based on a number of assumptions to facilitate simulations in practice. It indeed is not fully guaranteed that the assumptions do not rule out some important factors. The conceptual uncertainty for fracture statistical models is seen as high. The types of the statistical models employed in the current research are best described as descriptive, rather than genetic (i.e., based directly on the understanding of fracture genesis).

The research on the development of the fracture populations, based on the principles of fracture mechanics (e.g., Renshaw & Pollard 1992) may eventually furnish genetic arguments for particular models and for relatively simple deformation histories. For the rocks that have undergone multiple episodes of brittle deformation, fracture models will most likely continue to be descriptive rather than genetic, for the foreseeable future. However, a methodology for characterization of fractures with respect to rock type, tectonic evolution, infillings, and wallrock alteration is being developed within the Äspö HRL project (SKB 1997). On the other hand, the potential of the "traditional" approach is being tested with a real and well-documented modeling exercise within the TRUE (Tracer Retention Understanding Experiment) project (SKB 1997).

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"The approach is widely applied, especially for sedimentary rock formations. It is also applied for modeling the flow in crystalline bedrock. It may be suitable approach when the bedrock is highly fractured. In the cases of possible nuclear waste sites, the bedrock is sparsely fractured except for the rare fracture zones, and consists of separate hydraulic systems, such as flow paths formed by connected fractures. The hydraulic head distributions and the flow directions should be defined separately for each hydraulic system."

While we agree that there are limitations with regard to the applicability of the equivalent porous medium approach, it is difficult to make estimations *a priori* on what level of fracturing as such makes the approach inapplicable or applicable. However, the nominal number of the fractures even in the sparsely fractured rock is huge. For example, the number of such fractures in a simulation concerning a rock block of $16 \times 16 \times 16$ m^3 was 2000 (Poteri & Laitinen 1996). This implies that the number of the fractures over a typical site scale model of equivalent porous medium is order of 10^{10}.

The criticism fails to recognize the connection between the applicable approach and the *scale* of the flow domain or studied flow phenomenon. The groundwater flow modeling within the Finnish site selection programme utilizes different modeling approaches on several different scales. On the two largest scales, i.e., regional and site scale, the equivalent porous medium approach is deemed appropriate. The intermediate scale modeling will be performed using the stochastic continuum approach. The block scale modeling will be treated with (equivalent) fracture network model. On the smallest scale, the effect of the heterogeneity in an individual fracture on the flow and transport properties is to be tackled with the variable aperture approach. In general, the procedure is similar to that in the SITE-94 performance assessment (SKI 1996).

The appropriate modeling approach is selected to account for the presumed important features characteristic to the flow at the scale in question. Of course, this can be seen as a simplification in the sense that on the larger scale the smaller scale variability is lumped into the effective properties of the numeric blocks or elements of the larger scale element mesh. It simply is impossible in practice to perform numerical simulations on the site or regional scale with elements capable of accounting for the heterogeneity on its smallest observed scale. On the other hand, the applicability of the equivalent porous medium approach for site scale simulations has been tested with real and well documented modeling exercises (Gustafson & Ström 1995; Gustafson, Ström & Vira 1997).

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"*Based on the 200 (conditional) sequential indicator simulations, there are great differences in the calculated flow velocities (...). ... conditioning in simulations is a key ingredient in confidence building.*"

While it is self-evident in the case of any strongly heterogeneous medium that "*there are great differences in calculated flow velocities*" even without any calculation, the very purpose of conditioning basically is confidence building. As Section 4 explains, safety analyses need more detailed characterization.

"*Even if the stochastic continuum method takes the heterogenic and random nature of the hydraulic properties into account, it assumes a certain continuity for the variables by calculating the flow for the whole site in one simulation.*"

From the point of view of numerical groundwater flow simulation, this sentence is beyond comprehension. A certain *physical* continuity is assumed in the form of conservation of volumetric flow. To be precise, in nature the hydraulic head as well as the hydraulic conductivity are continuous quantities. On the other hand, the variability of the hydraulic conductivity can be so enormous, that the discontinuity-like treatment of it is justified. The hydraulic head, in turn, is much more continuous a quantity in this sense.

"*Because the crystalline bedrock is divided into separate hydraulic systems according to the fracturing (...) the hydraulic head measured on the surface may have nothing to do with hydraulic heads down in the bedrock. In the sparsely fractured bedrock, hydraulic head is not a continuous variable. The possible alternative could be to measure hydraulic head only in the fracture zones or densely jointed areas and to use these values in assessing flow in separate fracture systems.*"

The problem associated with the observed water table as the top boundary condition has been addressed a number of times in our reports. It is also explained in the reports, how this problem has been tackled in the calibration of the flow models. The water table has been applied as a boundary condition as long as there has not been better information on the reality. Inclusive measurements "*only in the fracture zones or densely jointed areas*" might, indeed, be useful. On the other hand, this may not be as straightforward as the critic implies:

- The location of the fracture zone below the terrain overburden is subject to large uncertainty.
- The water table in the locations of the fracture zones may still be incorrect as a directly applicable boundary condition. The overburden and/or near surface heterogeneity result in remarkable change in the observed hydraulic head along with depth (for illustration, see, e.g., TVO 1992). In this respect a more substantial boundary condition could be inferred with boreholes penetrating the uppermost layer of the bedrock.
- Drilling boreholes is expensive.
- The boreholes may affect the flow conditions in ways that should be seen as detrimental to the analysis assuming the natural conditions.

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"*Because of the difficulties in already applied methods, quite different approaches should be studied for assessing the flow in fractured media. The flow modeling may possibly be done using the fuzzy logic approach based on the hydraulic properties in separate cells inferred from fracture simulations. (...) fuzzy rule-based models offer a simple alternative for calculating the 1-, 2-, or 3-dimensional movement of soil moisture in a heterogeneous soil. Here the similar approach is proposed for flow modeling in the crystalline bedrock.*"

Undoubtedly, there are lots of "possible" modeling approaches — all infested by the "difficulties" of their own. Unfortunately, limited resources do not allow a thorough testing and application of every evolutionary and elaborate method; at least, not on the national level. The imperative role of the flow modeling is to evaluate flow and transport parameters used in safety analyses (SKI 1996; Andersson et al. 1997). Any presentation of "alternative" approaches should:

- Evaluate the general requirements of a site-specific analysis and assess how groundwater flow modeling can support the safety assessment.
- Discuss their relevance, data requirements, practical aspects, incorporation of the relevant features, events and processes and potential to the safety analyses.

Such an evaluation is introduced in Section 4.

3 TWO MODELING EXERCISES

This section introduces two well-documented modeling exercises, which were tackled with — besides the equivalent porous medium by the modeling group of VTT Energy — several other alternative modeling approaches as well. The purpose of this section is to show that the adequacy problem (see remark 2 in Laine (1997) on page 17) has been weighed with real test cases.

The Äspö HRL Task Force on the Modeling of Groundwater Flow and Transport of Solutes[3] has supervised two modeling exercises, Tasks 1 and 3, concerning large scale groundwater flow. The first modeling task concerned a large-scale field experiment, LPT2, a long-term pumping test with borehole KAS06 at the Äspö island (Rhén et al. 1992). The pumping in borehole KAS06 began in September 17, 1990. The drawdown phase continued until December 18, 1990 and the recovery phase until January 18, 1991. During LPT2, observations of drawdowns were made in about 100 packed-off borehole sections.

The modeling of Task 1 was performed by eleven teams from France, Finland (Taivassalo et al. 1995), Japan, Sweden and UK. Several groups applied the deterministic equivalent porous medium approach. On the other hand, stochastic approaches of the channel or fracture networks were also applied. The evaluation of the Task 1 modeling experiences is given in (Gustafson & Ström 1995), from which is the following excerpt:

> *"Eleven different groups have modeled Task No 1 using different conceptual and numerical methodologies for simulation flow and transport in fractured rocks. A wide range of approaches has been utilized, from rather straightforward concepts using assumptions of one-dimensional flow paths for tracer tests, to advanced discrete fracture network modeling using site fracture data, calibration and conditioning. All the modeling approaches used, which represent the whole spectrum of possible methodologies, have the capacity simulating the LPT2 set of test, both flow and transport of solutes. The LPT2 exercise has show that all modeling approaches are adequate for the purpose of analysing the groundwater flow characteristics of Äspö on the site scale."*

Task 3 was the modeling exercise to evaluate the hydrogeologic impact of the construction of the Äspö HRL access tunnel on the site scale. It consisted of subtasks 3A and 3B. The former aimed at the prediction of borehole drawdown history based on the existing Äspö site groundwater flow models of Task 1. The latter task was based on all data, including those collected during the tunnel excavation. The main goal of Task 3B was more generally to assess how the data from monitoring the

[3] The Task Force was initiated in the autumn in 1992. Its purpose is to be a forum for supporting the Äspö HRL Project to interact in the area of conceptual and numerical modeling of groundwater flow and solute transport in fractured rock. In particular, the Task Force will propose, review, evaluate and contribute to such work in the project.

hydraulic impact of tunnel excavation could assist in site characterization. For this purpose the modeling teams did different amounts of effort to match their modeling results to the measured drawdown effects. The task was participated by seven modeling groups from France, Japan, USA, Finland (Mészáros 1996), Sweden and UK. The approaches of Task 1 were also applied to Task 3. The adequacy of the equivalent porous medium is implicitly weighed in the following excerptions from the evaluation report (Gustafson, Ström & Vira 1997) [4]:

> *"It has been found very useful to test different modeling approaches to the same problem. As a rule the global results have been very similar if not exactly the same but local responses have been more variable, both because of the incompleteness of the presented structural model but also because of the different versatility of the different modeling approaches. Some approaches, i.e. DFN or stochastic continuum, thus give more versatile output than others, equivalent continuum, but need not necessarily be more 'true'. The more sophisticated approaches, though, give a better qualitative reflection of the conditions in the rock."*

And:

> *"Finally, Task 3 has shown that a major groundwater flow modeling task is very good way to get interaction between experimentalists and modelers. The link and understanding between these two groups seem to be much more important than the kind of computer code used. Task 3 has shown that this is possible to achieve with good results, and that groundwater flow modeling in a large volume of fractured crystalline rock is feasible."*

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[4] The evaluation report is under preparation. The excerpts are from the "final draft", dated 17.9.1997.

4 NUMERICAL FLOW MODELING OF NEXT FEW YEARS

According to the schedule set by the authorities the site for the spent fuel repository has to be selected by the end of the year 2000. The site selection will be supported by a site-specific safety analysis. This section introduces a strategy plan for groundwater flow and transport modeling to be considered for the safety analysis of spent nuclear fuel disposal (Anderson et al. 1997). The plan has been drafted by a working group of experts (from Finland and Sweden) of performance assessment, numerical flow modeling, hydrology and geostatistics. The plan builds on an evaluation of different approaches to modeling groundwater flow in crystalline rock, the abundance of data collected in the site investigation programme in Finland, and the modeling methodology so far developed in the programme.

The safety analysis assesses different release routes of the radionuclides from the repository to the biosphere. In the near field, the release pathways can be categorized as in the TILA-96 safety analysis (Vieno & Nordman 1996):

- The "fissure pathway" into fractures which directly intersect the deposition hole.
- The pathway from the top of the deposition hole into the excavation damaged zone below the tunnel floor.
- The pathway from the tunnel into the geosphere.

The far field migration modeling evaluates transport along a single one-dimensional migration path (Vieno & Nordman 1996). The retention is essentially governed by the ratio, or transport resistance, WL/q where W is the total width of channels per unit area of rock cross section, L is the transport distance and q the Darcy velocity. Regarding this approach, the following discussion, in particular, could be raised:

- There is a need to strengthen the conceptualization and estimation of flow distribution on the bedrock and derivation of the W/q estimates. In the simplified analyses, the estimates of conductive fracture frequency could clearly be made more explicit and the flow rates and flow distributions over fracture systems in various rock parts should be assessed. In a rock block with several conductive flow paths, it is likely that the flow will vary considerably between different paths resulting in a distribution of W/q values representing different paths. Furthermore, only those paths where migration actually takes place are important.
- A key aspect when determining W/q is the variability in the fracture plane. A small portion of the fracture area may account for a large portion of the flow (see, e.g., Tsang, Tsang & Hale 1991). An important issue is to what extent free water diffusion may even out the effects of the flow variability, which would make the estimation of the W/q and its coupling to the fracture geometry more robust. Some tentative studies on this subject were made already in the TVO-92 safety analysis (Vieno et al. 1992), but the issue seems to require further investigation.

A promising approach would be migration simulations with heterogeneous (as well as homogeneous) discrete fracture networks.

- A detailed groundwater flow modeling which includes the effect of small scale variability (i.e., stochastic continuum or discrete networks) may result in much faster pathways (and lower *WL/q*) than what results from the equivalent porous medium approach. TVO-92 and TILA-96 attempt to compensate the homogeneous model by selecting extreme values. However, the approach of selecting worst possible migration paths may thereby not disclose that the majority paths would have much more favorable migration characteristics.

- The present migration modeling does not imply a route dispersion term. Multiple path analyses could provide means of substantiating the dispersion effects and thus be used to validate the conclusions from the sensitivity analysis conducted within TILA-96.

The previous discussion implies that the groundwater flow modeling has a very important role in describing uncertainty and variability in migration parameters. Determination and uncertainty of *WL/q* in relation to available field information is in fact the main challenge for the far-field flow analysis. The plan recommends that these problems should be studied with the discrete fracture network and stochastic continuum models. The plan suggests an approach in which the geosphere is modeled with a system of nested models such that a larger scale model provides boundary conditions for the smaller one. Different conceptual models should be adopted for the different scales:

- Given the geometrical detail at the canister scale the most appropriate model is a discrete fracture network description. The size of the discrete model is to be limited to small blocks contained by larger size fractures. The objectives of the fracture network modeling are to:

  - Provide estimates on the range of flow rates on the scale of a canister and probability to encounter such flow rates.

  - Provide estimates of the migration properties on the scale from the repository to the nearest fracture zone and to evaluate the importance of velocity variations and spatial variability on the scale of individual fractures.

- Outside the smallest scale, on the intermediate scale, the stochastic continuum model is applied, but with hydraulic and transport parameters derived from a discrete network model. The main uses of the approach are the following:

  - To derive distributions of migration flow paths on a repository scale, while still taking into account spatial variability and uncertainty (through multiple realizations).

  - The results from a network calibration (as part of the stochastic continuum modeling) also give insight of the hydraulic heterogeneity of the site.

- The approach can be extended to transport calculations to produce integrated estimates of the ratio WL/q along each modeled migration path.

- On the site and regional scale, adoption of the equivalent porous medium is appropriate. The regional scale takes the regional fracture zones and watersheds into account whereas the site scale model describes the local fracture zones and deterministic structures found in the site. The objectives are as follows:

  - The primary interest is to establish the overall hydrogeological regime and thereby to provide boundary conditions to the more detailed modeling.

  - The effect of a repository itself on groundwater flow is also best established on the site scale. The site scale model may thus be used as one input to the groundwater flow in the tunnel system, which is of use in the near-field modeling.

  - The site scale model provides an estimate of the distribution of release points, which are of interest for the biosphere modeling.

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