Rock Characterisation Facility
Longlands Farm
Gosforth
Cumbria

Supplementary Proof of Evidence
of

Dr S R Hencher
BSc, PhD, DIC, MIMM, MHKIE, FGS, CEng, CGeol

Fracture Flow Modelling: PE/FOE/6/S1

Friends of the Earth Ltd
26-28 Underwood Street
London
N1 7JQ

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CONTENTS

1. SUMMARY

1.1 This supplementary proof provides responses to various points made in supplementary proofs of evidence by UK Nirex Limited as follows:

Dr R Chaplow Geology and Hydrogeology (PE/NRX/14/S1)
Dr A J Hooper Repository Performance (PE/NRX/15/S1)
Dr D W Mellor Role of the RCF (PE/NRX/16/S1)

1.2 My original proof (PE/FOE/6) emphasised the difficulties in establishing an adequate understanding of the nature of fluid flow through the rock mass at Sellafield. Such an understanding will be essential eventually for establishing a safety case. However, as yet, the necessary experimental techniques and theoretical basis are not well developed. The key points made in my original proof were as follows:

i) Establishing flow conditions through fractured rock is extremely difficult.

ii) Logging and characterisation of fractures from the proposed RCF is unlikely to result in a significant reduction in the uncertainties associated with the characterisation of the BVG fracture network.

iii) Given the current state of development of models for simulating fluid flow in fractured rock, they are unlikely to be validated from the proposed RCF.

iv) International underground studies of the kind proposed by Nirex have not provided an understanding of site specific hydrogeological conditions to the degree that would be required for a repository site.

v) The impacts of construction on hydrogeological conditions are poorly understood.

vi) The RCF proposal, as outlined by Nirex, is premature.

1.3 The purpose of this supplementary proof is to:

- to answer specific challenges that my points were invalid or that references cited were taken out of context;
- to discuss further evidence; and
- to re-emphasise major concerns which remain unchallenged.

1.4 It is concluded that none of the arguments presented by Nirex in their supplementary proofs demonstrate that the RCF proposal as outlined by Nirex will allow a safety case to be established for a repository.

1.5 Nirex have not provided evidence that they have resolved the fundamental unknowns regarding fluid flow through fractured rocks.

1.6 Although clearly it will be possible to obtain information and data from the proposed RCF, Nirex have not demonstrated that the measurements that would be carried out will generate the necessary understanding and parameter values required for the preparation of a safety case.

1.7 The RCF proposal is unique within the international research programme in that the location being used for experiments concerning flow within a saturated fractured rock mass is also being considered as the actual site for a nuclear waste repository. Such invasive experiments may result in long term damage to the integrity of the site. Nirex have not adequately rebutted conclusion 11.9 from my original proof that proceeding with the RCF stage of the development of a repository before the fundamental science is clearly understood may destroy the hydrogeological data on which a safety case would be based.

1.8 Subsequent to resolution of the outstanding scientific issues, an RCF would be expected to play an important role in the establishment of a repository safety case. However the state of knowledge concerning the appropriate scientific tools to apply within an RCF is not yet adequate to allow progression to this stage of site investigation.

1.9 To undertake RCF development prior to the development of adequate scientific tools would jeopardise the potential for generating a robust safety case for the Sellafield site.

2. FLOW THROUGH FRACTURED ROCK MASSES

2.1 In my original proof (PE/FOE/6 paragraphs 4.1 & 4.2 and section 5) I discussed the importance of fracture flow to the hydrogeological conditions at Sellafield. I emphasised how localised flow might be and how difficult it is to gain an adequate understanding of conditions. I commented on the problems in making relevant, quantitative observations in the field and in using those data for defining relevant parameters to be used within numerical modelling.

2.2 Dr Chaplow misquotes me by suggesting that I argue that the fracture network and fluid flow need to be *"fully understood"* (PE/NRX/14/S1 paragraph 8.65 i). He implies that I believe that a thorough deterministic understanding of the fracture network is necessary which, of course, is impossible to achieve. In my proof I actually argued that the *"nature"* of the fracture network needs to be fully understood and that the potential for this network to act as a conduit needs to be established. There is no conflict between these statements and that of Dr Chaplow that there is a need to understand the system *"adequately"*. In the following sections the capacity for currently available data gathering and modelling techniques for reliably quantifying fracture flow will be considered.

2.3 Dr Chaplow is also incorrect in suggesting that there is a conflict between aspects of my proof and those of Dr Kokelaar (PE/FOE/2) and Professor Smythe (PE/FOE/3). He suggests inaccurately that I *"recognise the importance of a stochastic approach to fracture flow"* whereas others argue that *"a deterministic approach is required"*. In my proof I stated that *"within **mathematical models** of discrete fracture networks", "the statistical potential for fractures to intersect on the basis of their perceived typical geometries within the rock mass **is the starting point**."* There is no dispute with PE/FOE/2 and PE/FOE/3 regarding *"the need for a combination of the deterministic and stochastic approach"* (PE/NRX/14/S1 paragraph 8.69).

2.4 Dr Chaplow fails to appreciate the implications of references I cite in paragraph 5.6 of my proof. He appears to assume that small scale observations and measurements will themselves inevitably reflect the natural heterogeneity of the system (PE/NRX/14/S1 paragraph 8.72). Paragraph 5.6 of my proof discusses the point that the most significant channels may be inadequately sampled and that their properties may be measured inaccurately during site investigation. I cite as an example the development of new oil wells. It has been observed that the drilling of a new well can cause a rapid response in a second, existing well several kilometres away even though other wells sited between those two showed no effect.

2.5 In my proof I state that *"if those intervening wells had been investigation boreholes, they would not have allowed identification of the critical flow paths"*. My concern that the rock mass at Sellafield may similarly not be sampled adequately has not been addressed in Dr Chaplow's rebuttal proof.

2.6 The recent crosshole tests (BH2 to BH4) carried out at Sellafield illustrate the problem of identifying the key pathways [see NRX/15/16] in that the sampling programme proved inadequate for generating reliable flow predictions. This paper is discussed further in paragraph 5.2.

3. NEED FOR AND NATURE OF MODELS

3.1 Dr Hooper in his supplementary proof (PE/NRX/15/S1, section 9) reviews the concepts and results of groundwater flow models. He states that comments made by myself and others in our evidence to the Inquiry;

> "*generally arise from a misunderstanding of the modelling approach and, in particular, from a failure to appreciate the roles played by the various models used in performance analysis.*" (paragraph 9.4)

3.2 Dr Hooper apparently fails to comprehend several critical areas of concern outlined in my original proof.

3.3 The problems associated with modelling flow in a complex fractured environment may be illustrated from the observations reported in [NRX/15/16] where it was found that:

> "*responses appear to cut directly across the gross structure*" (page 138)
> "*there is little support for a well connected fracture network that at an intermediate to large scale acts as a continuum*" (page 138)
> "*for a length scale of 10-100's metres, there is no apparent relationship between distance and drawdown*" (page 138)
> "*the relationship between observed geological structure and flow is not clear from the testing presented*" (page 139)

Thus it may be seen that the generation of a flow model of a complex fracture system will not be straightforward.

3.4 It is important to emphasise that those fundamental hydrogeological parameters such as hydraulic conductivity or intrinsic permeability which are used in the large scale continuum models developed for risk assessment are not measurable directly within the field.

3.5 Data from borehole tests such as changes in fluid pressure or flow with time must be interpreted with reference to a theoretical model of the ground in order that the parameters utilised within the continuum models may be derived. The interpretation methodology that is appropriate for borehole data obtained from fractured rock is the subject of an active international research programme, and the associated difficulties have only relatively recently been started to be addressed.

3.6 Recently the possibility of achieving the transition from field data to regional continuum models through an intermediate stage in which fractured rock is modelled using a discrete fracture network model has been developed. The degree to which this is currently possible given the limitations of state-of-the-art software is one of the main issues at dispute. These limitations are of fundamental importance to the safety assessment models used by Nirex. Thus in Report no: S/95/012 [COR/522]Nirex state that data concerning the fracture network is not used directly with regional flow models;

> "*Therefore, the regional flow is calculated using continuum porous-medium models, in which the fractures are taken into account* ***implicitly*** *through the use of appropriate effective parameters. The underlying parameters of the conceptual model (the distributions of the properties of the fractures) are, therefore, not used directly in the regional-scale continuum numerical models, but provide the framework which can be used to obtain effective parameter values for the numerical models that are consistent with the conceptual model.*" (page 1.2)

and in PE/NRX/15/S1 Dr Hooper states that the transition from fracture data to regional flow calculation is achieved through the use of fracture network models.

"*Numerical fracture-network models were used in the upscaling process to derive the regional-scale effective hydrogeological parameters for the BVG.*" (PE/NRX/15/S1 paragraph 9.6)

3.7 The difficulties associated with the transition are discussed below.

3.8 If the fracture network approach is not adopted, two alternatives for obtaining regional parameters are either a) to interpret borehole data derived from fractured rock as though they were derived from a continuum or b) to call for experts to estimate the parameters.

3.9 The problem with the first approach is that the influence of major transmissive features may be wrongly represented. The approach assumes that if enough fractures are included within the volume of rock modelled then the fractured rock will behave as a continuum, thus Nirex state;

"*effective continuum properties ... provide a good representation of the flow and transport in the rock between transmissive features providing that the volumes of rock involved are large enough to include many fractures. On a larger scale, different effective continuum properties may be used to represent the combined effect of the transmissive features and the fractures (and the rock matrix).*" (S/94/004 page 12)[COR/510]

3.10 However it may be seen from this quote that the parameter value obtained may be an artefact of the volume of rock included within the model; thus the Royal Society report (COR/605) states;

" *the approximation of treating fractured media as continua can be valid ... provided that the parameter values .. are chosen appropriately. There are also instances, however, when the approximation is not valid, whatever the parameter values.*" (page 131), and,

"*Such problems in applying a continuous media model to fractured media are mentioned because we are not convinced that Nirex are exploring them sufficiently in setting up NAMMU to represent hydrogeological conditions at Sellafield. The issues have serious implications for the derivation of the flow parameters required for modelling radionuclide transport, and possibly for the whole approach to such modelling in PCPAs for Sellafield.*" (page 132).

3.11 Dr Hooper notes (paragraph 9.21) that DFN models can cope with strongly heterogeneous geology. This is true. However the models are still highly idealised and aspects such as fracture storage and especially channelling are not readily modelled. The fundamental importance of channels to transport predictions is illustrated in the Royal Society report (Fig. 8.1, page 145). If significant channels exist then rate of transport will be underestimated by some unknown factor.

3.12 No evidence has been provided by Nirex that they are able to incorporate this effect within the derived parameters that are utilised within the continuum models used for the Sellafield risk assessment models.

3.13 Ohnishi (1995) [FOE/6/21] reports that the magnitude of parameters derived from borehole tests in fractured rock change according to the volume tested;

"*It is not clearly stated whether REV [representative elementary volumes] actually exist or not. Practically it seems that REV exist at different scale. When we increase the domain which we are interested in, the size of the REV also change..*" (page 4).

3.14 It may therefore be seen that it is possible that the use of continuum models for the flow through fractured rock is intrinsically inappropriate.

3.15 Expert group elicitation cannot be relied upon to generate robust data. For example it is of note that as recently as 1994/5 Nirex considered the Brockram to be a low permeability stratum. However, recent measurements of "*significant flows*" in the Brockram have caused a major change in this opinion (S/95/012 page 511)[COR/522]. The possibility for highly conductive paths through the Brockram seems clear. It is of concern that this possibility had not been included in the modelling carried out previously [see for example in S/94/004 [COR/510].

3.16 It should be noted that the possibility that pathways though the Brockram existed was recorded in the literature as early as 1937(Trotter 1937,page 70) [FOE/6/37].

3.17 Given the limitations associated with the continuum approximation and the use of elicited data, the recent literature pertinent to the status of the DFN/continuum research programme will be discussed below.

3.18 My comment (PE/FOE/6 paragraph 7.11) that fracture-network models have an unproved track record is disputed by Dr Hooper (PE/NRX/15/S1 paragraphs 9.19 and 9.20). Dr Hooper notes that fracture-network modelling is used within various waste disposal programmes. That they are used is not in dispute, however Dr Hooper has not been able to demonstrate that they have been proved to yield adequate and reliable predictions.

3.19 Professor Ohnishi of Kyoto University and Keynote Lecturer on this subject to the International Congress of the International Society for Rock Mechanics in 1995 writes;

> "*The modelling of flow and transport in fractured rock masses has been done deterministically or statistically, using either discrete or continuum representations, but transport through fractured rocks can not be considered as fully understood yet. Even flow in a single fracture cannot be modelled realistically. This paper will review the recent modelling concepts for fractured rocks..*" (Ohnishi, 1995, Abstract, page 1)[FOE/6/21], and

> "*Despite intensive investigation of fractured media, in terms of their geometrical characteristics, and flow and transport properties, parameter quantification and predictive capability in real fractured media remain severely limited. We have to admit that the physics of fluid flow in the fracture network of fractured rock masses is not yet well understood. This is particularly the case in fractured low and very high permeability rock masses.*" (Ohnishi, 1995, conclusions, page 7)[FOE/6/21].

3.20 Thus it may be seen that currently the capacity of DFN models to represent fracture flow is severely limited. These difficulties may be illustrated by the problems associated with the DFN predictions of borehole test results. For example Dr Black, a leading worker in this field, discusses the current difficulties in interpreting borehole test data. He writes;

> "*It is accepted as current "state-of-the-art" that the bulk of the fracture system has to be described probabilistically. Against this background, it is clear that there is no "unique" interpretation of a pumping test and that the consistency, or lack of it, between field results and expected results is not intuitively obvious.*" (Black, 1994, page 57)[FOE/6/32] .

3.21 In addition to the problems associated with the DFN representation of field data, the transfer of the DFN representation to a continuum model is also not straightforward. The problems in this area arise due to software limitations.

3.22 With respect to the Geier study [FOE/6/27] Dr Hooper argues that the software interface problems may be overcome through the adoption of continuum models other than stochastic continuum. Geier et al. do not consider in any detail the use of any other continuum model than stochastic continuum (SC) models (page 36). On page 42 they briefly note that "*If a suitably simple (though not necessarily geologically realistic) form is assumed .. .the parameters can be estimated uniquely from field data.*" Thus it is assumed that Dr Hooper is referring to the use of simplified models in order to effect the software interface successfully. However the use of simplified models would exacerbate the problems associated with the field data / model interface.

3.23 Dr. Hooper (PE/NRX/15/S1, paragraphs 9.15 and 9.16) cites the Geier et al. study [FOE/6/27] to indicate that these problems have been overcome. He states that;

> "*A major result has been the development and demonstration of a DFN methodology to interpret packer tests in terms of fracture network properties and predict relationships between packer test results and block scale properties*".

3.24 However the abstract of [FOE/6/27] (page ii) states that the methodology for estimating an effective stochastic continuum from a DFN model was developed but only "*partly demonstrated*". In fact "*only the DFN aspects of the interface were implemented*" (FOE/6/4, page 103) and "*software development is still needed from the SC standpoint*" (FOE/6/4 page 167). Thus Dr Hooper has misrepresented the conclusions of the Geier study. Nirex are using discrete fracture network models to derive effective continuum properties for risk assessment at Sellafield but provide no evidence that their approach is robust.

3.25 Dr Hooper refers to the summary paper on the Stripa project by Olsson and Gale (1995) [FOE/6/15] and cites their conclusions in which are expressed the following points, summarised below:

- During the SCV project discrete fracture flow codes evolved to practical tools capable of representing flow through fractured systems. It is true that these fracture flow codes were developed considerably during the Stripa project and also that they were used with some success in predicting total inflow to boreholes. However predictions of magnitude of inflow to the "*validation drift*" were less successful despite the drift being "*in the same place as the boreholes*" and the fact that "*the outer boundary conditions were essentially the same*" [FOE/6/15, page S27].

- DFN models can be constructed from field data. This point is not in dispute. However there are always limitations on the data quality, in identifying which data are or are not significant and in incorporating all data adequately. For example, the simulated drift maps of the Stripa validation drift produced by NAPSAC (Fig. 5-3-1, page 209, Stripa Project 92-22) do not convincingly represent mapped conditions (Fig. 4-3-4, page 136). The obvious sets of mapped joints, indicated as sine curves on the tunnel maps are not recognisable from the NAPSAC representations of the same rock volume. The implications of this poor representation of the true geological conditions could be significant.

- The third comment that "*using the discrete codes to generate the properties for large-scale porous medium models provides a tool for bridging a range of scales while retaining much of the inherent variability in the flow and transport properties of fractured rock masses*" is not in dispute. However the Stripa study did not demonstrate that the problems identified by Geier had been overcome. Thus the bridging 'tool' that DFN models provide is not presently capable of generating robust data.

3.26 In 1989 Herbert & Gale commenting on their work at Stripa, noted;

> "*The work so far, has concentrated on flow modelling. This is the easiest problem to solve in a site assessment, and indeed, conventional models will generally solve this problem well. The original motivation for fracture network models was to improve our understanding of nuclide transport through fractured rock. Continuum approximations are harder to justify for this problem, and an important extension to our work will be to develop fracture network models for transport.*" [FOE/6/35 page 231].

3.27 However, the tracer tests undertaken outside of the calibrate region of the validation drift were less successful [NRX/15/33] (see page 215, 216, 222). Furthermore, Ollson concludes;

> "*It is evident that the SCV project could not suffice for validation of the models in a general context, as it only provided comparison of model predictions with the outcome of a few experiments*". [NRX/15/33 page 309].

4. VALIDATION OF FRACTURE FLOW MODELS

4.1 Dr Hooper lists the stages that Nirex consider lead to validation (PE/NRX/15/S1 paragraph 10.10). Within that list of stages the requirement to make predictions using a model and to test these predictions against the results of experiments is set out. The eleven other stages outlined are descriptions of model development work rather than validation.

4.2 The term validation has a firmly established meaning in the scientific community. For example;

> "*The term validation...means the process of demonstrating that a conceptual model and its corresponding mathematical model(s) are an adequate representation of the real world.*" and,

"Validation involves comparing model predictions with experimental results and field observations.." (Royal Society, 1994 page 87) [COR/605]

4.3 Similarly, the Nirex report [FOE/8/38] states that;

> *"Validation is a process carried out by comparison of model predictions with independent field observations and experimental measurements. A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy."* [FOE/8/38 page E1]

4.4 Thus it is clear that a model may only be described as validated if it is adequately able to represent and predict conditions and processes in the real world.

4.5 Although Nirex, in their recently published Annual Report & Accounts (1994-1995) state (page 16) that flow modelling *"is based on the NAPSAC code developed for the modelling of discrete fracture networks and which has been tested successfully against field observations at a site in Cornwall"* it should be noted that the prediction was for a block of rock of width of only 5m (NAPSAC Release 3.0 Summary Document, 1994) [FOE/5/8]. This study appears to have been very poorly constrained. Geotechnical description of boreholes is non-standard and contains almost no reference to the nature of fracturing (Hancock 1989, Figs 3-5) [FOE/6/34]. Considering that the purpose of NAPSAC is to model the fracture network in a fairly realistic manner it is surprising that the very poor correlation between fractures mapped by Jancock & North (Figs 7,8,11,12) and the conductive fracture orientations identified by Bolt et al (1990)[FOE/6/33] for modelling within NAPSAC receive no discussion. Furthermore, the potential influence of matrix flow within the sandstone and siltstone sequence is not mentioned, presumably because NAPSAC has no facility for modelling this contribution. These factors limit the general applicability of this work.

4.6 Furthermore, several continuing limitations for NAPSAC were clearly identified during the experiments in Cornwall by Bolt et al. (1990) [FOE/6/33]:

> *"no method of determining lengths (of fractures) through the rock has been found"* (page 5)
>
> *"channelling was neglected"* (page 7)
>
> *"it was assumed that ..fractures have uniform apertures."* (page 7)

It is unfortunate that no attempt was made apparently to relate effective apertures to the physical nature of the individual fractures (Bolt 1990, page 1)[FOE/6/33]. This seriously limits the usefulness of this research. Thus the conclusion that; *"The minimum statistically representative volume of fractured rock for the Cornish slate site has been shown to have dimensions comparable with a few tens of fracture separation lengths."* (Bolt et al., 1990 page 7)[FOE/6/33] clearly cannot be taken as generally applicable to fractured rock masses.

4.7 The possibility of extending the capacity of the NAPSAC model such that it would be able to address *"long distance continuum modelling"* was considered. However it was noted that this would require the inclusion of phenomena such as channelling and would also require further validation work. (Bolt, 1990 page 3) [FOE/6/33].

4.8 At the recent (September / October 1995) International Congress on Rock Mechanics held in Tokyo, a workshop was conducted on flow modelling. The workshop was chaired by Professor Ove Stephansson who was also one of the authors of the Royal Society Report (1994) [COR/605]. A paper was presented co-authored by Professor Stephansson (Jing, 1995)[FOE/6/22]. The paper concerned the international co-operative project DECOVALEX for mathematical modelling flow within fractured media for underground nuclear waste repositories.

4.9 DECOVALEX is an acronym for **DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments in nuclear waste isolation.

4.10 At the workshop the results were presented from the BMT3 test problem that considered a model of a repository at 500m depth in rocks with a realistic fracture network. The problem was set up in order to examine the capabilities of mathematical models to represent a large number of randomly distributed fractures through rock. Eight different research teams studied the problem (including AEA using NAPSAC). The authors concluded that;

> ".. *great discrepancy is observed for hydraulic analysis between not only continuum and discontinuum groups, but also among different codes within the same group. It indicates that hydraulic process in fractured rocks is least understood*". (Jing 1995)[FOE/6/22 page 11]

4.11 Their final comment was that;

> "*Recognizing also the importance of models and codes for the design and performance assessments of repositories, the validation of the models and codes will remain necessary and important for the waste repositories until a relatively high level of confidence is achieved*". (Jing 1995)[FOE/6/22 page 20] (Emphasis added)

4.12 The validation work undertaken by Nirex for their groundwater flow models is discussed by Dr Hooper in an Appendix to PE/NRX/15/S1. He describes a progressive programme including the following stages:

1. crosshole testing between boreholes 2 & 4
2. the borehole RCF3 pump test
3. the RCF shaft drawdown experiments
4. work within the RCF

4.13 Only the results of the crosshole testing between boreholes 2 & 4 has been reported. [NRX/15/16]. This report notes that zones previously identified as flowing on the basis of results derived from single borehole tests showed no observable flow response in the cross hole tests. Furthermore flow responses in the cross hole testing were found outside the previously defined flow zones. Most importantly there was "*very little correlation with the predicted distribution of likely responses based on detailed assessment of the EPM Tests*" [NRX/15/16 page 136]. Clearly Nirex do not currently possess a valid model of fracture flow at Sellafield.

4.14 The results of the international research programmes carried out in Canada and Sweden indicate that these validation problems will be exacerbated by the proposed RCF excavation.

4.15 Dr Hooper (PE/NRX/15/S1 paragraph 9.23) argues that I am "*extremely misleading*" in suggesting that the failure of an attempt to predict inflow to the excavation at Stripa using NAPSAC has significant implications for the RCF proposal. The prediction made using NAPSAC was that flow would increase relative to previously observed flow to a series of boreholes at the same location. However an eight fold **decrease** was measured. Dr Hooper argues that it was the coupling of the NAPSAC code to an incorrect hypothesis that was at fault. The hypothesis coupled to the NAPSAC code was that the modification of the stress regime would be the primary determinant of the modification of the flow regime subsequent to excavation. As discussed below (paragraph 5.9), many other factors may have contributed to reduced flow at Stripa.

4.16 Dr Hooper's comments may be contrasted with PE/NRX/16/S1, Appendix A in which Dr Mellor outlines his understanding of the impact of excavation disturbance on fluid flow (PE/NRX/16/S1 paragraph 3.2(I)). Dr Mellor continues to consider only the consequences of stress changes on the rock mass.

4.17 This contradiction between the two Nirex witnesses has significant implications for the RCF proposal concerning as it does the key uncertainty - the characterisation of the flow regime - that the RCF proposal purports to address. 4.18 It should be noted that this failure to predict even the trends of the hydraulic disruption generated as a result of excavation is not unique to the Stripa test. The phenomenon was also observed for the Canadian URL test. For example, research prepared for the HMIP has concluded that;

> "*At the URL...numerical modellers were provided with information on the geometry of excavations and a full suite of rock property and site specific data. The authors conclude that the finite element models*

used for predicting the hydrogeological response did poorly and, in the case of permeability change, did not even predict the trend correctly." (DOE/HMIP/RR/92.098 page 107)[GOV/614].

4.19 It is essential that this issue is resolved prior to RCF construction in order that information obtained from an RCF may be of utility to the safety case.

4.20 The processes that disrupt fluid flow subsequent to excavation are the subject of an active and on-going research programme. Currently the causes of the disruption to the Stripa flow regime have not been resolved (Olsson, 1995)[FOE/6/15]. Furthermore it is not anticipated that the ZEDEX programme at Aspo will be able to resolve the uncertainties associated with the impact of the excavation disturbed zone on the hydraulic behaviour of the rock [NRX/16/1 page 2].

4.21 It is clear that NAPSAC models have not yet been able to represent the impact of excavation on the flow regime, partly because of a poor understanding of the processes in that zone but also because of the simple, uncoupled nature of the NAPSAC code.

5. IMPLICATIONS FOR THE RCF PROPOSAL

5.1 Nirex identify the principal area of remaining uncertainty concerning the Sellafield flow regime to be an inadequate characterisation of the flow zones and the way in which these are connected to permit the movement of groundwater (PE/NRX/14, par. 9.9).

5.2 Illustration of the magnitude of the problems faced by Nirex in characterising the flow zone of the Sellafield site is provided by [NRX/15/16]. Within this report it is noted that major difficulties were encountered with hardware and in particular the flow control system in the tests. Partially as a result of difficulties in flow rate control at very low flow rates a revised programme was devised such that all later tests were carried with drawdowns of 1500 to 2000 kPa (up to 200 metres head of water) in order to generate "*an analysable signal*". To do this a large pump had to be used which gave rise to rate fluctuations sometimes as much as .100% which "*precluded the detailed analysis of all source zone data during pumping*". The influence of the inevitable and significant increase in effective stress on the fracture flow system (through aperture reduction) is not addressed in the discussion of results. Similar operational difficulties are also likely to be found for the programme of works planned for the proposed RCF.

5.3 One of the conclusions from the detailed analysis was that it was only by refining the DFN models to account for the disturbance due to the effects of establishing the borehole that data could be explained.

5.4 I outlined many of the major difficulties in carrying out in-situ tests and making relevant observations in-situ in the first fifteen paragraphs of section 6 of my original proof (PE/FOE/6 paragraphs 6.1 to 6.15). The validity and relevance of these points has not been challenged in any of the supplementary proofs prepared by Nirex. Given the purported role of the RCF as a means of gathering in-situ data, this is a matter of great concern.

5.5 Nirex have not provided evidence that data obtainable from the proposed RCF will enable them to resolve the uncertainties concerning fluid flow at the Sellafield site.

5.6 Everitt (1990) [NRX/16/5] submitted by Dr Mellor, considers the experience of the workers at the Canadian URL. It is noted that;

"*Fracture spacings and fracture lengths were not determined during excavation, since the results from such confined areas as the tunnels or shaft are not very meaningful*." and,

"*Measurements of fracture aperture and width, and estimates of seepage rate were made during mapping, but these data were not representative of the long term*." [FOE/6/28 page 7]

5.7 Furthermore, the results of international research programmes indicate that the difficulties associated with disturbance effects (discussed above) are considerably increased when moving from borehole scale to excavation scale intrusions into the rock mass.

5.8 In paragraph 6.16 of my proof I cite Pusch & Stanfors (1992) [FOE/6/16] who report that adjacent to the excavation at Stripa bulk hydraulic conductivity was up to 10,000 times that of the virgin rock mass. In his supplementary proof Dr Mellor states that my use of the document cited is "*misleading*" (PE/NRX/16/S1 paragraph A1.14). Furthermore Dr Mellor deems it inappropriate to describe a reported increase of up to 10,000 times in bulk hydraulic conductivity as "*severe disturbance*".

5.9 Dr Mellor suggests (paragraph A1.16) that I may have misquoted the paper by Pusch and Stanfors. However it appears that Dr Mellor is referring to the wrong paper. Dr Mellor refers to page 79. I quote below directly from my original reference, published in the International Journal of Rock Mechanics Mining Science & Geomechanics Abstracts, Vol.29, No.5, pp.447-456, 1992, page 447;

> "*.. as illustrated by the conditions in the Stripa mine in Sweden where an international OECD project has been performed for 12 yr with the aim of developing techniques for characterization of rock and backfilling of excavations and sealing of near-field rock.* ***This work showed that while the virgin granite has a bulk hydraulic conductivity of 10-11 - 10-10 m/sec, the rock zone close to blasted tunnels had a conductivity that was up to 10,000 times higher***" (i.e. 4 orders of magnitude) (my emphasis).

5.10 These data have significance for two main reasons. Firstly these data fall outside the values used by Nirex in their assessment of the impact of excavation damage on the flow regime. Secondly they indicate that measurements within and from the walls of the proposed RCF are unlikely to provide the insight into hydraulic conductivity of the rock mass that Nirex require.

5.11 Nirex assume that the increase in conductivity due to stress relief and blast damage within the damaged zone of the shaft walls will be a maximum of two orders of magnitude. This figure is derived from a personal communication (Nirex Report 560, 1994, pages B13, B21) [FOE/5/19]. It is a matter of serious concern, that although the results of the Stripa research programme were widely available in the scientific literature at the time that Nirex Report 560 was produced, Nirex have not incorporated these results within their safety assessment programme.

5.12 Dr Mellor argues that the radial extent of the zone of disturbance will be limited. To support his case he uses field data from the URL (NRX/16/8) but fails to note that those data are for massive granite with very few fractures. (NRX/16/8 page 1). Such rocks are expected to respond to disturbance very differently to the rocks that underlie Sellafield.

5.13 Dr Mellor appears to imply that the reduction in radial conductivity that was observed following excavation at the Stripa site, has the same significance as the increase in axial conductivity that was observed (PE/NRX/16/S1 paragraph A1.14). Dr Mellor underemphasises the significance of the EDZ within the repository safety case. The EDZ will run parallel to the shafts, thus potentially providing a 'superconductor' for the transfer of radionuclides to the surface. Thus it is the axial conductivity presented by the EDZ that is of most concern. This point is not adequately addressed by Dr. Mellor.

5.14 Furthermore, Dr Mellor does not address the implications of the failure of the Stripa models to account adequately for the post-excavation flows. The Stripa Project Site Characterization and Validation - Final Report 92-22 states;

> " *The experiments performed within the SCV Project have unequivocally identified a significant skin around the Validation Drift. The experiments performed have not been able to distinguish what processes cause the skin...*" (page 296)

5.15 It is important to note that the cause of the lower than expected inflows at Stripa remains unknown. Dr Mellor emphasises the process whereby closure of radial fractures could lead to a reduced hydraulic conductivity *"as noted by Long et al. (FOE/6/10, page 563)."* However Long et al. (op cit.) also give many other possible reasons for the reduction in flow. Olsson & Gale (1995, page S28) [FOE/6/15] discuss the same case as follows;

> *"Processes that have the potential to produce the reduction in flow into the drift include two-phase flow and mechanical effects around the excavation (Olsson 1992). Two-phase flow conditions are assumed to have developed due to degassing of the groundwater and the development of a free-surface condition in the rock mass near the drift. Two-phase flow conditions may also explain the observed variations with time in the inflow distribution to the drift. Possible mechanical effects include those due to both dynamic loading of the fracture planes by blasting during excavation and fracture closure due to excavation-induced stress changes. There is clearly a need for further research in order adequately to understand the hydrogeology of the disturbed zone".*

5.16 It may be seen that the initial flow modification that was observed may be transient in nature. Thus it would be inappropriate to derive parameters pertaining to the long-term flow regime from such observations. It is therefore of concern that Nirex propose to replicate this test programme in order to obtain data for the proposed repository safety case. For example Dr Mellor states that direct measurements of flow into the proposed RCF are a crucial part of the programme for *"measuring the hydraulic conductivity of the BVG on a large scale"* (PE/NRX/16 p.27). Such measurements are critical to risk assessment as recognised by Nirex (S/95/012 [COR/522] Vol. 3 page 8.12);

> *"...there is the possibility of risks in excess of the regulatory target arising. This could arise as a consequence of a high effective permeabililty for the BVG ..."*

5.17 Further evidence for the transient nature of hydrogeological conditions following the perturbation generated by excavation effects is given by data from the Canadian URL (OECD, 1991, page 15)[FOE/6/36];

> *"Total seepage into the Canadian Underground Research Laboratory (URL) has gradually decreased over five-six years, along with a gradual recovery of groundwater levels in monitoring boreholes. This suggests that some fractures have sealed and are plugging groundwater flow. It is still unclear whether this short-term sealing is representative of an important long-term process."*

5.18 It should be noted that in Appendix A of Dr Mellor's supplementary proof (PE/NRX/16/S1) concerning the disturbance zone, he makes no reference to the Stripa findings and the current lack of consensus concerning the nature of the physical processes that determine the impact of excavation on the flow regime. Similarly he fails to note that workers at the ZEDEX project at Aspö which is planned to provide data for the Nirex RCF programme *"do not expect to be able to resolve the issues of hydraulic effects in the disturbed zone"* [NRX/16/1 page 2].

5.19 The consequences of excavation disturbance on the various experiments intended from the RCF excavations are clearly recognised by others. For example in the Overview Volume III for the Stripa Project [FOE/7/20; NRX/15/8] it is stated;

> *"Due to the perturbations caused by the presence of excavations it may never be possible to physically examine in underground laboratories, or from excavations at repository sites, the conditions under which radionuclides will migrate within either the engineered barriers or the host rocks that form the waste isolation system."* (page 199)

5.20 Dr Chaplow suggests that my call for delay in the construction of an RCF until Nirex have demonstrated that they understand existing data is in conflict with recommendations of the Royal Society Study Group (PE/NRX/14/S1, paragraphs 8.74 and 8.75). He quotes from COR/605 page 110 that *"The RCF will yield valuable information..." and "Construction of the RCF should proceed as soon as practicable."* However, given the results of the Canadian and the Swedish research programmes, it is clear that RCF excavation at this stage would not yield data that would be sufficiently conclusive to allow a safety case to be established. Furthermore it is possible that through the collection of data that might be obtained from an RCF, other possibly essential data might be lost. Thus the key word in the Royal Society quote is the word *"practicable"*. Until the difficulties with data gathering, experimentation and validation techniques that have been highlighted by the international research programmes have been satisfactorily resolved, it would be inappropriate to proceed with RCF development.

5.21 It is apparent that the construction of the RCF will disturb the hydrogeology of the site irreversibly. If the proposal were for a generic laboratory solely for the development and refinement of experimental and operational techniques and validation of modelling methods, then unexpected behaviour would not of concern. For example at the Canadian URL, the abandonment of long duration tracer tests in flow zone 3 due to unexpectedly rapid changes in the groundwater flow field during construction of the URL shaft was not disastrous (FOE/6/30 page 7). However, within the RCF proposal, as outlined by Nirex, problems such as these would not be acceptable.

5.22 As the site of the proposed RCF is also the site of the proposed repository, such an occurrence would be likely to cause considerable difficulties for a future safety case. It is therefore imperative that outstanding experimental difficulties are resolved prior to invasive disruption of a proposed repository site.

5.23 Given that the implications of excavation impact are evidently understood in only a superficial way, premature excavation of an RCF may cause damage which could prevent a reliable PCPA for the Sellafield site ever being achievable.

6. CONCLUSIONS

6.1 None of the arguments presented by Nirex in the supplementary proofs I have considered in this proof demonstrate that the RCF proposal as outlined by Nirex will allow a safety case to be established for a repository.

6.2 Nirex have not provided evidence that they have resolved the fundamental unknowns regarding fluid flow through fractured rocks. (See Para 3.3 and Paras 3.9 to 3.13)

6.3 Although clearly it will be possible to obtain information and data from the proposed RCF, Nirex have not demonstrated that the measurements that would be carried out will generate the necessary understanding and parameter values required for the preparation of a safety case. (See Paras 4.18 to 4.21 and Para 5.4 and 5.5)

6.4 The scientific understanding of flow through fractured rock masses is at a rapid stage of development. Nirex have not demonstrated that they are familiar with or fully comprehend the implications of the most recent research results. Given the implications of these findings for the utilisation of RCF data, Nirex's lack of understanding or awareness in this matter is of great concern. (See Para 3.19 and 4.8 to 4.10).

6.5 New evidence made available by Nirex, subsequent to the presentation of my original proof (PE/NRX/15/S1 paragraph A.1.1 and reference NRX/15/16) is a cause of grave concern over the methods being adopted within the validation programme. Very little correlation was found in the crosshole tests between the predictions and subsequently measured field data. (See Para 4.13)

6.6 As emphasised in my original proof, the RCF proposal is unique within the international research programme in that the location being used for experiments concerning flow within a saturated fractured rock mass is also being considered as the actual site for a nuclear waste repository. Such invasive experiments may result in long term damage to the integrity of the site. Nirex have not adequately rebutted conclusion 11.9 from my original proof that proceeding with the RCF stage of the development of a repository before the fundamental science is clearly understood may destroy the hydrogeological data on which a safety case would be based. (See Paras 5.10 to 5.11 and Para 5.13 to 5.19).

6.7 Subsequent to resolution of the outstanding scientific issues, an RCF would be expected to play an important role in the establishment of a repository safety case. However the state of knowledge concerning the appropriate scientific tools to apply within an RCF is not yet adequate to allow progression to this stage of site investigation.

6.8 To undertake RCF development prior to the development of adequate scientific tools would jeopardise the potential for generating a robust safety case for the Sellafield site.

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