Review of the potential processes and consequences of volcanic activity at the proposed nuclear waste repository at Yucca Mountain, Nevada.

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1. Introduction

In the event of a basaltic volcanic eruption through the proposed Yucca Mountain repository there is the possibility that some of the nuclear waste is incorporated into the erupting mixture and is dispersed into the environment as a consequence of volcanic activity. The central issues are how erupting magma interacts with the repository and how the nuclear waste is transported in the volcanic plumes that form during such an eruption. The performance of the repository may also be affected after an eruption. The main style of explosive volcanism expected in a Yucca Mountain eruption is strombolian to violent strombolian activity. Such activity typically generates eruption columns of a few kilometres height although higher columns (up to about 15 km) are commonplace for short periods of time (a few hours or days). There is also the possibility of explosive activity related to interaction of magma with water, but such activity only occurs occasionally in basaltic activity within continental areas.

This report considers these issues, drawing on our experience of volcanology and the application of fluid mechanics to igneous processes. We review our findings during a week of discussions with CNWRA staff (27 to 31 July 1998). Our findings include some scoping calculations as a preliminary basis for assessing interactions between ascending basaltic magma and the repository. The credentials of the consultants are summarised in annex 1.

2. Magma Characteristics and Volcanological Analogues

The CNRWA have developed a dual approach of studying the geological characteristics of the Yucca Mountain area volcanoes and investigating modern analogues such as the 1975 eruption of Tolbachik Volcano, Kamchakta, Russia and the 1995 eruption of Cerro Negro Volcano, Nicaragua. The CNRWA staff have argued that these volcanoes are close analogies to typical Yucca Mountain eruptions. We endorse their view and remark that the quality of the studies by CNRWA staff on these analogue eruptions is very high and is advancing understanding of this style of volcanism. We particularly note, in agreement with CNRWA staff, that any analogy with the more fluid and gas poor Hawaiian style of basaltic volcanism would be inappropriate and potentially misleading. The CNRWA staff have developed a convincing case that the Yucca Mountain volcanoes are water-rich basalts which are as a consequence significantly more explosive than typical Hawaiian eruptions. They have thus chosen their analogues well.

The issue of the gas content of the magma takes on particular importance with regard to the possible interactions of the magma with the repository. Typical Hawaiian tholeiitic basalts that erupt on Kilauea are thought to contain modest amounts of dissolved water plus minor amounts of CO_2 and SO_2. For a typical content of 0.5 wt% water solubility data (eg. Stolper, 1982) suggest that Hawaiian basalt magma will saturate at a pressure equivalent to a depth of about 200-250 m just above the typical depth of the Yucca Mountain repository. Thus the magma bubble content will be low, most likely containing mostly CO_2. We understand that studies commissioned by the US Department of Energy (DOE) have concluded, based on an analogy to Hawaiian basalts, that interactions with the repository will be not involve major explosive activity.

There are several reasons for supposing that basalts erupting in the Yucca Mountain area will be much more water rich than Hawaiian basalt. These reasons have already been recognised by CNWRA staff, but are worth summarising here because of the importance of the issue and because we understand that the alternative view has been expressed within DOE studies. Basaltic magmatism in many continental settings typically involves volatile-rich magmas, ranging from water-rich to CO_2 rich varieties. Arc basalts are typically water rich. There are numerous studies in the petrological literature which support this view, as illustrated by studies of melt inclusions, presence of amphibole in some examples of more evolved basalts, phase equilibria studies and the general observation that arc basalt eruptions are generally significantly more explosive than Hawaiian basalt. More alkaline basic magmas are much more variable, but some generalizations are possible. Basalt magmas generated beneath ancient parts of continents (such as the East African Rift) with no recent geological history of subduction tend to be water poor and CO_2 rich. Alkaline basalts formed in continental areas that have had recent (Cenozoic) episodes of subduction or mantle metasomatism tend to be water rich. Evidence for water-rich character comes from hydrous phases such as amphibole and phlogopite in the more evolved fractionated magmas. The mildly alkaline basalts and hawaiites of the Yucca Mountain area are good examples of this latter kind of province with the water-rich character of the metasomatism mantle source being linked to prolonged Cenozoic subduction and arc magmatism beneath North America prior to the relatively young Basin-and Range extension.

The hawaiite composition of the Lathrop Wells volcanic products is a good case in point to provide support for the water-rich character of the basaltic volcanism in the Yucca Mountain area. The lava is poorly phyric and a few percent of olivine are the only phenocrysts. Experiments on similar compositions suggest that plagioclase should be the liquidus phase at one atmosphere and that high water pressures would be necessary to make olivine the liquidus phase. The Mg numbers of the olivine and magma also imply extensive fractionation from any plausible primitive basalt that could be formed directly from the mantle. Fractionation concentrates the water further. Phlogopite and kaersutite crystals in other Yucca Mountain area lavas also indicate water-rich character. We consider the estimates of 2 to 3 wt% water for this lava by CNWRA staff as reasonable. Routine experimental investigations of the lava composition from Lathrop Wells would allow the water content to be constrained further.

Basalt magmas containing about 2 wt% water are much more explosive than Hawaiian basalts. Solubility data indicate that saturation will occur at pressures equivalent to about 2 km depth and that the equilibrium gas bubble content at the depth of the proposed Yucca Mountain repository would be about 60 to 70 vol%. Bubbles grow in basalt magma sufficiently rapidly that the system should be close to equilibrium (Sparks, 1978). Such a bubbly high pressure magma will be highly explosive if it encounters low pressure regions such as a large tunnel containing air at one atmosphere and this matter is explored in more detail below.

3. Source Conditions

In this report we describe some of the issues concerning the source conditions associated with a hypothetical volcanic eruption intersecting the proposed nuclear waste repository. These discussions focused on the modelling efforts presently being undertaken at CNWRA, but also some new possible processes and consequences of volcanic activity occuring at the nuclear waste repository. The main hazard concerns explosive basaltic eruptions, associated with water rich (2%) basaltic magma, which typically lead to cinder cone formation and large convecting eruption clouds of fragmented magma and gas.

During the discussions, some key issues directly related to volcanic activity and the transport of waste material back to the surface environment emerged. The three main issues, which we describe in detail, are: (i) the impact of the repository on the magmatic flow pattern, and especially the diversion of magma from a vertical planar dyke into the repository tunnels; (ii) the effect of high temperature, high speed flow on the mechanical and thermal properties of the cannister, and its ability to remain intact; and (iii) the mechanism of mixing the pellets of waste material into the erupting magma.

3.1. Interaction of dyke and tunnels:

The work presented by the CNWRA staff relating to volcanic hazard has, to date, focussed on the hazard associated with a conventional basaltic cinder cone style of eruption. This involves the ascent of magma along a conduit, towards a localised vent at the surface. For simplicity this has been modelled as a circular vent. Although this picture of a basaltic eruption is sensible, it has been used by the CNWRA primarily in a qualitative fashion to motivate the modelling of the ensuing eruption column and ash dispersal. Following considerable discussion, we believe that this basic picture needs to be revisited. In particular, the presence of a closely spaced network of tunnels 300 m below the surface introduces considerable complexity during the initial stages of an eruption. As described below, we conclude that it is likely that, for an open repository with no back-fill in the tunnels, the magma will be diverted into the tunnels within the repository before continuing its ascent to the surface. All of the processes described below require further investigation; during our visit we have only made some preliminary estimates of the potential magnitude and importance of the different phenomena. A more complete and considered report will be produced, giving more detailed quantification of these processes.

The repository footprint normal to the tunnel directions is close to the upper crustal minimum principal stress direction and runs about 3.5 km. Therefore feeder fissures of a few hundred metres to a few kilometres length are likely to intersect a substantial proportion of the tunnels. The presence of the tunnels also produces an anisotropic stress field around the repository area. Such distortions in the stress field can influence the initial ascent phase of the dyke. Depending on the orientation of the dike to the tunnels, the dike may be rotated and break up into a number of parallel fractures, intersecting successive tunnels. However, even if the dyke advances normal to the plane of the tunnels, so that there is less distortion of the dyke, many of the tunnels will be intersected. Since the inter-cannister spacing in the tunnel is 15-20 m, and the cannister length is about 5 m, then, with 100 tunnels, one would expect that up to 25 cannisters will be intersected directly by the dyke.

Once the tunnels are breached, the ensuing motion of the magma depends on whether the tunnel is filled with backfill or is still empty. Here we consider the case of no backfill. When the dyke intersects the tunnel, the pressure at the dyke will fall from the lithostatic pressure plus any overpressure associated with the dyke propagation, to atmospheric pressure. For a tunnel 300 m below the surface this may represent a decompression of about 8 MPa. The magma will then have a strong tendency to flow into the tunnel drawn by such a low pressure. Indeed, the cross-sectional area of each tunnel is 20 m^2 and it will drain that part of the dyke between the two bounding tunnels, of width 20 m and thickness 0.5-2 m. Therefore the cross-sectional area for flow in the tunnel is comparable to that in the dike. The frictional resistance in the dyke depends on the dike thickness (0.5-2 m) while tthe resistance in the tunnel depends on the radius (2.5 m). Therefore, the flow resistance in the tunnel will be smaller than that in the dyke, suggesting that much of the flow is diverted into the tunnel. Furthermore, since the magma experiences a large pressure drop on reaching the tunnel, we anticipate a considerable acceleration to a much larger flow rate.

A key point is that it is much easier for pressurised magma to flow into an open cavity at low pressure than to continue advancing upwards along a dyke which requires considerable energy. In dyke propagation a fracture is thought to advance well in front of the magma-filled dyke tip. However the viscous magma has to exert considerable pressure to push the dyke walls apart by distances of 0.5 to 2 m and intrude. The minimum pressure required will be comparable to the minimum principal stress normal to the fracture surface (Pollard, 1973). In an extensional area the minimum principal stress at 300 m depth will be a significant fraction of the lithostatic pressure. Therefore, not only are the tunnels less resistant to flow, but the pressure gradients into the tunnel will be much larger than the pressure gradient driving further dyke propagation above the repository.

Magma of typical water content 2 wt% will be quite vesicular, with a void fraction of 60-70%. Under such rapid decompression, the mixture will expand and flow at high speeds, of order 100 m/s, down the tunnel (Woods, 1995a, Woods and Bower, 1995; Chapter 3 in Sparks et al.,1997). The leading edge of the advancing high pressure mixture will form a shock wave across which the pressure increases rapidly. The shock will take about 10s to reach the end of the tunnel, potentially disturbing the cannisters en route. This will be followed by the fragmented mixture of magma (Chapter 3 in Sparks et al., 1997). Subsequently, as the tunnel pressure builds up, the flow will gradually wane, until the tunnel becomes pressurized close to the original dyke pressure. As the tunnel fills it may drain part of the dyke in the process. The repository has a volume of about 0.01 km^3, and this would drain a dyke 3 km wide, 300 m deep and 1 m thick.

The typical erupted volumes in such explosive basaltic eruptions ranges from 0.1 to 0.5 km^3 while the tunnel complex has volume 0.01 km^3. This suggests that once the tunnel complex is filled, the flow will continue. It is not clear how the eruption would procede after the filling of the tunnels. If the dyke flow becomes re-established, the dyke may resume propagation to the surface, thereby forming a conduit for explosive activity at the surface. If this occurs, then the magma will fragment at some depth in the conduit, prior to erupting at the surface, and the pressure will fall (Sparks, 1978). Magma may then flow from the now highly pressured tunnel and back into the conduit through decompression of the gas in the vesicular magma. Alternatively the flow might find a weakness such as a major fault that intersected the tunnel system and choose to propagate a dyke elsewhere. The doors separating the tunnels from the main drift tunnel into the repository could be breached in which case much of the subsequent flow would be in unexpected directions in comparison to a similar eruption in an undisturbed natural environment. High speed flows in the tunnel may lead to considerable damage to the cannisters, and may transport the cannisters up and down the tunnel. This could have important implications for the release of waste material to the atmosphere during the eruption, but also for the longer term release of waste material through ground water flow.

In the case of a backfilled tunnel, the scenario may be less serious, in that on intersecting the fracture the magma would expand some distance, but would be resisted by the large frictional resistance and inertia of the backfill. Detailed calculations would be necessary to evaluate the possible implications of this on the eruption evolution.

We know of only one case where an artificial cavity was intersected by a basalt dyke. In the 1976 to 1980 eruption of Krafla volcano, Iceland a series of dyke propagation events occcurred where basalt dykes were laterally emplaced from a shallow level magma chamber into the northern rift zone of Iceland. A geothermal bore hole, thought to be about 15 to 20 cm diameter and a few hundred metres deep, was intersected by the dyke. The basalt magma was diverted by the bore hole and a small explosive fountain eruption involving about 30 m^3 of basalt occurred at the surface. This event was described in a Nature paper but we were unable to check the details at the time of writing the report.

3.2. Cannister response to volcanic activity:

Depending on the eruption scenario, the cannisters in the tunnel may be exposed to either (i) a flow of hot, bubbly magma, with velocities of order 1-10 m/s and temperatures of 1400K, (ii) a very high speed flow of fragmented magma and gas, travelling with speeds as large as 100 m/s; (iii) a shock wave, travelling with speed of order 100 m/s, involving a pressure increase of order 10 to 100 atmospheres. On longer time scales of the overall eruption and eventual cooling of the magma emplaced within the tunnels the cannisters may be surrounded by high temperature magma for many years.

Although the mechanical properties of the steel and nickel chromium alloy used in the cannister have been investigated at normal atmospheric conditions, more information is required about their performance under such high temperature, high pressure flow conditions. Any estimate of the volcanic dispersal of the waste material depends on the ability of the magma to disrupt the cannisters and release the waste. This is poorly understood at present.

Particularly important issues in this context include:

(i) Mechanical response of the cannister subject to high stresses at high temperature. In particular, how the cannister deforms under bombardment by volcanic rocks, of order 0.1-1m in size, with speeds of order 10 m/s, and possibly as large as 100 m/s. Such bombardment will occur if a full explosive eruption develops, or if magma explosively degasses into the tunnels. It is also important to determine the response of the cannister to a shock wave involving a pressure increase of 10-100 atmospheres.

(ii) The thermal response of the cannisters. The cannisters could be exposed to temperatures of order 1400K for prolonged periods possibly for months during the eruption and then for years following an eruption. The high conductivity of the metal cannister compared to basalt indicates heating to the magmatic temperatures relatively rapidly. Differential expansion will lead to considerable stresses on the steel and nickel chrome alloys, which may cause rupture and eventual release of the waste material. This may be an important issue for transport of the waste both in the short term by the volcanic activity, and on longer time scales for transport by the ground water. The themomechanical properties (notably mechanical strength and rheology) of the steel and alloy will be important as the cannisters are heated. One issue is whether the steel becomes sufficiently ductile that it may be removed from the cannister.

(iii) The chemical response of the cannister to the magma. We do not know whether rapid chemical reactions of the cannister materials with the magma are going to be important. The cannisters however will be in a potentially hostile chemical environment for months to years. Investigations of the chemical equilibria and chemical reactions between basalt magma, volcanic gases (notably H_2O, SO_2 and HCl) and cannister materials at temperatures of order 1400K would seem desireable. Some information may already exist within the metullurgical and petrological literature. Reactions between metals and silicate melts have for example been a major area of research for understanding the origin of the Earth's metallic core and the differentiation of planets. There may well be relevant experimental studies and thermodynamic data in these fields to assess this issue.

(iv) The physical response of the cannisters. The drag forces control the motion of the cannister along the tunnels and in a volcanic conduit subject to high speed, high pressure flow. Initial estimates suggest that the bulk density of the undamaged cannister may be of order 8000 kg/m^3. In order to move the cannister along the tunnel, the drag exerted by a magma flow has to overcome the static friction. Initial estimates suggest that for degassed low viscosity melt this would require flow velocities of order 10 m/s for a cannister that is not bolted to the floor. For a water rich melt (2 wt%) the mixture would become highly vesicular and would have a higher speed and lower density leading to comparable or greater drag forces. It is therefore possible that a magma flow along the tunnel might displace the cannisters. Similarly, in order to lift the cannister to the surface, flow speeds of dense magma in excess of about 10 m/s would be required, while higher flow speeds would be necessary to raise the cannister in a more vesicular, lower density mixture. The cannisters are sufficiently large that they are likely to be too wide to move through any initial dykes. It is however assumed these effects would be compounded if some fraction of the cannisters were corroded or damaged prior to volcanic activity. Cannister damge seems likely because of the potential for increased seismicity and volcanic emissions through the repository in the days or months prior to volcanic eruption. Fragments of the cannisters could be easily moved to the surface and a cannister might be able to pass through a widened conduit later in an eruption.

3.3. Grain size distribution of waste pellets and method of incorporation into magma

Coupled to the process of failure of a cannister, improved understanding of the breakup of the waste pellets and their incorporation into the erupting magma is important. The present modelling of this process at the CNWRA is simple and would benefit from further development in order to account for a range of scenarios of waste release. In particular, one can imagine the incorporation of waste pellets en masse into the flow or as large fragments in the flow. Depending on the time of mixing with the magma relative to the onset of fragmentation and dispersion through the atmosphere, the waste pellets may either (i) remain localised within the magma, even if the pellets are composed of small constituent particles, or (ii) become well mixed throughout the magma. To include these cases, one could examine the evolution of a variety of grain size distributions of waste particulate, and a variety of hypotheses for the mixing of these particulate with the melt. End-member cases would include (a) a well-mixed melt, in which the mass fraction of waste was the same in basaltic fragments of all sizes, and (b) a localised pellet model, in which waste particles were distributed either in the small (10-100 micron) or the large (0.1-1 cm) fragments; (c) a model in which the waste particles remain isolated from the ash, but are transported through the ash column and plume.

4. Eruption Column

The CNWRA research presently models the eruption column using the law for column height as a function of eruption rate as developed by Wilson et al. (1978) and updated in Sparks et al. (1997). This provides a good leading order model for the height of rise, a key parameter in the study of the ensuing ash dispersal. Although this is a good approach, some of the limitations of the model should be borne in mind, particularly associated with the effects of strong winds, atmospheric moisture and particle aggregration which may lead to variations of the column height and the grain size distribution of the particulate (Woods, 1995b). However, we feel that owing to the other uncertainties in the modelling approach, the present modelling approach of the CNWRA should be sufficient, particularly if a more complete study of the impact of different grain size distributions and waste-magma mixing models on the ash dispersal is carried out. We note that the source conditions for the dispersal model could be simplified from the Susuki model. In particular, the particulate material could be released uniformly from the upper 20% of the eruption plume, corresponding to the umbrella cloud.

5. Modelling the dispersal of volcanic ejecta and repository contaminants

The modelling of dispersal of volcanic ejecta and repository materials from an explosive eruption has been approached by CNWRA using a method developed by Suzuki (1983). This method treats the volcanic eruption column as a vertical line source of particles which are then advected downwind and diffused into the atmosphere. The original paper solved the advection-diffusion equation in a standard way to generate an analytical expression which describes the accumulation of particles of each size on the ground. The method can cope with a range of particle sizes and densities and assumes a constant single wind speed and direction. The results are dependent on several parameters, including the size distribution of the ejecta, a source function which describes how the particles are distributed with height at the origin, a parameter C which relates to the apparent atmospheric diffusivity and a parameter β which determines the vertical distribution of particles in the plume. The source parameter can be changed appropriately as a function of column height. Several studies, including the recent work by CNRWA staff on the Cerro Negro deposits, indicate that the Suzuki method can be applied successfully to reproduce approximately observed natural deposit patterns relatively close to the volcano. In the context of the Yucca Mountain repository the method has been used to develop probablistic maps of the distribution of contaminants by random sampling of the distributions of the main parameters such as wind velocity, column height and particle size distribution of magmatic ejecta.

We endorse the CNWRA view that the Suzuki method is a valid approach to modelling approximate fall out patterns of volcanic ash and therefore to assessing the dispersal of repository contaminants in the environment. In fact the alternatives are limited. A more general theory of the dispersal of ash in wind plumes has not yet emerged although progress is being made towards that goal (see Sparks et al., 1997). One alternative is to apply more sophisticated finite difference models to the problem as exemplified by the numerical code developed by the Pisa University Group in Italy. Such models are however more computer intensive and do not allow large numbers of realisations to be run. The more advanced diffusion models suffer from the same fundamental problem as the Suzuki models, as described below. We do not think that there would any significant gain in changing at this stage in the programme to a more advanced model, although some comparisons with the results of other research groups using alternative codes modelling the same eruption conditions might be worthwhile as one way of validating the CNRWA code.

The Suzuki method is appropriate provided that the user is fully aware of the limitations and pitfalls of the approach. The most fundamental point is that advection-diffusion models do not account for the physical processes controlling the evolution of medium to large volcanic eruption plumes, particularly during the intial stages of dispersal over scales of tens of kilometres from the volcano. Observations and theory show that atmospheric diffusion is a slow process and only dominates the spreading of most medium to large volcanic plumes at distances of many tens to hundreds of kilometres. In the near field, the main processes that cause plume spreading are the entrainment of air in the rising plume, mixing and entrainment of air as the plume accelerates downwind, and gravitational spreading of the plume as it intrudes into the stratified atmosphere (Sparks et al., 1991; Bursik et al., 1992). The reader is referred to Sparks et al (1997) for more details. None of these spreading processes are related to atmospheric diffusion. In this sense the application of advection-diffusion models for near-field ash deposition should be seen as a form of curve-fitting and therefore essentially an empirical approach.

There are several free parameters in the Suzuki method and it is relatively straightforward to adjust these a parameters to get reasonable agreement between the model and the observations. The method therefore needs calibration against real examples and the user needs to be aware of the potential to give incorrect results for situations well outside the conditions where the model has been tested or calibrated. For example a choice of parameters which agrees with the dispersal pattern of near source ejecta may break down for the dispersal of distal fine ash. If the dispersal of contaminants at distances of many tens to hundreds of kilometres were to become of interest then it is doubtful whether the Suzuki approach would be adequate and would certainly need testing and further development. There is definitely scope for more comprehensive testing of the robustness of the Suzuki method over a wide range of conditions and against laboratory experimental results. Another example of the limitations of the Suzuki method is that it cannot take account of variations of wind speed and direction with height (Woods et al., 1996). This might be a problem with models of plumes that penetrate the tropopause in the Yucca Mountain area.

The most serious concern about the modelling work of CNWRA thus far is that the algorithms for describing the distribution of the repository contaminant within the ejecta do not look realistic and we recommend that these are rethought. The models are such that the proportion of contaminant is selectively concentrated in the coarser volcanic ejecta. This is not a distribution which is found in nature for materials incorporated into natural magmas for which there is a large amount of data and reasonably good understanding. Natural magmas contain crystals, inclusions and accidental rock fragments which are mixed into the magma with varying degrees of homogeneity. These materials have a wide range of sizes, densities and mechanical strength which are the main properties which determine their ultimate distribution in the deposit and concentrations relative to the primary volcanic ash. Patterns analogous to the current CNWRA models have not been described in nature. We would expect that the repository waste would behave in similar ways to the natural examples of materials incoporated into magmas. There are a wide variety of patterns in the dispersal of these accidental materials. Observations show that it is common for such materials to be distributed in non-homogeneous ways which depend on the contrast in grain size distribution of the ejecta and the accidental material.

We recommend that the modelling should develop by considering two end member models. First the repository contaminant may be distributed homogeneously throughout the magma on such a fine scale that every volcanic fragment has the same mass fraction of contaminant irrespective of size. In this case the dispersal pattern of contaminant will be only a function of ejecta size distribution, eruption column parameters and the wind. Second the repository contaminant is considered to be fragmented into particles which are independent of the ash ejecta in which case the size distribution of the contaminant particles becomes an additional variable. Cases could range from those in which the contaminant is in the form of coarse lumps to those where the contaminant has fragmented into a fine powder. If the contaminant is in a fine-grained form (<50 μm particles) then the effects of particle aggregation in the atmosphere on dispersal will need to be considered as an additional process. For fine grained particles the Susuki model may not be appropriate or may need further devlopment. We are unable to find any rationale to discriminate between these different models in terms of their likelihood since there are large uncertainties about how the repository contents might be disrupted.

We draw attention to the role of secondary dispersal of contaminants and contaminated ash after an eruption. Erosion processes can transport particles to areas not initially inundated by the primary ejecta blanket. Wind erosion in particular is observed for long periods after ash fall and can be proficient at transporting fine particles well away from the original site of deposition. We also draw attention to the fact that rather little is known about the proportions of very fine ash (<10 μm) that are typically produced in eruptions of the style that is expected in the Yucca Mountain area. Since such very fine particles are important for the health aspects of contaminant ingestion by humans. Research to place estimates of fine dust abundances on a firmer basis might be desireable.

Recommendations:

We do not think that it will be possible to model the consequences of volcanism on repository performance with currently available information. Further work might include the following.

1. Development of new analytical, numerical and experimental models for the interaction of a dyke and the repository tunnels. We outline below a possible programme of research to investigate this complex process.

The analogue laboratory experiments would explore the basic flow phenomena which develop when both a non-volatile and a volatile liquid migrate up a vertical fracture, and at some depth, interact with a low pressure horizontal tube. The experimental fracture would consist of a Hele-Shaw cell, connected to a pressure controlled source of liquid at the base and a vacuum chamber at the end of the tube, in order to pump down the pressure far below atmospheric. The tube would be connected to the fracture. However, there would be a seal which is only broken once the liquid has risen above the elevation of the tube. The working fluids will be a viscous syrup for the non-volatile experiments and a pine-resin acetone mixture for the volatile experiments. The pine-resin acetone system is known to have analogous solubility relations and physical properties as magma, but it may be used at ambient temperature and pressure (Phillips et al.,1995; Mader et al.,1996). Pressure sensors and high speed video recordings will monitor the evolution of the flow once the seal has been broken. Using dimensional analysis, the experiments could be designed to be dynamically similar to the large scale system. The phenomena and quantitative measurements from the experiments would then be important in the development and validation of the theoretical models of magma-repository interaction.

The analytical and numerical modelling would involve calculations of the rate of propation of a magma-water mixture along the repository tunnel from the dyke. First, the case of a water-poor melt would be considered, examining the interaction of the flow with the tunnel geometry, and the response of the dike on this flow. These calculations would be compared with the scaled laboratory experiments to validate the various assumptions used in the analysis. Second, the case of a water-rich melt would be considered. This would involve the analysis of a high speed, high pressure fragmented mixture moving along the dike, behind a shock wave, coupled with the propagation of a vesiculation, and possible fragmentation front moving back through the dyke (Woods, 1995a). Subsequently, the analysis would involve calculation of the interaction of the continuing flow along the tunnel with the reflected pressure wave propagating back from the end of the tunnel. As the pressure in the tunnel builds up, the flow becomes less vesicular, resembling a bubbly-melt flow rather than a fragmented mixture. Again, the model would be developed for the small-scale laboratory system as well as the large scale flow, to test the key assumptions and predictions of the calculations.

2. New models of cannister interaction with magma and volcanic gases, including mechanical, thermodynamic and dynamic response, as outlined earlier in report. Some of the key processes which merit study include:

a. The heat transfer to the cannister when exposed to the high temperature magma for time periods of months to years. Calculations could be made of the evolving temperature distribution of cannisters immersed in relatively static magma and for cannisters surrounded by a high speed flow, for which the heat transfer will be greatly enhanced. Information about the evolving radial temperature distribution would be directly applicable for conducting a study of the differential stresses set up in the cannister when exposed to high temperature magma.

b. Some analysis or estimates of the potential interaction of the cannister material with basaltic magma and associated gases, including information about the phase relations. This may be very relevant for predicting the response of a cannister when immersed in basalt magma.

3. Development of new models for the mixing of waste pellets with magma, as an input into the models of the ash and contaminant dispersal. This will identify the range of possible dispersal patterns of the waste material for an eruption of given strength. If the waste material is largely concentrated in the fine grain fraction of the ash, or indeed, does not mix with the ash, then the dispersal range may increase. In contrast, if whole pellets of waste are incorporated into single large fragments of melt, then the waste may be localised much closer to the source.

4. A variety of approaches could be conducted to validate the plume dispersal modelling, and examine deposition from a plume consisting of various particle sizes. Analogue experiments on a laboratory scale (Sparks et al., 1991) would complement existing studies in which the model predictions have been compared with dispersal data from historic deposits. In particular, particle laden plumes which are swept downwind can be modelled using an analogue aqueous system in a flume. Unpublished data of this kind already exist (Ernst, 1996). Particle deposition patterns may then be measured for plumes of different strength relative to the wind speed. These data could be compared with a scaled version of the ash dispersal model. Further advances in understanding plume dispersal in small to medium strength basaltic eruptions could come from studies of satellite images (Woods et al., 1996).

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Annex 1. Credentials of consultants

Professor R.S.J. Sparks is Professor of Geology at the University of Bristol, UK. He has researched in volcanology and the application of fluid dynamics to geological systems. He was Head of the Geology Department from 1989 to 1994 and is currently NERC (Natural Environment Research Council, UK) Research Professor based at Bristol (to 2002). He has 172 scientific publications in peer-reviewed journals and has recently published, together with colleagues including Profssor Woods, a book on Volcanic Plumes (John Wiley, 1997). Honours include election as a Fellow of the Royal Society (1988), the IAVCEI Wager Medal (1983), the Bigsby medal of the Geological Society of London (1986), the Murchison Medal of the Geological Society of London (1998) and election to a Fellowship of the American Geophysical Union (1998). He has held a Sherman Fairchild Scholarship at the California Institute of Technology (1987) and was President of the Geological Society of London (1994-1996). He served as a member of the scientific advisory panel to UK Nirex (1993-1997) in their programme for the storage of nuclear waste in a deep geological repository in the UK and he has been one of five Chief Scientists in rotation at the Montserrat Volcano Observatory.

Professor A.W. Woods is Professor of Applied Mathematics at the University of Bristol, UK. He took up this appointment in 1996 from a lectureship in the Department of Applied Mathematics and Theoretical Physics at Cambridge University. He obtained a Green Scholarship to carry out research at the Scripps Institution of Oceanography (1989-1990) and has been a regular visiting scientist at Woods Hole Oceanographic Institution. His research involves fluid dynamics applied to a wide range of environmental problems including volcanoes, geothermal systems, ventilation problems, traffic flow, physical oceanography and sediment transport. He has published 81 scientific papers in peer-reviewed journals and has recently published a book with colleagues, including Professor Sparks, on Volcanic Plumes (John Wiley, 1997). Honours include the Marcello Carrapezza International Scientific Prize for volcanology awarded by the Gruppo Nazionale per la Volcanogia, Italy (1997), the ItalGas Prize for Research and Technological Innovation for his work on geothermal systems (1997) and he delivered the 1998 Bullerwell lecture to the Geophysical section of the Royal Astronomical Society, UK.

Together Professor Sparks and Woods founded the Centre for Environmental and Geophysical Flows at Bristol University in 1996. The Centre has facilities for laboratory and theoretical studies of natural and environmental flows.

YUCCA MOUNTAIN: EVALUATING EXPOSURE TO VOLCANIC ASH FOR RADIATION DOSE ASSESSMENTS IN ERUPTION SCENARIOS

Report on a meeting by Dr Peter J. Baxter MD, FRCP

1. A meeting was held at the Center for Nuclear Waste Regulatory Analyses (CNWRA) at Southwest Research Institute, San Antonio, Texas, on 27-31 July 1998, to discuss consequence models of volcanic disruption of the proposed nuclear waste repository at Yucca Mountain. The aims were to review current approaches, including identifying areas needing additional work, and to develop where necessary research strategies for refining the consequence models. The writer accompanied Prof Steven Sparks and Prof Andrew Woods, both of the University of Bristol. This report deals with health aspects of volcanic ash blankets in relation to estimating the inhaled radiation dose in an event involving plume dispersion.

2. Recent eruptions of basaltic volcanoes such as Cerro Negro, Paricutin, Tolbatchik and Heimey were regarded as possible models for a future event at Yucca Mountain. Ashfalls can extend for many kilometres away from the volcano in these types of eruptions and it has been proposed that radioactive material stored in the repository could become entrained in the eruption column and be distributed with the ash in a future eruption at Yucca Mountain. Some plume dispersion modelling has already been performed by CNWRA, but the meeting concluded that more consideration will be needed on the source factor and other modelling issues in order to predict the most foreseeable area and depth of ash fallout.

3. However, for regulatory purposes a community located 20 km south of Yucca Mountain is considered as the "receptor group". It is assumed that the receptor area is affected by an ashfall at least 10 cm thick. In terms of radiation dose to a hypothetical individual, it has been proposed elsewhere that as much as 90% could be from inhalation of the radionuclides plutonium and americium, with only small contributions from direct external radiation or from the ingestion of food and water. For modelling purposes, two types of hypothetical individual need to be considered, an active outdoor worker, such as a miner, and an ordinary resident. The main time period for risk assessment purposes was given as the first year after the ashfall event. This report focuses on ash fallout containing a significant proportion of suspendable material, i.e., <100μ diameter, including a respirable fraction (<10μ diameter).

Exposure factors

4. Air quality standards have been set for particles (and occupational exposure limits for dusts, including crystalline silica content), but these have no bearing on assessments for radiation dosages. They may be used, however, to give general advice on exposure to ash in industrialised communities after volcanic eruptions. Definitions differ according to the sampling methods used in occupational and environmental studies, e.g., total inhalable dust and total suspended particulates, and these can be confusing. Particles of the greatest interest in dose-estimation and risk analysis are PM_{10}, or particulate matter less than 10μ diameter. These particles are small enough to be inhaled into the airways of the lung. Currently, health interest in urban air pollution is focusing on $PM_{2.5}$, but the respirable fraction, i.e., the size fraction which will enter the alveoli or deep lung, is generally considered to be <3.5μ diameter and is included in PM_{10}. However, there may be a need to consider exposure to total suspended particulate (TSP) – technically, the mass of particles <25-40μ – and include suspendable particles up to 100μ diameter as these can be deposited in the nose and nasopharynx. Deposition and retention of particles in the lung, together with estimates of radiation dosage to the tissues of the lung and other organs, can be evaluated using ICRP models.

5. Whilst exposure can be measured using static air monitors, as in urban air quality measurements for regulatory purposes, this will not equate with individual exposure and will fail to reflect the individual dose for a particular pollutant of interest. Individuals produce their own microclimate, particularly as human activity is the main determinant of exposure to volcanic ash, and exposure methods need to take this aspect into account. The amount of time spent out of doors in ash areas will be the most important, but exposure to PM_{10} can also readily occur inside homes and offices, e.g., when sweeping the floor, making beds, dusting, or just moving about. Thus an integrated measure of exposure is needed which takes into account the individual's activity over 24 hours (though exposure will usually be low when sleeping).

6. Experience from eruptions at Mount St Helens in 1980 and the Soufriere Hills volcano, Montserrat, 1995 - present, has shown that the main determinants of exposure to fine ash particles are human activity, both inside and outdoors, occupation (outdoor workers are most exposed), and weather conditions, especially wind and rain. Fine particulate ash is readily resuspended by winds and traffic, as well as any movement which will disturb the ash deposit, whilst the key factor in limiting the resuspension of ash in the ambient air is rainfall. Advice to the public to limit exposure by reducing activity, wearing masks or staying indoors has only limited value. However, substantial protection can be provided by high efficiency lightweight masks, or airstream helmets for workers, and in N. America housing of good quality has generally low infiltration rates so that staying indoors can be protective. In reality, for most people unless they are elderly or already suffer from respiratory disorders, such advice often presents practical difficulties, and so is not adhered to, and the best method to reduce or eliminate the risk of exposure would be to relocate to outside the affected area.

7. The response to major eruptions is much the same world-wide. During the period of the ashfall people will take shelter inside their houses and other buildings. In any but the lightest ashfalls, moving around outside becomes difficult or impossible with ash in the air, and most individuals will remain indoors. In weakly constructed houses there is the possibility that deposits of 10 cm or greater will cause bending and even collapse of the roof with a sudden infilling of ash. This can be dangerous, and in single storey buildings the collapse can cause death from direct impact of the roof elements, or asphyxiation from burial by ash. This risk is greatest if the ashfall is accompanied by rainfall, as a soaking by rain water can double the density of the ash. Some individuals will attempt to remove ash from their roofs, even during an ashfall, if they think that the roof could collapse. After a sizeable ashfall, people will want to clean ash from their roofs and from around their properties, and attempts will be needed to remove ash onto the sides of roads as driving behind another vehicle becomes impossible because of the poor visibility due to clouds of resuspended ash. In the absence of rainfall, extremely dusty conditions will prevail for many weeks, and efforts will be needed to water down ash around houses and along roads to assist in clean-up operations and make movement of people possible.

8. Rainfall will dramatically clear the air and make the ash much less resuspendable, but on drying out after a few hours the concentrations in the ambient air are likely to be kept at elevated levels by the winds which will blow mostly from the north over the ash blanket and towards the receptor area. After the eruption of Cerro Negro, Nicaragua, in 1993, a dense plume of resuspended ash, visible from the air and from the ground, was blown constantly out to the sea from the volcano and the affected downwind area. On Montserrat, similar wind effects have been visible as wind has regularly resuspended ash from the heavily covered flanks of the volcano during dry periods for months after the last fallout event. Occupational exposure in areas affected by thick ash deposits will be raised for weeks and possibly months, e.g., for open-cast miners and agricultural workers, as well as police dealing with traffic control, clean-up crews, gardeners, and outdoor construction workers.

Previous work

9. Substantial work on determining exposure of workers and the general population to volcanic ash took place after the eruptions of Mount St Helens in 1980 (1), and during the volcanic crisis on Montserrat in 1995 - 98 (2). The results from the two events were very comparable, except that the Mount St Helens eruption was a 'one-off' event, whilst repeated ashfalls have occurred on Montserrat. The experience gained can be applied to the Yucca Mountain risk assessment. In addition, certain studies on Montserrat are continuing in order to protect the population from the risk of silicosis. In particular, studies are needed on the long-term impact from the large deposits of ash lying on the flanks of the Soufriere Hills volcano and how this toxic respiratory hazard may limit the reoccupation of the south of the island. Very little, if any, comparable work has been performed at other volcanoes. At Sakurijima volcano in Japan the eruptive style is quite different from that proposed for Yucca Mountain, but small ashfalls have occurred irregularly over many years in Kagoshima City(3). Eruptions of Irazu volcano in Costa Rica in 1963-65 resulted in repeated small ashfalls occurring in the capital city of San Jose(4).

10. The ashfall in Central Washington State after the May 18,1980, eruption of Mount St Helens may well be one of the best analogous events to date. About 10 cm of ash fell in the Moses Lake and Ritzville areas, where there is a relatively small, mainly agriculture-based economy in an arid zone. About 10-12 wt % of the ash was less than 10µ diameter (1). Eruptions of the Montserrat volcano have mainly yielded ash containing 15-20 wt % of respirable ash (5). A subsequent eruption of Mount St Helens on May 25 1980 deposited a maximum of 1 cm of ash to the west of the volcano in the Cascades region. A health and exposure study of loggers was undertaken by the National Institute for Occupational Safety & Health (NIOSH) which was discontinued after 4 years because there was no longer any evidence of a health hazard (6).

11. The writer reported to the meeting his experiences at the eruption of Cerro Negro, Nicaragua, in 1993 and subsequently reviewed his photographic slides taken on two visits to the area, one about one week after the eruption in April and the other about nine months later. Prof Sparks questioned the proportion of suspendable material that would be present in this basaltic eruption which could be an important analogue for an eruption at Yucca Mountain. Accurate data on the size and composition of the erupted ash do not appear to be available, but the ash was substantially coarser on average than the ash from Mount St Helens and on Montserrat, as would be expected from differences in magma composition. However, a significant proportion of the ash was visibly very fine and in the respirable range. Numerous respiratory complaints were reported in the Leon area (7). The eruption had occurred towards the end of the dry season and the fine material was readily resuspended in visible clouds by winds and whirlwinds across fields where 10 cm was deposited, and by traffic in the city of Leon (5 cm thickness), where the occupants used hoses to wet down the ash to prevent its resuspension. Nine months later, a visit to the same farming area showed that extensive natural re-vegetation had occurred during the wet season and sugar cane and other crops were growing astonishingly well. Grass had grown up through the ash layer, but fine material stuck to the hand when parting the ash to look at the roots. Photographs show bullocks kicking up clouds of fine ash. Thus vegetation was playing an important part in entraining ash, but exposure to elevated amounts of respirable ash could still occur if the ash was disturbed. These findings indicate that abundant respirable particles would be retained in the deposits for many months and, perhaps, years after an eruption.

12. Large ash deposits will gradually become incorporated into the soil. Agricultural activities will promote this as layers of up to 10 cm can be readily ploughed in and the soil mixture used immediately to grow crops, as was done in Central Washington in 1980 and in Nicaragua after the Cerro Negro eruption in 1993. The ground can rapidly revegetate with rain or irrigation and a cover of new growth will help to stabilise the ash and reduce resuspension. However, this will take at least six months to begin to any extent. Fine material will continue to be resuspended

from the soil whenever it is worked upon. At least some exposure to agricultural workers and others may therefore continue intermittently in the long term. In the area of Cerro Negro it was evident that there were places where very fine volcanic ash from past eruptive vents had accumulated over many years down farm tracks and other places.

Key exposure issues for radiation dose assessment

13. *What are the differences between levels of ash in the air as measured by static monitoring and personal monitoring?* The differences are very great as static monitors do not reflect individual exposures, even for inactive people staying indoors. The difference is greatest for outdoor workers and young children. The latter disturb deposited ash when they play. Data already exist from surveys on Montserrat, but these need refinement in regards to the reoccupation of Salem, when reassurances are going to be needed in the next few months that clean-up operations have been successful. Further work in this area is being planned, and will need to include obtaining personal samples over at least 12 hours in individuals performing representative outdoor and indoor activity.

14. *How does exposure to fine particles vary with the thickness of ash deposit?* This does not appear to have been studied before. A broad answer could be given by a trial on Montserrat, comparing exposure to an outdoor worker in Salem (deposit 4-6 mm) with the same tasks being done in an area in the current Exclusion Zone (when it becomes safe to enter the area), with a depth of ash of 5 to 10 cm. However, elevated exposures can occur with only 1-2 mm of fine ash when it has been freshly deposited, and exposure may not vary much if the ash has a substantial fine component. Weathering can remove the fine deposit over a period of weeks, and so the duration of exposure will be much less than with a thick deposit.

15. *How long does it take for an ash deposit of >10 cm depth to be removed under typical weathering conditions (i.e., by wind and limited amounts of rainfall, as in Nevada)?* The question is of general importance and is also applicable to reoccupation of areas on Montserrat, but to my knowledge this topic has not been previously considered worthy of special study. People involved in the clean-up operations in Central Washington could give an answer from their experience. Reincorporation of volcanic ash into soils will be a long-term "sink". In the logging areas in the Cascades affected by the May 25 1980 eruption of Mount St Helens, the maximum thickness of deposit was 10 mm and exposures in loggers to respirable dust were down to background occupational levels by September (the job is a dusty one under normal conditions) (6). An attempt could be made to evaluate this issue in Montserrat by selecting a test site, such as a flat field, and following the progress of the ash over time. The weather on Montserrat is frequently windy, but in the wet season it may rain at least briefly once a day and once a week in the dry season. In Nicaragua the wet season had a dramatic effect on regrowth of vegetation, which we have also observed on Montserrat to result in suppression of the fine ash in windy conditions, but vegetation has the effect of trapping and entraining fine ash particles so that they remain to be resuspended in the air when the ground is disturbed. This effect is most apparent in Montserrat (and was also seen after Mount St Helens) if people cut their lawns in dry conditions when large clouds of fine ash can be produced. Thus weather and growth conditions need to be carefully assessed in the Yucca Mountain area for evaluating exposure to resuspended ash over a year following an eruptive event.

16. *What is the typical particle distribution of resuspended ash?* This may, or may not, vary with the particle size composition of the ash deposit (and with distance of the deposit from the source). On Montserrat, almost all attention has been given to PM_{10} rather than TSP, and further air samples would need to be studied. In addition, experiments could be performed at Cerro Negro and Paricutin by exposing and sampling the layers of recent ash deposits and reworking them with a shovel to generate ash in the air which could then be sampled.

17. *What level of exposure can we find in high risk groups such as outdoor workers and children?* This information has been obtained on Montserrat and estimates of average exposures made (Table). Further work will be needed to ensure that the comparison with Montserrat is valid, at least as far as worker exposure is concerned, and an appropriate adjustment made for differences in grain size. The method proposed would be the same as that described in the previous paragraph. For exposure estimates, the results obtained from Mount St Helens and Montserrat will almost certainly need to be reduced by a factor to allow for the coarser material emitted at Cerro Negro.

18. *What is the effect of walking and vigorous exercise?* Estimates have already been made on Montserrat. Again, further information could be obtained by conducting experiments using the DustTrak instrument in the study proposed above.

19. *What are the expected societal responses to a heavy ashfall?* The best example for this purpose, especially for N. American societies, is the ashfall which occurred from the May 18 1980 eruption of Mount St Helens into central Washington State, an arid agricultural area sustained by irrigation. The depth of ash was 10 cm in the Ritzville and Moses Lake areas, and no rain occurred for five days. All road and rail traffic ceased for this period until the air was cleared by an unseasonal rainfall. The population tried to resume normal living as soon as possible after this, and clearance operations got underway which included home-owners removing ash from their roofs and gardens. A few people were very anxious about the possible health effects of the ash, but voluntary mass evacuation of the areas did not occur. Even people with pre-existing lung disorders continued living in the Yakima area, even though their symptoms were made worse by the ash (8).

Conclusions and recommendations

20. The meeting found that further consideration was needed on the form in which the waste material in the repository could be released and the extent to which it could be incorporated in the ash. A better idea on the likely dispersion of the ash and the waste material was needed using plume dispersion modelling, including drawing up isopach maps of potential deposition. This would assist in devising more realistic assumptions about exposure, including the effects of wind direction, etc. Assumptions on particle size need to be carefully assessed. There is insufficient information available from previous eruptions of Cerro Negro and comparable eruptions to be confident about the proportion of fine, suspendable material that may be expected, as opposed to fine dust released from reworking of the ash by traffic, etc.

21. Certain assumptions can already be made about the effectiveness of methods to limit ash exposure, e.g., by wearing of masks or staying indoors. Overall, it is best to assume that relocation away from the affected area is the only effective way of ensuring exposure reduction. Exposure to resuspendable ash will be markedly elevated after an ashfall of over 10 cm and can last for weeks or even longer in the absence of rainfall. Human activity is the main determinant of exposure, but raised background levels may be maintained by strong winds blowing from the volcano to the receptor area during dry periods. Rainfall makes a dramatic difference to background and personal exposure to fine ash, and the low rainfall in Nevada means that exposures could persist for longer than was experienced at Mount St Helens.

22. Sufficient information is available from the eruptions of Mount St Helens (1) and Montserrat (2) to make some preliminary estimates of occupational and community exposures. Individuals with the highest exposure will be outdoor workers and children. However, in modelling a future eruption there is little doubt that the exposure values will need adjusting downwards to take into account the differences in ash size and composition in basaltic-type eruptions. Further work is

needed to determine if the previous deposits from eruptions at Cerro Negro and Paricutin volcanoes give comparable results when they are reworked under controlled conditions and what adjustment in exposure values may be required. This project should involve the use of personal cyclone samplers and pumps, as well as a direct readout instrument (e.g., DustTrak), as in conventional studies of industrial exposure to workplace dusts. Training is needed in the use of such equipment and the analysis of dust samples. Expertise in the USA can be found at the National Institute for Occupational Health & Safety (NIOSH), Cincinnati.

23. Further work on Montserrat may be useful in determining the rate at which thick ash deposits are removed by natural processes. However, over the first year after an event at Yucca Mountain it can be assumed that exposure will fall away only slowly in the absence of regular rainfall. It would be helpful to have more information on how exposure may vary with activity, such as walking or vigorous exercise, in areas with different depths of ashfall, but even light deposits of fine, dry ash can give rise to markedly raised exposures until they become dispersed from the ground by natural processes. If detailed studies were considered necessary, a test site on Montserrat, such as a flat field covered by a thick ash layer, would be equipped with a static ash monitor (e.g., DustTrak), a weather station to record wind velocity and humidity, and be evaluated periodically by taking surface ash samples, together with air samples collected under windy conditions, to determine the particle size distribution of the resuspended ash. The location of the test-site needs careful consideration - if on a slope, for example, it will recollect ash whenever rainwater flows over it. It should be located down-wind of the volcano so that the concentration of resuspended ash in the air can be monitored and deposition of wind-borne ash can occur. In a wet climate, the rate of erosion may be countered by growth of grass and other vegetation through the ash layer. This will serve to retain the ash unless it is disturbed by human activity.

24. Studies of suspended particles should also be undertaken in Nevada in the Yucca Mountain area to obtain information on background conditions there, in particular measurements of PM_{10}. Little appears to be known about the local persistence of fine particles in dry remote areas; their characteristics and sources should be investigated further.

25. Societal responses to ashfalls are uniform throughout the world, in that people will try to resume normal life as soon as conditions allow and they do not initially attempt to leave the affected area. Instead, very high contact with the ash is the norm as communities attempt to remove ash from around their homes and work it into the soils of fields to continue agricultural production. Both of the ashfalls after Mount St Helens and Cerro Negro are good examples.

26. I would be glad to amplify on any of these issues or refer anyone interested to sources of advice, as well as assist in drawing up fieldwork protocols and exposure/dose modelling, on a collaborative research basis. Exposure assessment studies were performed by NIOSH in the Mount St Helens eruption and the Institute of Occupational Medicine, Edinburgh, in the Montserrat crisis.

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Table: Montserrat Volcano: Estimates of personal exposure to PM_{10} ($\mu g/m^3$) associated with various activities on days of differing background environmental dust concentrations (regardless of location)

	High Ash	**Moderate Ash**	**No Ash**
background environment	1000	300	30
indoors housework	5000	1000	50
outdoor walking/driving	3000	1000	50
outdoor play	10000	5000	100
dusty occupations	10000	5000	200

[Data from Institute of Occupational Medicine, Edinburgh]