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HAZARDS AND SAFETY MEASURES IN GEOTHERMAL PROJECTS

Neville D Dench

Consultant, GENZL, Auckland

ABSTRACT

In the exploration and exploitation of geothermal resources, there are potential dangers to human life and property which are rare or absent in many other developments. They are the immediate or eventual consequences of volcanism, seismicity, or human attempts to improve that environment, and recognition of the possible hazards and their mitigation is necessary for responsible project planning.

Particular dangers to the person include physical injury from falls, flows or explosions, poisoning or suffocation from gas concentrations, burns and deafness. Severe damage to property may be caused by earth movements of various sorts, ash showers, corrosion, flooding, etc.

Acceptable levels of protection can be sought under three general headings, namely:

(a) avoidance, where possible, of the hazardous circumstances;

(b) design to resist the effects of unavoidable events;

(c) preparedness to undertake necessary and timely remedial action.

This paper elaborates on the range of disasters possible and on the measures which can be taken to minimize their repercussions.

1.0 INTRODUCTION

1.1 Within the space available for this paper, the emphasis will be placed on those dangers and precautions which are special to volcanic regions and geothermal developments. However, so that they may be considered in their proper context, the principle aspects of safety also encountered in general engineering construction will be mentioned. In this paper, 'hazard' is considered as the combination of likely severity, frequency and exposure.

1.2 Because of its fairly recent growth, and also due to its relatively small scale in the world scene, geothermal technology has relied heavily on the appropriate selection of standards and practices devised in the first place for other types of development. Thus, for instance, the design of casing strings for geothermal wells places most emphasis on the effects of thermal stressing and expansion, although it still leads to the choice of products which are manufactured primarily for the petroleum industry. Similarly, safety codes detailing the precautions required when operating in places of high concentrations of hydrogen sulphide gas - as found in some geothermal situations - have been published independently of geothermal needs.

1.3 The achievement of a good safety record follows from a knowledge of the hazards which can occur, plus proper application of the appropriate remedies. Engineering projects frequently require the employment of a Safety Officer, whose duties are to anticipate the dangers and, like a broker, to identify the most suitable responses proposed by experts in the various disciplines. In many cases the situation will be covered by contractual or legislative requirements, but these may not be fully appropriate or up to date. Furthermore, there are circumstances where there is not sufficient awareness of the possibility of danger, and guidelines will be needed before work begins.

1.4 While this paper has been prepared in recognition of the often inadequate attention paid to safety, it should be appreciated, also, that there can never be absolute, 100 percent protection against injury, and that the acceptable level of risk may be very difficult to establish. The competing uses for available resources (including money) place limits on what can be achieved. In the case of safety measures, the cost of improvements should not exceed the value of the benefit to be gained in reducing the hazard, which may be calculated as the probability of an injury occurring times the cost of that injury. Frequently, however, the cost of improvements is trivial in comparison with the likely gain in safety, and the problem is lack of motivation to make the changes - not the cost of them. In an ideal world, financial incentives will accrue from the reduced cost of insurances which, of course, compensate for injury and damage after the event, rather than pay for preventive measures.

1.5 The advice of colleagues on various aspects of this topic is gratefully acknowledged.

2.0 VOLCANIC HAZARDS

2.1 Volcanism introduces some quite obvious and immediate dangers to life and property; instance the results of eruptions of say Mount Vesuvius or Mount Tarawera. Other effects may be delayed but equally serious - such as the Whangaehu lahar event which destroyed a rail bridge and train after increased crater lake heat had melted an ice dam. We can also recall two airliners which had their jet engines blocked by ash over Java.

2.2 The following list includes the effects of present and past volcanic activity which may influence whether or where or how a geothermal project may proceed:

a) lava flows

b) rock and ash showers

c) lahars (mud flows) and landslides

d) eruptive cratering - phrearic or hydrothermal

e) poisonous and corrosive gas venting

f) boiling and corrosive springs and pools

g) fumaroles and steaming ground

h) fragile ground surface.

As was shown in the Krakatoa eruption in 1883, tsunami generated from marine eruptions can cause huge loss of life and property, but the possibility of such a disaster is most unlikely to influence geothermal developments, and has therefore Jjeen omitted from the list. Similar comments apply to major nuees ardentes (glowing avalanche) type eruptions such as the 1902 Mont Pelée catastrophe in Martinique, which destroyed the town of St Pierre with its 30,000 inhabitants.

2.3 Although the likelihood of lava flows engulfing a particular area can be assessed by a volcanologist, there have indeed been instances during the last two decades when power plants have been sited in danger areas. Ash showers, however, pose a considerable problem, as their effects can be spread by veering winds over very large areas of countryside for extended unpredictable periods of time. The eruptions in 1982 from Mount Galunggung in Java (alluded to in 2.1) provide an excellent example.

2.4 Galunggung's half year of intermittent effusions caused direct and indirect loss of life, while the cost in disturbance to normal human activity was high, and included the following aspects, most of which affected the Kawah Kamojang Geothermal Plant then under construction:

a) Ash deposits settled on roofs, pipelines, etc which were not specifically designed to support such loadings.

b) Fine particles penetrated machinery which required to be taken apart for cleaning, to avoid both abrasion and corrosion.

c) Ash fouled the cooling water which then required replacement (several times).

d) Silicosis was suggested as a possible hazard to health.

e) The acidic nature of the deposits caused a degree of corrosion on those metal surfaces which were not able to be kept clear.

f) Close to the mountain, thick deposits of ash killed all growth and forced the evacuation of the inhabitants under threat from.the possibility of major lahars.

2.5 Lahars and landslides are very potent destroyers of life and property, as they can occur suddenly and reach sufficient size to engulf whole settlements. Ash accumulating on steep slopes may be close to neutral equilibrium until set in motion by rain or ground tremors. Over a longer time scale, with exposure to hydrothermal and climatic influences, volcanic ash breaks down readily to clay minerals which have reduced shear resistance. With such materials, even quite gradual slopes can be set into motion - particularly under the influence of excess water. At Wairakei, a hot mud flow was initiated by leakage of steam into hillside clays, and as soon as the top layer had slid away, hydrothermal eruptions followed - fortunately with no loss of life.

2.6 At locations which are distant in time and space from direct volcanic activity, it is possible to have eruptions of near surface material caused by the buildup of gas, steam or hot water pressure under impermeable surface materials. These events tend to be quite local in their effects, and except within the crater area, any injury is due to falling material or gas emanation. Hydrothermal eruptions can occur in flat areas which, from the air, have a typical pock-marked appearance. Both landslides and hydrothermal eruptions can be caused by adjacent drilling activities when the flow of reservoir fluids in the drilled hole is not properly controlled. A companion paper discusses hydrothermal eruptions in more detail.

2.7 Some geothermal areas, such as part of the Dieng Field in Java, are known for their unusually high emission of deadly gases - either from natural ground vents or from drilled wells. Typically, more than 90 percent of the gas is carbon dioxide, which can suffocate by displacing oxygen, and up to 5 percent may be hydrogen sulphide which is actively toxic. While CO2 is invisible (without water vapour) and has no smell, H2S has a strong characteristic odour, but in moderate concentrations quickly deadens the sense of smell. As both gases are heavier than air, they flow in valleys or collect in confined spaces like excavations, cellars and even tree-enclosed areas. Table 1 indicates a wide range of H2S concentrations and their physiological effects.

Table 1: Physiological Effects of Hydrogen Sulphide (after World Health Organisation, 1980)

Concentration (mg/m^3)			Effect
0.0007	-	0.2	Threshold of odour
15	-	30	Threshold of eye irritation
70	-	140	Serious eye injury (gas eye)
210	-	350	Olfactory paralysis
430	-	700	Pulmonary edema, imminent threat to life
700	-	1,400	Strong nervous system stimulation, apnea
1,400	-	2,800	Immediate collapse with respiratory paralysis

2.8 Geothermal waters can contain poisons such as arsenic, mercury and boron, the first two of which can reach humans in more concentrated forms via the river bottom weed consumed by fish. Natural hot pools contaminated by soil can cause the usually fatal illness known as amoebic meningitis, particularly if forced up the nose.

2.9 Geothermal waters often contain high concentrations of chloride (and carbonate) ions - the former up to an order of magnitude greater than that of seawater. Thus two strong acids, hydrochloric and sulphuric, can be found, and their attack is particularly harmful on casing steel and its cement sheath close to water level where a favourable environment for corrosion exists and where leakage could endanger the wellhead. Other chemical constituents may form deposits which cause operational hazards - such as the sticking of valve spindles due to silica formation at gland leaks.

2.10 Natural thermal areas - often tourist sights as well as valuable survey locations for geothermal scientists - contain several types of hazard for people working in them. The most frequent injuries are burns, which are easily sustained by a shoe breaking through a thin crust of Unstable steaming ground, or by slipping on greasy thermal clay or algae, into boiling water or mud. As in the NZ volcanic zone, acid leaching of ash deposits can form cavities (Maori, tomos) close to the ground surface, which may give way under concentrated loads.

2.11 Depletion of hot water from a geothermal reservoir over a number of years of production can cause subsidence at the surface if the reservoir rock structure is too weak to support the overburden without help from the buoyancy effect of the water. This may affect structures, but is unlikely to cause personal injury. The maximum amount of vertical movement of the ground surface at Wairakei exceeds 10 metres, and the associated horizontal movements can be measured in metres.

3.0 OTHER DANGERS

3.1 In general, the other hazards encountered in geothermal work are also experienced in less specialist activities. However, they present no less of a threat, and should be acknowledged as clearly as the volcanic risks, because people involved in geothennal projects are drawn from a very wide range of experience, and may have no familiarity with, for instance, the drilling industry or the requirements for pressure vessels.

3.2 The same geologic situations which encourage volcanic activity - namely, the boundaries of continental plates - are also linked to seismicity. So it is normal for geothermal development to be undertaken in zones of high or moderate earthquake intensity and frequency. Thus, for example, the Pacific Ocean 'Ring of Fire' associates seismicity with volcanicity along the west coast of the Americas and the eastern part of Asia. Sometimes the two effects mix - as in the triggering of unstable, thermally altered earth slopes by ground vibration, or the causing of earth movement by reservoir fluid depletion. Poorly consolidated volcanic material may intensify the effects of earthquakes on structures.

3.3 Deep drilling operations for petroleum or geothermal fluids expose people and property to a number of potential risks which include:

a) Blowouts, with the possibility of cratering around the well and the loss of equipment, the well itself, and the energy contained in the fluid discharged.

b) Accidents to crews carrying out manual work which involves moving heavy tools and machinery through considerable heights.

3.4 In addition to the conventional construction and industrial type accidents met in most engineering developments, geothermal production requires the extensive employment of pressure vessels - pipes, valves, separators, pressure relief devices, etc, including casing and drill pipe through to power plant equipment. Fatal accidents have occurred at wellsites due to faulty valve assembly, and a particular danger exists in the erection of inadequately designed, temporary production test equipment which may be required to withstand steam pressures exceeding 150 bars.

3.5 Casing strings are subjected to a variety of conditions which are more severe than in oilwells of comparable depth. Aspects which require particular attention include:

a) Thermal compressive stresses up to the ultimate strengths of casing and connections designed primarily for tensile resistance.

b) The entrapment of water, particularly between casings, which then undergoes heating, with the accompanying buildup of very high fluid pressure.

c) Variable neutral temperatures at which cement set occurs, and in exploration wells, quite unpredictable service temperatures and pressures.

3.6 Some potential dangers arise because many geothermal resources are found in mountainous or other unpopulated areas where there exist wild animals, poisonous insects, or toxic plants. The incident may be told of a resistivity survey crew in Kenya being surprised by a leopard chasing the end of their electric cable as they moved it to the next observation station. Of course, resistivity measurements also create their own hazards in the high voltages needed for deep electrical penetration into the ground.

3.7 The release of high velocity steam into the atmosphere generates noise of high frequency and intensity which can cause permanent damage to hearing after long exposure to it. As with other health or safety aspects, it is during the early testing phase that there is likely to be least deliberate attention paid to it, and therefore the most chance of danger. The noise of drilling machinery can also be harmful.

3.8 This paper does not cover the safety aspects of plant operation, as these are normally the subject of formal standing instructions and periodic training.

4.0 SAFETY PLANNING FOR NATURAL HAZARDS.

4.1 Having identified the dangers possible in pursuing a particular project, appropriate designs and practices must be planned and adopted to reduce their effects to acceptable levels. The first question to be asked is whether they can be avoided completely. For instance, if an area is known to produce high levels of gas, can the dangerous part of the field be avoided, or is it preferable even to develop another field altogether, as an alternative ? Again, can the drilling and production equipment be dimensioned so as to eliminate a deep drilling cellar, and thus avoid that possibility of poisonous gas collecting ?

4.2 Project planning for safety should include at an early stage the study of all relevant safety requirements specified by the law and by any contractual obligations. For hazards not covered by these documents, experts in each discipline should prepare project codes of practice based on the most relevant experience elsewhere. If local health standards do not cover some of the objectionable constituents, or do not reflect current knowledge, then World Health Organization recommendations may be used as the basis - coupled with a realistic appreciation of the particular circumstances of the project. If safety in drilling is not covered by geothermal legislation, many of the provisions of petroleum requirements may be adopted or adapted.

4.3 Notwithstanding the development of comprehensive guidelines as outlined above, there will be occasions which are not covered by them but which can be dealt with safely if the nature of the possible dangers is understood. This applies particularly to the early phases of a project - reconnaissance and scientific exploration - when the major concern will be that of people working in the thermal areas. The risk of serious injury is then much reduced by:

a) never entering such areas alone;

b) wearing clothes and footwear to cover and protect the body - particularly against burns;

c) using a probe ahead of footsteps when walking off beaten tracks, and observing fresh deposits indicating intermittent natural activity;

d) being prepared with detectors, first aid equipment and perhaps radio communication with a base station.

In active volcanic areas, familiarity with mountaineering practices will prove of value - rope belaying, for instance, to assist rescue in the event of an accident.

4.4 As part of the feasibility study for a project, it is recommended that a hazards and safety report for the area be prepared to identify and locate all significant dangers applying to that development, and to suggest solutions to the problems found. For the conceptual design phase, a hazards map should be prepared to help in the proper location of access and pipe routes, well and plant sites and transmission lines, etc. Danger areas may include valleys exposed to possible lahars or even lava flows. Obviously, designing against the effect of lava is a matter wholly of avoidance - not resistance - although attempts at deflection have sometimes been successful.

4.5 Ash showers, however, covering such wide areas and often to little depth, should indeed be designed for. To a large extent, precautions can be embodied in special operating procedures to be implemented in the event of significant ash fallout. But some of the problems summarized in 2.4, can be considered during detailed design, including:

a) additional loading on non-vertical surfaces - recognizing the highly adhesive property of the material.

b) ample provision for sealing, filtering, settling and possibly chemical treatment in fluid systems like cooling water, lubricating oil and pressurized air.

c) convenient means of cleaning, washing and removing ash material.

Both the thickness and the average particle size of volcanic ash decrease exponentially with distance from the source. In the case of Galunggung, the grains which fell at Kamojang, 30 km away, were smaller than 0.4 mm.

4.6 Landslides can take many forms, and particularly when the surface is concealed by growth, the soil and terrain conditions favouring their occurrence are often difficult to detect. Hence, it is important that an engineering geologist experienced in volcanic materials be employed to recognise the conditions in which they are likely to occur and to ensure that adequate geotechnical investigations are undertaken of those slopes which pose dangers to life and property. These studies will establish whether and how failure may occur, and what measures can be taken by way of drainage, support, reshaping or stabilization to prevent undue damage. While these comments apply generally, they are particularly relevant to geothermal situations because:

a) the conditions occur very frequently in young volcanics, and

b) geothermal projects tend to spread across considerable areas of countryside.

4.7 As areas of hydrothermal eruptions can be recognised - particularly in aerial photos - avoidance of such areas is the first option for safety. However, if work there is desirable, precautions can be taken, namely:

a) assess their age, and therefore the probability of further events;

b) from geotechnical studies (especially shallow drilling and testing) establish the likely circumstances triggering them;

c) if possible, improve those circumstances - maybe by drainage, grouting or cooling;

d) programme the work to avoid the triggering mechanism - for instance, in the choice of casing depths for a deep well.

4.8 The value of (c) and (d) was exemplified at Waiotapu Bore 4, where broken casing allowed steam leakage into an aquifer at about 140m depth, and led to the eruption of the overlying impermeable formations out of a crater which formed 30m from the wellhead, and to smaller eruptions under the drilling equipment. Subsequently, the site was consolidated by injecting a cement slurry into the shallow permeable horizon, and by cementing a more competent liner in the well.

4.9 Before commenting on how to cope with gas venting, it may be useful to reiterate some of the circumstances in which it is encountered, namely:

a) From natural eruptions or leakages, causing the gas to flow into valleys and low lying areas.

b) From wells, during drilling, testing, or emergency blowoff.

c) From plant exhausts.

By far the greatest number of fatalities have occurred from natural events, including 1,700 Cameroonians who suffocated when Lake Nyos released an estimated 240,000 tonnes of carbon dioxide gas one night in 1986. There is a need to educate people who live or work in or near thermal areas to the potential dangers, the recognition of lethal conditions, and the precautions needed before attempting rescues. In a recent incident, the first victim to be overcome survived, but several rescuers died, due to a variety of factors which included unsuitable rescue gear and training.

4.10 The generally preventable accidents involving CO_2 and H_2S gases relate to working areas where high volumes of gases, or long periods of accumulation in confined spaces, occur. Precautions include:

a) Detectors and warning signals.

b) Portable ventilating fans.

c) Appropriate breathing equipment.

d) Regular training in rescue and first aid procedures.

e) Design criteria and concepts for safe venting, dispersion, absorption and treatment.

f) Constant awareness of the possibility of accumulations.

The petroleum industry has developed thoroughly tested equipment and procedures which are immediately applicable to geothermal situations.

4.11 Gas emissions from plants can be rendered safe, either by elevated venting with subsequent atmospheric dispersion, or by chemical processing to remove the sulphur. The results of dispersion can be assessed from wind patterns and other climatological records, and the cost is clearly much less than any of the hydrogen sulphide abatement plants necessary where gas concentrations are high and allowable limits low.

4.12 Long term hazards are caused by corrosion when H_2S and CO_2 dissolve in groundwater and attack steel, concrete and even the natural rock itself. Geothermal wells suffer particularly where oxygen is present - at water level. Measures to combat this include the choice of acid resistant materials and the addition of sacrificial layers to extend the life of critical components like anchor or production casing strings.

4.13 If long term exploitation causes ground surface deformation where structures are located, remedial work must be undertaken. The Wairakei examples of steam line length adjustments illustrate this point. Importance should be attached to conducting regular, precise ground surveys for the purpose of detecting relative vertical and horizontal movements at an early stage, so that means of accommodating them may be designed into the structures, and preparations for modifications may be made to avoid long shutdown periods.

4.14 The illness, amoebic meningitis, is largely avoided by paving around pools used for bathing, and by avoiding any bodily intake of the water.

4.15 Seismic resistance design is generally covered by legal requirements, recognised codes of practice, and the employment of engineers qualified in the field. It is sufficient here to recognise the need. Structural integrity may also be prejudiced by the choice of volcanic concrete aggregates having alkali reactivity.

5.0 SAFETY IN DEVELOPMENT

5.1 Well safety during and after drilling relies on a fully engineered programme expertly implemented, and on follow-up inspection and workovers as necessary. Assuming adequate surface equipment and supplies, plus experienced crews, the avoidance of potentially disastrous blowouts relies on properly designed casing and drilling fluid programmes. The various casing strings ensure that deep-sourced, high energy fluids cannot enter weak, shallow formations; the drilling fluids keep formation pressures under control at all times. Casing depths are chosen after consideration of the expected formation conditions - both rock properties and fluid temperatures and pressures; casing diameters are selected to suit drilling and production requirements; and casing strengths reflect the stresses imposed by the range of temperatures and pressures expected throughout the life of the well.

5.2 Personal safety during drilling is assured as far as practical by the extensive standards, procedures and training courses developed by the petroleum industry - particularly the American institutions. As almost all of their equipment and practices have been adopted for geothermal development, a good record should be expected in this aspect.

5.3 Extensive codes which have been published for the design of pressure vessels and their controls, effectively ensure the adequacy of all pipework, valves and vents between the well casings and the turbine exhaust system - providing independent checks are carried out on both design and construction. Generally, the most likely dangers occur in the well testing phase (when strict rules sometimes tend to be ignored for temporary installations) and in erection work during the lifting and shifting of large loads. However, the risks are little different from those of most other construction activities, and do not merit detailed mention.

5.4 Like the wearing of hard hats, steel-capped boots, gloves and other protective clothing, ear muffs should also be compulsory at times of high noise levels. While 'silencers' (built as boulder pits, atmospheric separators or other large area vents) are demanded when close to habitation, uninhabited areas invite economy on this aspect - which is acceptable when there is sufficient discipline in supplying, carrying and donning the individual muffs.

5.5 Geothermal projects rate just like other engineering workplaces in their need for a positive attitude by management (and employees) towards safety, and for the setting up of a formal structure to ensure that it is implemented. This includes:

a) Qualified staff dedicated to this role.

b) Adequate quarters and equipment - with emphasis on gas dangers.

c) Regular communication, training and safety drills.

These requirements should be regarded as additional to those promulgated in the civil defence precautions adopted in many countries - and highlighted on the back covers of the 1988 NZ Telephone Directories, which summarize what action should be taken in the event of earthquake, flood, storm, eruption or tsunami. (See figure)

5.6 The protection of lives and property in geothermal development can be summed up in the following points:

a) There needs to be an awareness of the range of hazards possible - both directly and indirectly from volcanic activity, but also from seismic and normal construction-type events.

b) A risk assessment should be undertaken to determine how each possible situation should be met - by avoidance, deflection, resistance or rehabilitation.

c) Proper designs and safe practices can then be devised and instituted.

d) Regular reviews are necessary to ensure continued relevance and readiness.

6.0 SOURCES OF SPECIFIC DATA

The following organisations are indicative of those which may be consulted for detailed advice on possible hazards and their avoidance. In most instances, there will be counterpart bodies in other countries undertaking functions similar to those quoted for New Zealand.

6.1 Regional volcanological, geological or scientific bodies;
eg NZ Geological Survey

6.2 National associations concerned with earthquake-resistant engineering design;
eg NZ National Society for Earthquake Engineering

6.3 World and local health organisations;
eg World Health Organisation
NZ Department of Health

6.4 Drilling industry associations;
eg American Petroleum Institute
International Association of Drilling Contractors

6.5 National or international standards associations;
eg International Organisation for Standardisation
American National Standards Institute
Standards Association of NZ

6.6 Government agencies responsible for industrial and construction safety;
eg Marine Division, NZ Ministry of Transport
NZ Labour Department

6.7 Civil defence organisations, including police and rescue services;
eg NZ Ministry of Civil Defence