Radiation associated with Hot Rock geothermal power

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Water in Hot Rock reservoirs is in contact with granites containing radioactive elements (radionuclides). The wider community is generally aware of this fact through publicity by the Australian geothermal industry. It is less clear to the public what radiation hazards may exist for Hot Rock projects, and how significant they may be. The aim of this study was to investigate likely radiation hazards associated with Hot Rock geothermal power, with a particular emphasis on radon emission. The study consisted of a review of literature and quantitative estimates of radon emission and dispersion from a typical Hot Rock reservoir. This information has been used to develop a fact sheet, published by Primary Industries and Resources South Australia (PIRSA, 2009).

Keywords: radiation, radon, radium, uranium, Hot Rock geothermal.

Dissolved radionuclides

The radionuclides of interest are those with long enough half-lives to travel to the surface from the reservoir, including isotopes of uranium, thorium, radium, and radon.

Uranium and thorium in granites are mostly found in monazite, zircon and allanite mineral phases. These phases are highly insoluble under most conditions, therefore the controlling mechanisms for radionuclide release are dissolution at the rock-water interface and alpha-recoil (ejection from the rock due to alpha-decay of the parent radionuclide).

Uranium solubility is a strong function of the oxidising or reducing nature of the geofluid. Uranium contents in granite groundwaters are frequently less than the recommended limit for drinking water (20 μg/L), but may exceed 800 μg/L in oxidising groundwaters (Gascoyne, 1989). Uranium does not emit gamma radiation, therefore it is only hazardous if ingested or inhaled.

The solubility of thorium is low since it tends to form the insoluble hydroxide. Thus, thorium concentrations in groundwaters rarely exceed 1 μg/L (Langmuir and Herman, 1980).

Radium is released from the rock by alpha-recoil, but is readily scavenged from solution by sorption onto mineral surfaces. Cations compete with radium for sorption sites, thus the solubility of radium increases strongly with total dissolved solids (TDS), as indicated by groundwater data shown in Figure 1. Where natural waters exist in Hot Rock reservoirs, they are typically quite high in dissolved solids, eg. TDS = 100 g/L at Soultz (MIT, 2006) and 21 g/L in the Cooper Basin (Wyborn et al, 2004). The TDS of water in an operational field will depend on the extent of dilution of natural water with injected water. At Fenton Hill, substantial dilution was achieved during open-loop operation (Grigsby et al, 1983). On switching to closed loop operation, the TDS reached a steady value of ~3 g/L. Thus, natural water in Hot Rocks may have radium activities at the upper end of the scale shown in Fig. 1, but the activity can be reduced to low levels by dilution of dissolved solids. To gain some perspective on what constitutes "low" levels, we note that groundwater sources for drinking water may contain radium at up to or exceeding 0.5 Bq/L (NHMRC, 2004), a level corresponding to TDS ≈ 5 g/L according to the trend in Fig. 1.

Hot Rock reservoirs are at significantly higher temperatures than the groundwaters for which uranium, radium and thorium data exist. Solubility is typically enhanced by increasing temperature and higher concentrations of these radionuclides than cited above are therefore possible, depending on the other contributing factors. The Hot Rock geothermal literature reports measurements of radon in solution but not other radionuclides of interest. Such measurements in current and future projects would be of scientific value, and would directly address radiation concerns.

Deposition in surface equipment

The Hot Rock geothermal power concept involves circulation of water through an artificial reservoir and surface equipment in a closed loop. Cooling and depressurising of water in surface equipment may lead to solid deposits in the form of scales and sludges. There is potential for these deposits to be radioactive due to inclusion of precipitated radionuclides. This problem is encountered in the oil and gas industry, where highly saline produced waters with significant dissolved radium are handled. These waters tend to be saturated with barium and strontium sulphates, which precipitate as scales and sludges. Dissolved radium readily substitutes for barium and strontium in the solids, creating a radioactive waste material which must be periodically removed. Workers are exposed to gamma radiation, which is able to penetrate pipe and vessel walls. Additionally, inhalation of radioactive dust is an exposure hazard when removing the deposits. Hamlat (2001) provides estimates of radiation doses received by workers in the oil and gas industry which suggest that the exposure is low - generally < 1 mSv per year - compared with the Australian occupational dose limit of 20 mSv per year (ARPANSA, 2002), provided that appropriate protective measures are taken. This level of exposure is less than the average background radiation dose in Australia of 1.5 mSv per year (ARPANSA, 2009).

The levels of dissolved solids, radium, and of strontium and barium sulphates are expected to be lower for Hot Rock waters than generally encountered in the oil and gas industry. Hence, lesser quantities of radioactive deposits are anticipated, with lower concentrations of precipitated radium. The gamma radiation hazard associated with solid deposits may therefore be small compared to that managed in the oil and gas industry. The data of Fisher (1995) in Fig. 1 is representative of waters produced from oil and gas fields, which frequently have TDS in excess of 100 g/L. Diluted water circulating in Hot Rocks is expected to have at least 10 times less TDS than this, and therefore 7 times less radium activity according to the trend in Fig. 1. The same reduction in radioactivity of the barium and strontium sulfate deposits can be expected. Considering that the occupational radiation exposure in the oil and gas is already relatively low, the exposure from Hot Rock geothermal power plants is therefore likely to be very small. However, the ALARA (As Low As Reasonably Achievable) principle of radiation protection will still apply, which calls for monitoring of exposure and protective measures. In particular, workers involved with removing solid deposits from equipment will need to avoid inhaling dusts.

Radon

Radon is an inert radioactive gas which is formed by the alpha-decay of radium. It is normally present at low levels in ambient air. The average radon level in Australian homes is 10.5 Bq/m^3 (ARPANSA, 2009). The decay products of radon can lodge in the lungs if inhaled, exposing them to ionizing radiation and increasing the risk of lung cancer. The action limits for radon in air are 200 Bq/m^3 in dwellings and 1000 Bq/m^3 in workplaces (ARPANSA, 2002).

In a geothermal reservoir, radon enters solution predominantly by alpha-recoil and remains dissolved until its decay. The maximum radon content is achieved when the rates of solution and decay are equal This occurs if the residence time of water in the reservoir exceeds 25 days (^{222}Rn has a half life of 3.8 days). Radon activity in water was a maximum of 500 Bq/L at Fenton Hill (Grigsby et al, 1983) and 200 Bq/L at Rosemanowes (Richards et al, 1992).

Radon emission and dispersion

Radon emissions will occur during open-loop circulation testing of newly created reservoirs, from uncontrolled flows of geothermal water, or from venting of light gases from steam condensers.

If the Hot Rock reservoir is assumed to consist of planar, parallel fractures with even spacing, the radon emanation rate, R (atoms/s) is given by:

$$R = \frac{2FV}{S}$$

where F is the radon flux from fracture surfaces (atoms s^{-1} m^{-2}), V the fractured rock volume (m^3) and S the fracture spacing (m).

The radon flux from plane surfaces of Carnmenellis granite cubes in water was measured at 30 atoms s^{-1} m^{-2} by Andrews et al. (1983). The granite had an average uranium content of 13.5 ppm, and we have assumed that a similar flux value is appropriate for Cooper Basin granites, which typically contain 16 ppm of uranium (Geoscience Australia, 2008).

Kruger (1995) inferred a mean fracture spacing of 50 m from circulation tests at the Rosemanowes site.

Steady-state emission of radon from a field can be estimated by assuming that the emission rate at the surface is equal to the emanation rate. Decay of radon in the reservoir is neglected. Assuming the above cited values for fracture spacing and flux in the Cooper Basin, this method yields an emission rate of 1.2 billion atoms (2520 Bq) per second, per cubic kilometer of fractured rock.

Radon is emitted from steam-venting stacks during circulation testing, therefore downwind radon levels are of interest. A simple Gaussian dispersion model was used to predict the maximum radon activity at ground level downwind of a single emission source with respect to effective emission height (physical vent height plus an allowance for plume rise), and wind speed. Results for a 1 km^3 reservoir are shown in Figure 2. Radon levels are generally negligible for emission heights of 10 m or more, except in calm conditions (wind speeds less than 1.8 km/h). In the latter case, levels are expected to be less than the action limit for dwellings.

During an uncontrolled flow of geothermal water from a well, the effective emission height is close to ground level, eg. 2-5 m. Figure 1 suggests that for a 1 cubic kilometre reservoir, downwind radon levels would be significant but not exceeding the workplace action limit except under calm conditions. However, it should be remembered that Figure 1 is based on a steady-state emission rate. If the water in the reservoir has been still for a period, its radon content will be higher than during circulation. Therefore the initial emission rate will initially be higher than the steady-state value. For example, if still water in the reservoir attains a radon level of 500 Bq/L, then a sudden flow of 50 L/s will cause an initial emission rate of 25,000 Bq/s, a value 10 times the steady value assumed for Figure 1 and therefore increasing downwind radon activities by the same factor.

Calm conditions usually occur at night in central Australia and may last several hours. Estimates suggest that during calm periods radon emission may be a significant hazard for the area within 200 m downwind of an uncontrolled flow. However, the simple Gaussian dispersion model results become spurious as wind speed approaches zero, and more advanced dispersion models are required to more accurately predict radon levels in calm periods.

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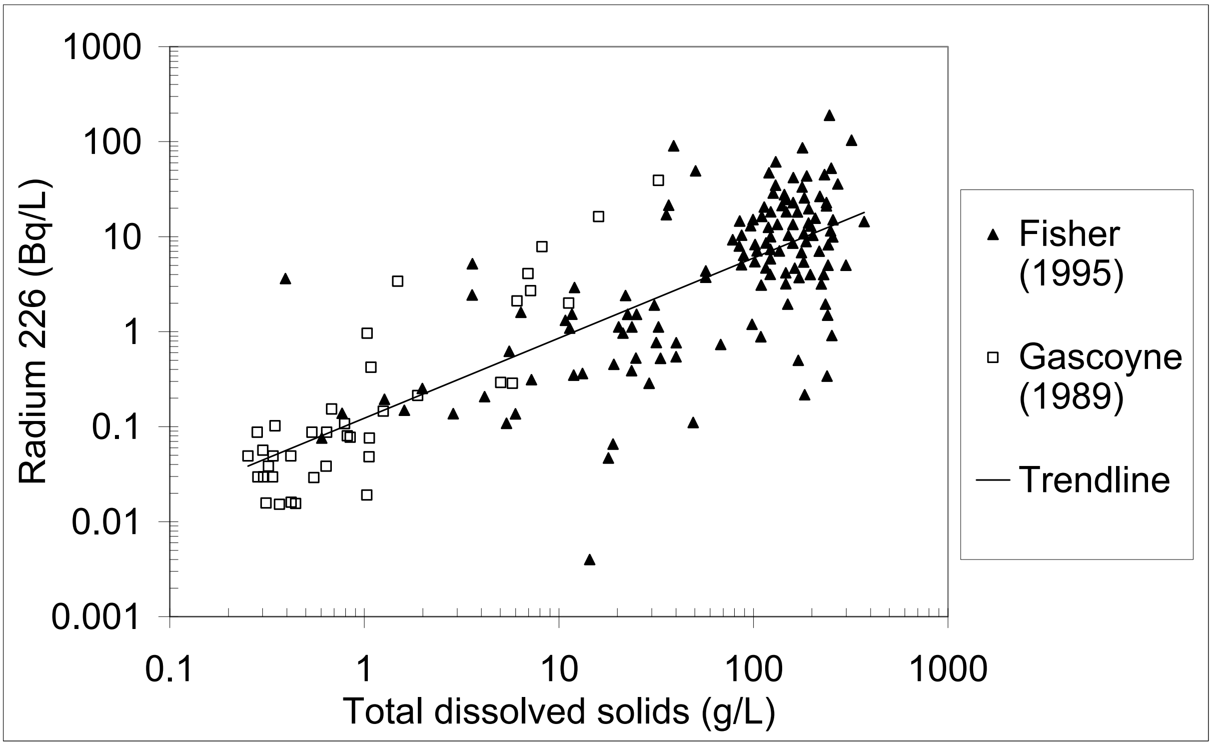

Figure 1: Radium-226 activity versus total dissolved solids in groundwaters. Fisher (1995): Oil, gas and geopressured-geothermal wells in Texas. Gascoyne (1989): Granite groundwaters, Whiteshell Research Area, Canada.

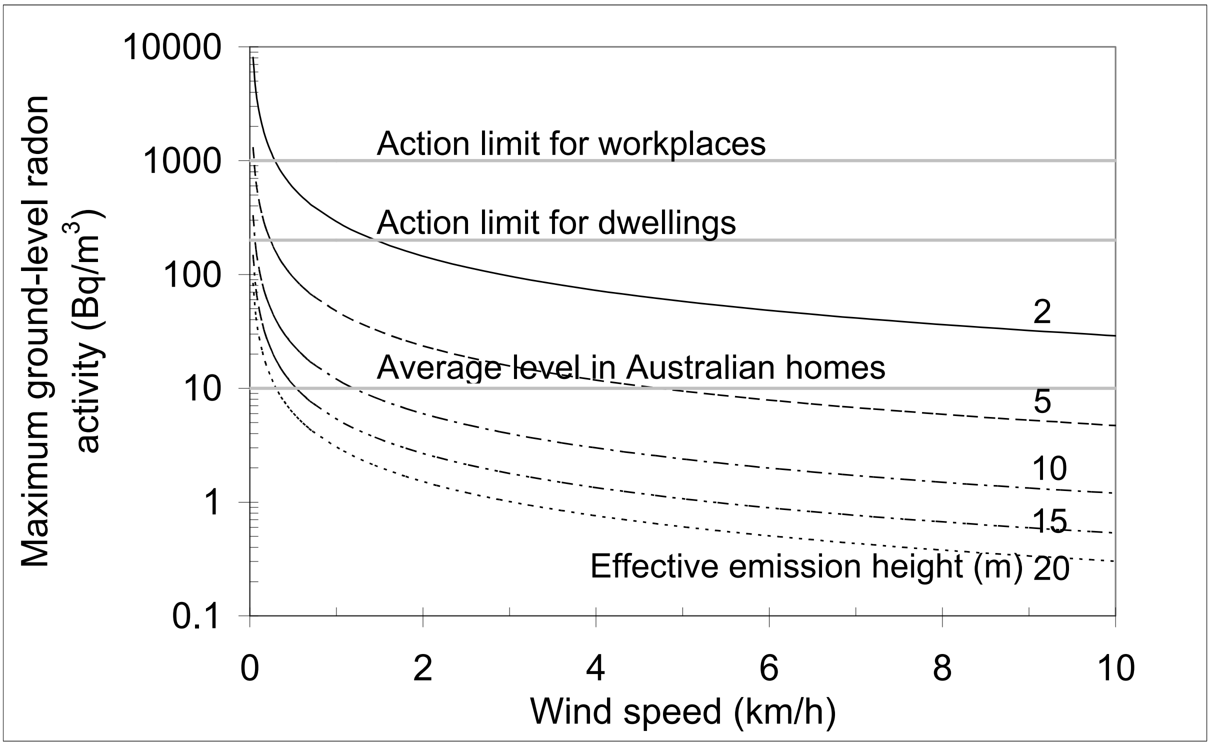

Figure 2: Maximum ground-level radon activity directly downwind of a single emission source, with respect to wind speed and effective emission height. Assumes an emission rate of 2520 Bq/s, based on steady-state emission from 1 km^3 of fractured rock, 50 m mean fracture spacing, 30 atoms s^{-1} m^{-2} radon flux from fractures, and neglecting decay of radon. To determine radon levels at another emission rate, E (Bq/s), multiply the radon level in the plot by E/2520.