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PHYSICAL LIMITS ON STEAM GENERATION BY RADIOACTIVE DECAY HEAT

UCRL-ID--108153

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A dramatic statement was attributed recently to Charles Archambeau: "You flood that thing and you could blow the top off the mountain." This set me to wondering -- could we in fact have such a catastrophe if water were suddenly to contact rock heated by radioactive decay?

A good place to start is to ask: just how much heat are we expecting? The answer depends upon many variables, including the waste form (spent fuel or glass), how long the waste has been out of the reactor core, how much power was generated while it was in the core, how much is contained in each waste package, the spacing between packages, and so on. The effects of such variations have been studied extensively by scientists and engineers at Lawrence Livermore National Laboratory and elsewhere [Ballou et al. (1990), Johnson & Montan (1990), and Nitao (1988)].

A quick perusal of these sources shows that the most important parameter controlling the amount of heat accumulated in the rock is the thermal output per unit area at the time the waste packages are first emplaced, usually expressed as the number of kilowatts of heat released per acre of repository area. Values considered vary from about 34 Kw/acre to about 74 Kw/acre, with the actual operating range to be determined by detailed performance analyses of specific designs as additional site-specific data become available.

Since 1 Kw/acre may not mean much to most people, I converted these values to BTU per square foot per day, multiplying Kw/acre by 1.880 (see the Appendix for the conversion factor). On this basis, the initial rate of heating ranges from about 64 BTU per square foot per day to 139 BTU per square foot per day.

For comparison, I estimated the amount of heat released by burning a single paraffin wax candle. First, I measured the amount of wax burned in one hour by burning the candle on the pan of a triple-beam balance and recording the mass lost (4.0 grams, with a precision of about 0.1 gram).

Each gram of wax burned releases about 42.3 BTU, so the observed burning rate of 4 grams per hour releases 4064 BTU per day, or 29 to 63 times the amount of heat released by radioactive decay per square foot of repository area. Stating this another way: *the heat released by burning a single candle would have to be spread out over a square ranging from 5 to 8 feet on a side to produce the same*

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power density as nuclear waste immediately following emplacement. This does not sound like the making of a catastrophe.

Another perspective may be gained by considering the power density of sunlight at the earth's surface. Kreider and Kreith (1975) give a table of calculated values showing that, in Denver, Colorado, the average amount of solar energy striking a horizontal surface ranges from 840 BTU per square foot per day in December to 2440 BTU per square foot per day in June.

A reasonable question now is: if the amount of heat released is so small, why does the rock get hot around a waste package? The answer is that rock of any kind is a very poor conductor of heat -- the tuffs at Yucca Mountain are only about twice as conductive as firebrick -- and even a small but continuous source of heat placed within such a medium will cause an increase in temperature until the medium reaches a "steady-state" condition. In this condition, heat "leaks away" from the source as fast as it is supplied, and the temperature is highest at the source and decreases rapidly as the distance from the source increases.

For radioactive decay, the thermal output is not constant, but decreases as radioisotopes disintegrate into stable non-radioactive nuclides at a rate averaging 3% to 4% per year for the first 100 years out of core [Johnson and Montan (1990)]. This continuing decrease in the rate of heat generation causes the temperature to pass through a maximum a relatively short time after placement of the waste. The peak temperature is highest, and the peak is reached in the shortest time after placement, near the package. At greater distances, the maximum temperature is lower and occurs later.

Examination of detailed calculations by Johnson and Montan (1990) reveals that peak temperatures above the boiling point of water (about 207°F. at Yucca Mountain) at the waste package are reached in less than 50 years after emplacement. The highest calculated temperature reported is 426°F. (219°C) , in rock that is dried out from the heat.

For any particular temperature, there is a corresponding pressure above which water cannot exist as vapor; this is known as the *saturation pressure* for that temperature. From Perry (1950), 420 °F corresponds to an absolute saturation pressure of about 309 pounds per square inch (psia), and 430 °F to about 344 psia. *At temperatures of 430 °F or below, it is physically impossible to generate steam with a higher pressure than 344 psia.*

To "blow the top off the mountain," pressures must be greater than the weight of the overlying rock per unit area; this is known as the *lithostat*, and averages about 1 pound per square inch per foot of depth from the surface. Since the potential repository is to have a depth of burial of about 1000 feet, the lithostat would be about 1000 pounds per square inch, or almost *three times the maximum steam pressure that could possibly be generated in a closed system.*

There are some other difficulties in generating steam even at the saturation pressure corresponding to the highest rock temperature. During the entire heating and cooling cycle, calculations by Nitao (1988) indicate that the pressure of air and water vapor within the fractures and pores in the rock increases by less than 15%; the fluid pressure is thus very low. We must somehow supply liquid water by flow through these pores and cracks, then keep it from escaping through these same openings while it heats up and forms steam at much higher pressure. We could certainly do this by putting hot rock and water into a pressure cooker and sealing it, but it is hard to see how this could happen without human intervention.

However, it is interesting to compare the heat required to vaporize water with the heat stored in the rock at the peak temperatures anticipated. Rock at the potential repository horizon has a total void space, or porosity, of about 0.11 cubic feet per cubic foot of rock. To be specific, assume that this volume of water at 86°F, [86°F is the average temperature observed at 500m in Yucca Mountain boreholes G-1 and UE25a1, as reported by Dudley et al. (1989)] is added to a cubic foot of dry rock at 426°F., and that no heat or mass is allowed to escape. If the system is confined, the resulting "mixture" of hot rock and hot liquid water will reach a final temperature of 366°F and a pressure of 165 psia.

If the pressure is then reduced, steam will form; the lower the pressure, the greater the fraction of water that can be vaporized. At 163 psia, just under 0.5% of the water would be vaporized, and the temperature would be only 365 °F. At 67 psia, 41% would be vaporized and the temperature would fall to about 300°F. Not quite all the water could be vaporized by reducing the pressure to 13 psia, which is normal atmospheric pressure at the elevation of Yucca Mountain; this corresponds to a boiling point of 207°F.

The point is made: at worst, small, localized amounts of low pressure steam could be generated, but a catastrophic steam explosion lifting the top of Yucca Mountain is not possible.

Heat of 1 Candle Compared to 1 Square Foot of Other Sources

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Appendix

Repository Power Density

Johnson and Montan (1990, p. 6) show a repository power density range from 33.7 to 74.1 Kw/acre. Using values from Perry (1950, pp. 40-41), the following conversion is obtained:

$$1 \text{ Kw/acre} \times 24 \text{ hr/day} \times 1 \text{ acre}/43560 \text{ ft}^2 \times 3.413 \times 10^3 \text{ BTU/Kw-hr}$$

$$= 1.880 \text{ BTU/ft}^2/\text{day}$$

Using this conversion factor to multiply the minimum and maximum power density values from Johnson and Montan gives a range from 63.4 to 139 BTU/ft²/day.

Heating value for wax

In a chart on page 1571, Perry (1950) gives fuel oil heating values in BTU per pound, which is almost constant at about 19,200 BTU/pound, or 42.3 BTU/gram. Since wax and fuel oils are composed mostly of hydrocarbons, their average heating values should be reasonably close, and this value was used to estimate the heat released by a burning candle.

Rock and Water Physical Properties

Nitao's values in metric units were converted to English units using conversion factors from Perry (1950). The initial temperature of water contacting the waste packages and surrounding rock is set equal to the present temperature at the water table under Yucca Mountain, which is about 30°C. The average value of the latent heat for water was calculated from the steam tables in Perry (1950).

ρ_r = bulk density of rock, lb/ft ³	-	161	Nitao, p. 14
C_r = specific heat capacity of rock, BTU/lb/°F		0.201	Nitao, p 14
t_r = initial temperature of rock, °F		variable	
ϕ = porosity of rock, fraction		0.112	Nitao, p. 13
ρ_w = density of water, lb/ft ³		62.4	Perry, p.41
C_w = specific heat capacity of water, BTU/lb/°F		1.0	
t_w = initial temperature of water, °F		86	
t_s = final temperature of rock/water/steam mixture, °F		variable	
y = mass fraction of water turned to steam		variable	
Δh_v = latent heat of vaporization of water, BTU/lb		900	(average, 200 °F - 400 °F)

Heat Balance Calculations

Assume that the mass of water contacting the rock is equal to the pore volume contained in one cubic foot. For the purposes of this discussion, specific heats and densities of rock and water, and the latent heat of vaporization of water, are treated as constants. Then

Change in heat content of rock: $\Delta h_r = \rho_r C_r (t_s - t_r)$

Change in heat content of water: $\Delta h_w = \phi \rho_w C_w (t_s - t_w) + y \phi \rho_w \Delta h_v$

The sum of these changes must be zero since no heat is allowed to escape; let t^*_s represent the value of t_s when $y = 0$ -- i.e., when no steam is formed and latent heat does not have to be considered. Some simple algebraic manipulation yields:

$$t^*_s = \frac{\rho_r C_r t_r + \phi \rho_w C_w t_w}{\rho_r C_r + \phi \rho_w C_w}$$

Note that $t_s \leq t^*_s$ in order for any steam to exist -- i.e., for y to be non-zero.

After solving the equation for y and substituting the value of t^*_s , we obtain:

$$y = \frac{(\rho_r C_r + \phi \rho_w C_w)(t^*_s - t_s)}{\phi \rho_w \Delta h_v}$$

Substitution of different values for t_s and using the steam tables gives the following table:

Fraction Vaporized	Temperature, °F	Pressure, psia
0.000	366	165
0.004	365	163
0.098	350	135
0.255	325	96
0.412	300	67
0.568	275	46
0.725	250	30
0.881	225	19
0.994	207	13

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