Proc. 7th NZ Geothermal Workshop 1985

# GEOTHERMAL SYSTEMS CREATED BY UNDERGROUND NUCLEAR TESTING

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## ABSTRACT

The detonation of nuclear bombs in deep drillholes is associated with the sudden release of heat energy which vaporizes and fuses rocks in the immediate vicinity of the explosion, creating a "cavity". Surrounding rocks around the cavity are intensely shattered, and collapse into the cavity creating a vertical "chimney" structure. Significant fracturing also extends upwards beyond the chimney. In saturated, permeable rocks, condensation of hot gases takes place and the temperature of the fluids seeping into the backfilled cavity is raised. After equilibration, the volume of shattered rocks filled by heated pore waters constitutes a geothermal reservoir.

Simple two-dimensional models for hypothetical explosion chambers beneath Mururoa Atoll are presented which show the role of thermal convection if the reservoir cools by convective heat transfer. These models indicate that high permeabilities of the order of 10. to 50 Da can be created by such explosions. Computed mass flow rates point to flow velocities of the order of 25 to 150m/yr within the inner and outer fracture zones surrounding the explosion chamber.

## Introduction

Underground testing of nuclear bombs has been conducted more frequently since atmospheric tests have been banned. If underground testing is conducted in saturated, permeable rocks, an artificial geothermal system is created as a result of the heat generated by the explosion. Thermal convection of heated porewaters, contaminated by radio nuclides, will produce secular fluid movement.

Underground testing at Mururoa, an uninhabited atoll about 5000 km NE of New Zealand, has caused some concern in New Zealand and other Pacific countries about the long term effects of these tests. The effects can only be assessed from realistic estimates of movements of radioactive wastes beneath the atoll. A scientific mission with scientists from Australia, New Zealand, and Papua New Guinea visited Mururoa in 1983 and presented its findings in the form of' an official report (NZ MFA 1984); the mission found no significant evidence for adverse long term effects. The reports has been criticised (Reid 1985) because no independent assessment of the likely movement of radioactive waste was attempted; the report, however, contains data which allow an assessment of the problem.

The problem of convective heat transfer in under; ground nuclear explosion chambers has apparently not been studied. Older studies have dealt with chambers standing in undersaturated or dry rocks where convection is not maintained because of the lack of recharge fluids (Heckman 1964). A literature search showed that data for chambers in saturated, permeable rocks are available only for Mururoa Atoll and Amchitka Island (Alaska); both are Pacific volcanic islands.

In this paper the results of model studies of fluid flow within and outside a nuclear explosion chamber are .presented. The problem was studied by using a computer program (Pruess 1983; O'Sullivan et al. 1983) which is widely used to study fluid movements and energy transfer in geothermal systems. Data from the Cannikin underground nuclear test at Amchitka Island (Claassen 1978) were also used to obtain additional restraints for the model.

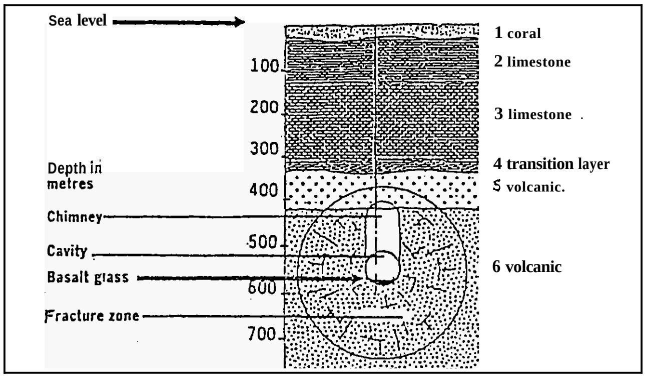


Fig. 1: Geological setting of an underground nuclear explosion chamber at Mururoa Atoll.

## Characteristics of an artificial geothermal system created by an underground nuclear explosion

At Mururoa a 500 to 1000m deep hole is drilled into the volcanic pedestal of the atoll (see Fig. 1); after the nuclear bomb is inserted, the hole is permanently sealed. The nuclear explosion produces temperatures greater than $10^5$°C and gas pressures of more than 1 Mbar which cause rocks in the immediate vicinity to vaporize and further away to melt. The explosion therefore creates a "cavity" whose size depends on the yield (measured in kilotonnes (kt) of equivalent TNT), saturation of the porous rocks, and upon burial depth. On cooling, the molten rocks solidify at the bottom of the cavity, trapping most of the radionuclides. The explosion also fractures rocks around the cavity, the roof of which collapses into the cavity thus creating a vertical chimney structure above the cavity (see Fig. 1). After the explosion, pore water from outside the cavity condenses the hot gases (gas bubble), seeps into the backfilled cavity, is heated but also cools the fragmented rocks until equilibrium temperatures are reached. The heated fluids move then by convection into other permeable strata. Since for a normalized yield the cavity radius and hence the initial-geothermal reservoir decreases with depth of the explosion, the temperature rise after initial equilibration increases with depth. A different situation occurs in chambers standing in hot, dry rocks where equilibration does not occur and where heat transfer is only by conduction.

For modelling the fluid movement associated with a nuclear underground explosion in saturated permeable rocks, the following information is required:

1. the original permeability structure, thermal properties and initial temperature field of the section shown in Fig. 1;
2. dimensions of the geothermal system, i.e. dimension of cavity, chimney, and fracture zones;
3. heat liberated during the explosion and stored in the reservoir;
4. permeability structure of the section after the explosion, and temperature changes inside the reservoir.

In addition, the following points have to be considered:

5. effect of additional heat released by decay of radionuclides within the cavity, and
6. effect of nearby explosion chambers.

Information covering points 1 to 3 and point 5 is not directly available but can be extracted from data cited in the Mission Report (NZ MFA 1984), in Glasstone and Dolan (1977), and Claassen (1978). Information about points 4 and 6 was obtained from computer models by retaining the permeability structure around an explosion chamber as parameter.

## 1. Original permeability structure and initial temperature field of Mururoa test sites

Over 70 underground nuclear tests have been carried out at Mururoa since 1975; the geological cross-section of the atoll is well known, and a simplified section of a reef test site is shown in Fig. 1. Temperature profiles from some untested holes are also known (NZ MFA 1984); a temperature profile from one hole (ZOE, southern part of the reef) is shown in Fig. 2 together with a temperature profile of the outer reef (sea temperature profile). It can be seen from Fig. 2 that the bottom layer (dolomite) of the limestone cap is highly permeable as indicated by the temperature inversion at about 350m depth. Similar temperature profiles were observed in other other holes and it can be inferred that some steady state, lateral movement of seawater occurs which infiltrates the island from the seaward side and which upon heating rises slowly through the limestone cap to the surface inside the lagoon.

This phenomenon can be used to obtain an approximate permeability structure of the island by computing the temperatures of a few models which reproduce the observed temperature profile of Fig. 2, retaining the permeability of the various layers as a variable. This has already been attempted by French authorities, and a steady-state permeability structure of the island is listed in the Mission report (NZ MFA 1984, Fig. 20).

We re-assessed the original gross permeability structure by using the model shown in Fig. 3. As model we used a two-dimensional structure (width of blocks = 100m) since the island is elongated in E-W direction; symmetry with respect to the median axis was assumed. The terrestrial heat flow was taken as 80 mW/m$^2$ beneath the axial line (0 km in Fig. 3) which decreases linearly towards the reef; under the reef (2 km in Fig. 3) it is about 45 mW/m$^2$. These values agree with heat flows inferred from undisturbed temperature gradients in deep drillholes. A horizontal structure was also assumed (see Fig. 3); the limestones and dolomites (layers 2 and 3) decrease slightly in thickness towards the centre of the lagoon; this is compensated by an increase in thickness of the subaerial volcanics (layer 5).

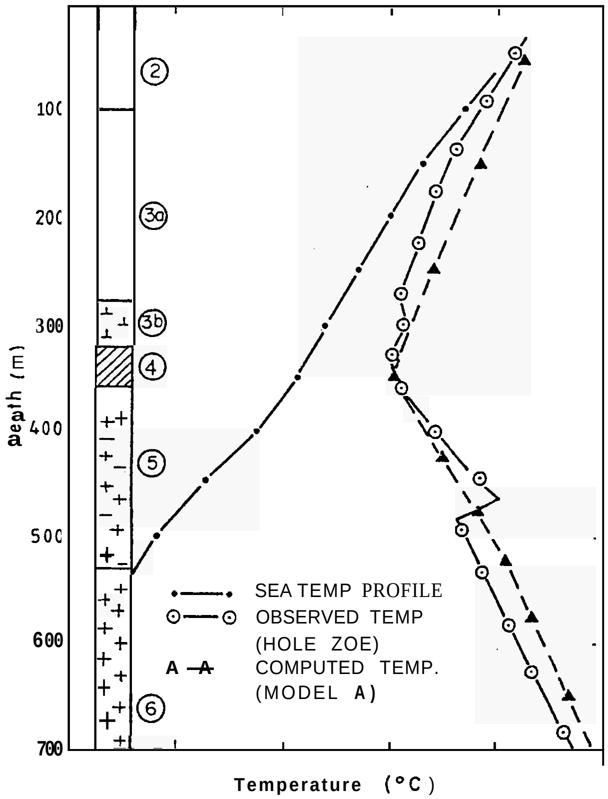
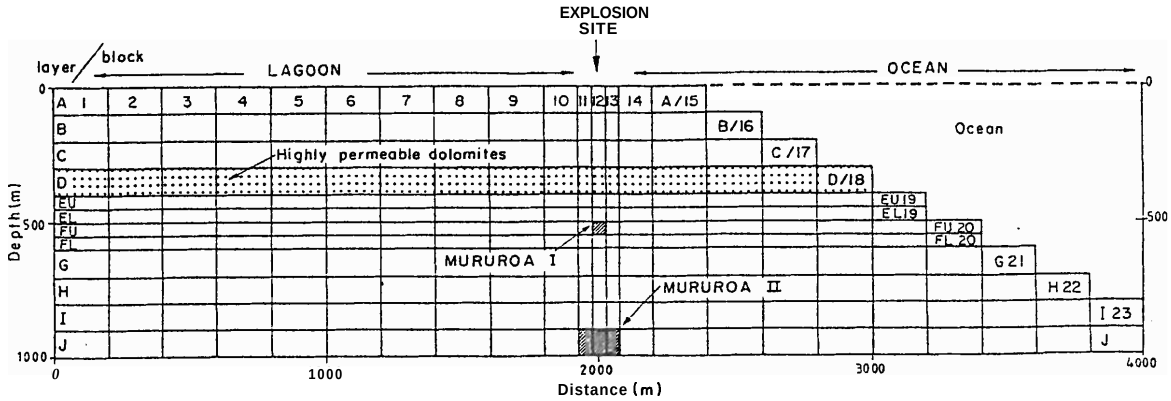


Fig. 2: Observed and computed temperatures for hole **ZOE** (Mururoa); a lithostratigraphic column is shown on the left hand side (the encircled numbers indicate layers as listed in Table 1).

These changes, however, do not affect the temperature profile beneath the reef, and the structure shown in Fig. 3 can be reconciled with the actual structure by assuming that the transmissivity of these equivalent layers approximates the "in situ" transmissivity. The thin weathering layer (layer 4) was neglected. The MULKOM program (Pruess 1983) was used to compute theoretical temperatures and mass flow rates for the model in Fig. 3.

An undisturbed temperature profile of the model beneath the reef is shown in Fig. 2; the physical parameters used (model A) are listed in Table 1. The model was run to reproduce steady state conditions after 5 x 10$^6$ yr. The permeability data listed in Table 1 might be uncertain by an order of magnitude; the data, however, are similar to those obtained by French authorities. Using appropriate porosities, the computed mass flow rates can be converted to flow speeds. It was found that flows in the volcanics do not exceed 0.3 m/yr and that only in the highly permeable dolomites are values of the order of 30 m/yr indicated. These data are similar to those quoted in the Mission Report (p.124) based on French assessments.

Some of the results obtained by model A can also be obtained by a simple heat balance calculation. If all the fluid movement is assumed to be confined to the high permeability conduit at approximately 350m depth, the temperature rise of approximately 14°C along it must balance the heat input from depth of 60 mW/m$^2$ (on average). A simple calculation gives a required mass flow of 0.3 kg/s. This mass flow corresponds to average volume fluxes of 1-5m/yr for a thickness of the high Permeability dolomite layer between 20-100m and fluid speeds of 10-50m/yr for a porosity of 0.1. These figures agree with results from the computer model.



Pig. 3: Model of Mururoa Atoll used to compute steady state flows and dynamic flows caused by artificial geothermal systems in underground explosion chambers (Mururoa I, II). The model shows only half of the section; widths of blocks: 100m.

Similar estimates using Darcy's law show that such a high flow rate in a relatively thin layer can only occur, driven by the density difference between cold sea water and warm saline water, if the permeability in the dolomite layer is 10–100 Da. In model A, a value of 50 Da was used, and in the Mission Report a figure of 30 Da is quoted for the French model.

Table 1: Physical parameters of steady–state flow beneath Mururoa (Model A)

| Layer | Geology | Assumed thick–ness (m) | Particle density ($10^3$ kg/m$^3$) | Inferred porosity | Thermal conduc–tivity (W/mK) | Average permea–bility (darcy) |
|---|---|---|---|---|---|---|
| 2 | limestone | *100* | 2.5 | 0.1 | *1.8* | *0.1* |
| 3a | limestone | 200 | 2.5 | 0.05 | *1.8* | *0.1* |
| 3b | dolomite | 100 | 2.5 | 0.03 | 1.8 | 50 |
| 4 | clayrich volcanics | (0) | n.a. | n.a. | n.a. | n.a. |
| 5 | subaerial volcanics | 100 | 2.5 | 0.2 | *2.0* | **0.1** |
| 6 | dense basalt | infinite | 2.85 | 0.1 | 2.5 | *0.01* |

## 2. Dimensions of geothermal systems created by underground nuclear explosions

Data in Glasstone and Dolan (1977), Claassen (1978), and Butkovitch and Lewis (1978) indicate that the cavity radius $c_r$ (in m) for saturated rocks is approximately given by:

$$c_r = 100\ W^{0.333}/(\bar{\rho} z)^{0.307}$$

where W is the yield in kt, $\bar{\rho}$ the average overburden density (in $10^3$ kg/m$^3$), and z the depth (in m) of the explosion. Results of the Cannikin underground explosion on Amchitka Island (Claassen 1978) indicate that the effective radius $c_{r\ eff}$ of the gas bubble when condensation took place was about 1.4 $c_r$. Initially it was assumed that the dimension of the original geothermal reservoir after condensation is given by $c_{r\ eff}$. Implications with respect to the likely energy input will be discussed in the next paragraph.

The radius of the inner fracture zone around the explosion chamber, where all rocks have been shattered and fragmented, is about 4.2 $c_r$ according to Butkovitch and Lewis (1978). This value is usually taken to define the top of the collapsed chimney structure and which has been checked by deviated holes drilled into the cavity after explosions. Rocks are also fractured beyond the inner fracture zone. At Amchitka Island, where a 5 Mt bomb was detonated at 1.79 km depth ($c_r \approx 133$m), fractures extended from the top of the chimney up to the surface as indicated by the rapid drop of water levels in a deviated well which showed that groundwater was able to enter the explosion chamber about 100 days after the explosion. We will use the term "extended chimney" to describe this structure and assume in the following that an extended chimney structure also occurs at Mururoa which, according to the Amchitka data, can extend to distance of at least 13 $c_r$.

The implications for a geothermal system created by an underground explosion on Mururoa are therefore:

(a) the initial size of the reservoir after condensation of the gas–bubble is given approximately by an effective radius of about 1.4 $c_r$;

(b) mixing of heated fluids can also occur initially within the chimney structure, whose height would be about 4.2 $c_r$;

(c) vertical movement of fluids is possible within an extended chimney structure whose height is of the order of 13 $c_r$.

## 3. Heat input into an underground nuclear explosion chamber

Only a few published data are available which allow an assessment of the magnitude of heat created during an underground explosion. A minimum value $E_{min} \approx 0.6 \times 10^{12}$ J/kt is cited in Glasstone and Dolan (1977, p.510) for the energy liberated as heat in the fire–ball of an atmospheric explosion; a value of E = $1.45 \times 10^{12}$ J/kt is cited (Glasstone and Dolan, p.277) for the total radiation liberated during such an explosion. Information in the Mission Report (NZ MFA 1384, p.84) indicates that ultimately up to $2.3 \times 10^{12}$ J/kt could be produced.

An order of magnitude estimate can also be obtained from temperatures observed in deviated holes drilled into explosion chambers. In the following we consider only explosion chambers which stand in porous, permeable, saturated rocks where equilibration of fluid temperatures can occur inside the chamber. These temperatures are not necessarily representative of the average temperatures of the reservoir but constitute the most suitable parameter allowing an assessment of the heat transfer of various models. Using realistic values for average porosity, thermal capacity of reservoir rocks and pore fluids, an order of magnitude estimate for the energy input (normalized for yield) can be obtained from observed temperatures.

If one assumes that the radius of the gas bubble at the time of condensation extended to 1.4 $c_r$ and that mixing of heated pore fluids took place within this volume, one obtains a value of 0.8 x $10^{12}$ J/kt for Cannikin event neglecting heat loss during the first 250 days, and about 0.9 x $10^{12}$ J/kt for a Mururoa chamber at about 500–600m depth. These figures (see Table 2.1) lie within the range of published values. Differences can be explained by the unknown state of mixing and differences in volume of the initial thermal reservoir.

For the modelling, a mean input of 1.5 x $10^{12}$ J/kt was assumed and the models were restricted to a hypothetical explosion chamber at 550m depth created by a 10 kt explosion and one at 1000m depth (100 kt explosion). Originally we considered a fractured reservoir whose volume is given by that of the cavity and the chimney (reservoir I in Table 2.2). This was then increased by 25% (reservoir II) to obtain agreement between observed and theoretical temperatures for the 550m deep chamber, i.e. to match the observed temperature rise in the shallow chamber and which is shown in Fig. *4;* the time delay between explosion and condensation of the gas bubble was neglected. As can be seen from data listed in Table 2.2, the volume of reservoir II for an explosion at 550m depth is about 2.5 x $10^5$ $m^3$ which can be modelled by a single block of 50m x 50m x 100m (block EL12 in Fig. 3); the volume of reservoir II at 1000m depth is about 1.5 x $10^6$ $m^3$ which was modelled by three blocks (J 11, 12, 13) in Fig. 3. The height of the extended chimney is about 300 and 600m respectively; the possibility that fractures in the outer fracture zone can extend into the permeable dolomites (layer D in Fig. 3) was also considered.

Table 2.1: Energy input into underground explosion chambers at Amchitka and Mururoa

| Site | Amchitka | Mururoa |
|---|---|---|
| Depth (m) | 1790 | 550 |
| Yield (kt) | 5000 | 10 |
| Av. porosity | 0.1 | 0.3 |
| Obs. maximum ΔT (°C) | 61 (256d)* | 20 (50d) |
| Obs. decline ΔT (°C) | n.a. | -9 (250d) |
| Inferred volume ($m^3$) | 2.67 x $10^7$ | 1.59 x $10^5$ |
| Normalized energy input (J/kt) | >0.8 x $10^{12}$ | 0.9 x $10^{12}$ |

* The observed max. ΔT value was taken from a temperature profile taken 256 days after the event cited in Merritt (1973).

Because of the proportionality between energy input, dimension of the reservoir, and yield, the likely temperature rise in other underground chambers can be predicted (see Mururoa II in Table 2.2) and which is almost independent of yield.

Table 2.2: Observed and inferred temperatures in two explosion chambers at Mururoa (reef) for E = 1.5 x $10^{12}$ J/kt

| Site | Mururoa I | Mururoa II |
|---|---|---|
| Depth (m) | 550 | 1000 |
| Yield (kt) | 10 | 100 |
| Amb. temp. (°C) | 24 | 40 |
| Av. porosity | 0.3 | 0.1 |
| Volume, reservoir I ($m^3$) | 1.9 x $10^5$ | 1.1 x $10^6$ |
| Volume, reservoir II ($m^3$) | 2.5 x $10^5$ | 1.45 x $10^6$ |
| ΔT reservoir I (°C) | 28 | 56.5 |
| ΔT reservoir II (°C) | 21 | 42.5 |
| ΔT observed (°C) | 20 | No data |

## 4. Modelling of heat transfer within an underground thermal reservoir

Thermal convection is quite significant, as can be seen from the temperature profiles shown in Fig. 4 observed over 486 days in an explosion chamber at Mururoa and which is confined to subaerial volcanics, i.e. layer 5 (taken from Figs. 8 and 22 of NZ MFA report).

The steady-state model as summarized in Table 1 was used as basic model; the permeability structure around the explosion chamber was changed for the Mururoa I site until the theoretical temperature decline within the reservoir attained values which were similar to those observed (i.e. maximum temperatures shown in Fig. *4).* The modelling was then extended to assess the transfer in the deeper chamber (Mururoa II site).

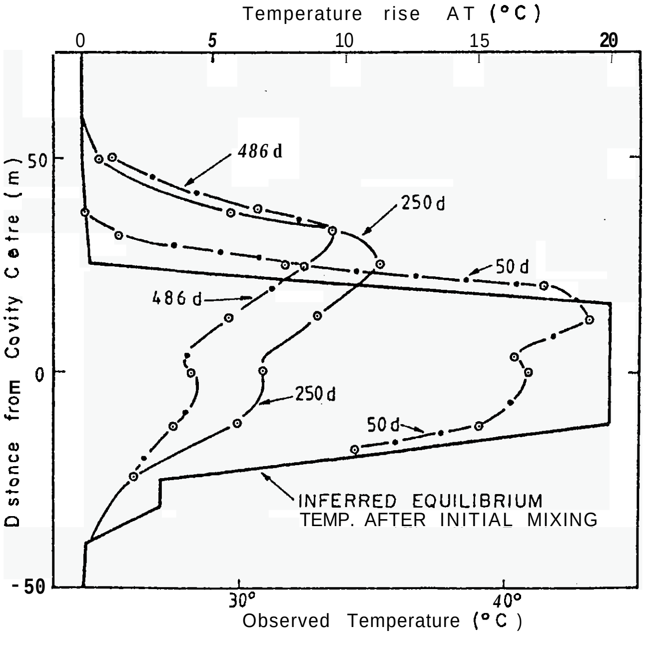


Fig. *4:* Temperatures observed in an inclined drillhole intersecting a shallow explosion chamber beneath Mururoa; explosion occurred in layer 5, inferred depth about 525m; $c_r \approx 25$m (10 kt).

## Xururoa I site

For the first model of Mururoa I site (model B, Table 3), it was assumed that increased permeability (1 darcy) is restricted to the inner fracture zone. Heat transfer is limited and causes a temperature drop of only about 0.5°C after 500 days. In model C, the permeability of the inner fracture zone was increased to 10 darcy and that of the surrounding fracture zone to 1 darcy; a somewhat higher convection was obtained which lowers the temperature by about 2°C after 500 days (see Fig. 5), but this decrease is only a fraction of that observed, i.e. 10°C. It should be noted that model C is similar to the conceptual model as described in the report (NZ MFA 1984), i.e. a fractured reservoir which has no connection with the permeable dolomite layer (layer D) and where horizontal movements outside the fracture zone are similar to those of the steady state model. The results of our models B and C clearly indicate that this conceptual model has to be modified and that the effect of the extended chimney must be considered to allow cooler fluids to move into the explosion chamber. This was achieved by extending the outer fracture zone into the permeable dolomite layer.

For model D the permeability of the initial fracture zone was increased to 50 darcy and that of the outer fracture zone, which was extended to blocks 10 and 14, to 10 darcy. This model produces some significant cooling, and the temperature inside the initial reservoir dropped by about 7°C after 500 days. Although the observed temperature drop is somewhat greater, we did not refine model D since in terms of actual energy transfer it explains about 2/3 of the energy loss as indicated by the observed temperature drop. An increase in width of the highly permeable chimney structure would produce higher cooling rates although fluid flow might no longer approximate Darcy flow. Another important result of model D is that the speed of fluid movements can be assessed.

Vertical mass flow rates of about 5 kg/s occur within the reservoir and the chimney structure, and horizontal (outflow) rates of the order of 1 kg/s are indicated for each of the layers EL, EV, and D (after 500 days). Using the appropriate cross-sectional areas for these blocks and average porosities, speeds of 50 to 150 m/s are indicated for the upward, vertical flow within the chimney and extended chimney, whereas speeds of 25 to 75 m/s are indicated for the horizontal layers intersected by the chimney structure with a maximum in layer EL, i.e. subaerial volcanics directly above the explosion chamber.

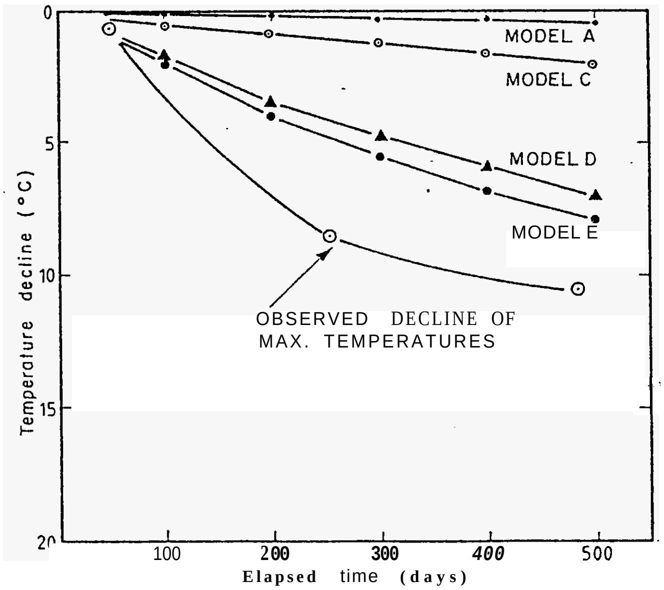


Fig. 5: Observed and computed temperatures inside Mururoa I explosion chamber.

The effect of nearby older fracture zones caused by hypothetical explosions surrounding the outer fracture zone of model D was studied by model E. In this model the outer fracture zone was extended into blocks 8, 9 and 15, 16 (10 darcy) within layers EU to G. Such extension of the outer fracture zone produces a widening of the convection pattern but does not significantly affect the mass flow rates.

The computed average vertical mass flow rates of model D can also be used to assess the role of additional heat released by the decay of radio nuclides deposited in the explosion chamber and the degree of dilution of liquid radioactive waste. Model D indicates that the average rate of energy transfer by convection for a reservoir created by a 10 kt explosion at 550m depth is about 0.15 MW during the first 500 days; the heat input by radioactive decay, nainly $^{240}$Pu, $^{239}$Pu, $^{137}$Cs, $^{90}$Sr, is of the order of 0.025 MW for a 10 kt explosion (P.M. Lewis, pers. comm.). The effect of heat produced by radioactive decay can therefore be neglected for the Mururoa I models, although this input will be the ultimate power source for long term movements.

The input of about 5 kg/s of non-radioactive sea water into the reservoir of model D implies a dilution rate of about 0.5/200 days for a reservoir of $2.5 \times 10^5$ $m^3$ with an average porosity of 0.3, i.e. after 500 days the concentration of radioactive waste should be only about 1/4 that of the original concentration if liberation of additional radio nuclides by leaching of glassy material can be neglected. At Mururoa the $^{137}$Cs concentration in a shallow explosion chamber remained almost constant during a period of 500 days (refer to Fig. 23 of NZ MFA report), thus indicating that radioactive constituents within the explosion melts can be liberated by leaching.

## Mururoa II site

The heat transfer of a hypothetical deep chamber was assessed by only one model (model G); the dimension of the initial reservoir was taken as $1.5 \times 10^6$ m3; dimensions and assumed permeabilities of inner and outer fracture zones are listed in Table 3. In this case no observed temperature data were available for the explosion chamber and there are no restraints with respect to the likely permeabilities within the fracture zones. Because of the greater depth we assumed that permeabilities are somewhat lower (20 and 5 darcy for inner and outer fracture zones respectively) than those used for model D.

The model showed that convection increases with time and that computed mass flow rates had not reached a maximum after 500 days; at Mururoa I site maximum flow rates occurred at only 100 days after the explosion. The temperature inside Mururoa II reservoir decreased from 82.5°C to 73°C after 500 days; the average heat transferred out of the reservoir was about 0.8 MW. Since the heat generated by radioactive decay might be as high as 0.25 MW for a 100 kt explosion, this effect becomes important for deeper chambers although it was neglected in model G. Vertical mass flow rates can reach values of about 10 kg/s and significant vertical flow extends to layers 300m above the chamber after 500 days; inferred speeds of vertical flow are of the order of 50 to 500m/yr; horizontal flows can attain magnitudes of between 25 and 100 m/yr.

Table 3: Permeability structure of inner and outer fracture zones of hypothetical Underground explosion chambers at Mururoa

| Model | INNER FRACTURE ZONE | | | OUTER FRACTURE ZONE | | |
|---|---|---|---|---|---|---|
| | Layer | Block | Permea-bility (darcy) | Layer | Block | Permea-bility (darcy) |
| Mururoa I site | | | | | | |
| B | EU to FL | 11 to 13 | 1 | As for model A | | |
| C | EU to FL | 11 to 13 | 10 | EU to FL<br>G | 10, 14<br>10 to 14 | 1 |
| D | EU to FL | 11 to 13 | 50 | EU to FL<br>G | 10, 14<br>10 to 14 | 10 |
| E | As for model D | | 50 | As for model D | | 20 |
| F | As for model D | | 50 | EU to FL<br>G | 10, 14<br>10 to 14 | 10 |
| | | | | EU to G | 8,9;15,16 | |
| Mururoa II site | | | | | | |
| G | EU to J | 11 to 13 | 20 | EU to J | 9,10;14,15 | 5 |

## Discussion

The studies described in this paper have shown that the initial permeability structure of Mururoa Atoll can be modelled by using undisturbed temperature profiles of deep holes. The permeability of the bottom layer of the limestone cap is unusually high (order of 50 Da) and fluids can move freely within this layer prior to any underground explosion.

The permeability of the volcanic rocks beneath the limestone cap is significantly increased by underground nuclear explosions. For a chamber at 550m depth created by a 10 kt explosion, it was found that the permeability within an inner (about 150m wide) and outer (about 400m wide) fracture zone increases to about 50 and 10 Da respectively. These values are only order of magnitude estimates and are based on a two-dimensional model; actual permeabilities might be somewhat lower in a three-dimensional setting. Average flow velocities of the order of 25 to 150 m/yr are indicated for the inner fracture zone; horizontal flow reaches a maximum of 25 to 75 m/yr in a layer of subaerial volcanics which include hyaloclastites. The computed energy transfer is about 2/3 of that indicated by observed temperature drops inside the chamber. Increased permeability around adjacent hypothetical explosion chambers induces a broadening of the convection cells but does not significantly affect mass flow. rates within the chimney structure. The effect of changes in porosity upon the mass flow rates is small; such changes, however, directly affect the inferred flow velocity rates.

The effects of a large (100 kt) explosion at 1000m depth was also studied; however, no temperature data were available which could be used to check the assumed permeability structure, and predictions based on this model are limited. The energy transfer within a deeper chamber, however, appears to be lower in comparison to that of shallow chambers, and a longer time is indicated for the setting up of the convection cells. Heat input by decay of radionuclides inside the chamber can no longer be neglected for large, deep explosions.

No information is available which can be used to assess the movement of fluids between the permeable dolomite layer and the surface, and without this information the likely flowrates within the limestone cap cannot be computed. The study, however, has shown that the heat transfer associated with underground nuclear explosions in saturated, permeable rocks can be modelled, and that these explosions create artificial geothermal systems.

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