millirem per year. Assuming, in a most unlikely case, that this applies to the whole population of a neighboring town of 20,000 people, the total dose integrated over population would be 500 man-rems per year, or $500,000 a year at $1000 per man-rem. This corresponds roughly to the total societal cost and is much less than $100,000 per day for a power reduction, but it seems quite enough incentive to persuade a plant superintendent to collect a spare part by private jet plane. Although the pollution charge will go into the utility company rate base, it will be only partially passed on to the consumer; there is always some incentive left to a utility company to be financially efficient.

It might be objected that the integrated doses considered are not only smaller than the integrated natural background radiation, they are smaller than the 5 percent variations in this background due to such matters as snow cover on the ground, and therefore a pollution tax would call excessive attention to nuclear power as a radiation source. However, NRC regulatory practices already bring this attention (*2*). My proposal, by allowing power stations to run at a higher power level than is often the present case, would reduce the excessive attention.

It is, I believe, important to consider this payment as a pollution charge, and not a tax or a fine; it is closely related to the problems caused by the pollution but no blame should necessarily be assigned. In principle, it would be desirable that this charge be paid to the people most affected by the pollution. This, in technical matters, is the principle of negative feedback or closing the feedback loop. Various articles have been written on the application of this principle to social affairs (*6*).

One possibility would be to transfer the payment, less the cost of collection, to the township in which the power station is located to reduce its taxes; another, to a local cancer hospital.

In several recent cases of excess emissions of radioactivity from nuclear power stations, power reductions have been ordered. The power has been made up by oil- or coal-fired power stations, and this has caused either an increase in balance of payment problems, or an increase in air pollution, with its own health cost, or a little of both. It is my belief that any self-adjusting system based on a pollution charge should allow these power stations to operate at full capacity, and thereby prevent wastage of scarce human resources and also reduce the world's total pollution problems.

Since I envisage this replacing an appreciable fraction of NRC regulatory activities and rules with the certainty that power companies will, literally, pay for any mistake, there should be no problem in administering a charge of this sort. Administering the design criteria can be left, to a greater extent than is presently planned, to the utility company.

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Composition of Atmospheric Particulate Matter from the Eruption of Heimaey, Iceland

Abstract. *The chemical composition of atmospheric particulate matter and rock samples collected on the island of Heimaey after the January 1973 eruption indicates that volcanic activity is a possible source of global significance for particulate material containing elements such as Br, Se, Sb, and Zn. Atmospheric aerosols from such remote areas as the North Atlantic Ocean and the South Pole are found to be highly enriched in these elements.*

Studies of the composition of atmospheric particulate matter in remote areas such as the North Atlantic Ocean and the South Pole indicate that atmospheric aerosols from such locations are substantially enriched in certain elements (Se, Sb, Pb, Br, Zn, and Cu) (*1, 2*). The relatively high volatility of these elements and many of their compounds suggests that a high-temperature dispersal process may be responsible for injecting these elements into the atmosphere. Although the North Atlantic Ocean and the South Pole are widely separated, the fact that the enrichment factors are similar in these two regions suggests that the sources for these elements are natural and widely dispersed (*1*).

Volcanoes have long been recognized as a major source of atmospheric aerosols and could conceivably be responsible for at least part of the observed elemental enrichments. On a global scale, it is estimated that volcanoes produce between 25×10^6 and 150×10^6 metric tons of fine particles (radius, < 20 μm) per year (*3*). This represents between 1 and 20 percent of the total estimated natural aerosol production rate (*3*). The importance of volcanoes as a source of atmospheric particulate material in the lower stratosphere and its subsequent global transport has been discussed elsewhere (*4*). It has been suggested that trace elements of high volatility could easily be transported out of the magma

Table 1. Elemental composition of Heimaey aerosols, lava-ash samples, and fumarole deposits. Abbreviation: ppm, parts per million.

Element	Aerosols		Lava-ash	Fumarole deposits
	Site A (ng/m^3)	Site B (ng/m^3)		
Cl	56,000 ± 8,000	14,000 ± 2,000	540 ± 190 ppm	4.4 ± 3.8%
Na	34,000 ± 5,000	9,500 ± 1,400	3.9 ± 0.7%	2.7 ± 1.3%
Fe		2,300 ± 700	9.8 ± 0.5%	6.7 ± 4.6%
Ca	2,200 ± 400	1,800 ± 300	8.4 ± 0.7%	5.9 ± 2.6%
Al	2,000 ± 300	1,900 ± 300	11.0 ± 1.3%	8.7 ± 3.3%
Br	310 ± 45	570 ± 85	~ 5 ppm	950 ± 1,060 ppm
Zn		85 ±12	491 ± 100 ppm	200 ± 68 ppm
Mn		79 ± 12	1,990 ± 60 ppm	1,200 ± 770 ppm
V		3.3 ± 1.4	270 ± 60 ppm	210 ± 170 ppm
Se	7.6 ± 2.3	25 ± 4	1.0 ± 0.30 ppm	265 ± 260 ppm
Co		1.9 ± 0.6	33.5 ± 1.5 ppm	23 ± 18 ppm
Sb	0.47 ± 0.14	0.53 ± 0.08	0.60 ± 0.30 ppm	0.93 ± 0.76 ppm
Sc	0.47 ± 0.14	0.41 ± 0.06	19.2 ± 4.7 ppm	17 ± 9 ppm
La		0.30 ± 0.09	25.9 ± 2.0 ppm	13 ± 9 ppm
Hf	0.17 ± 0.05	0.14 ± 0.02	5.9 ± 0.6 ppm	0.79 ± 0.04 ppm
Th	0.066 ± 0.013	0.058 ± 0.009	2.2 ± 0.1 ppm	1.2 ± 0.8 ppm
Eu	0.08 ± 0.04	0.025 ± 0.004	2.9 ± 0.4 ppm	0.28 ± 0.05 ppm

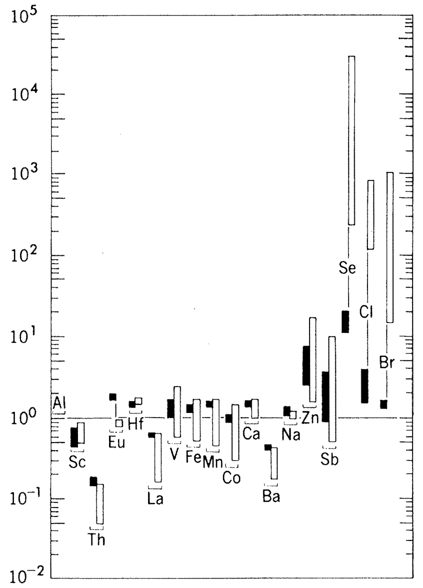

Fig. 1. Enrichment factors for lava-ash (closed bars) and fumarole deposits (open bars) from Heimaey, Iceland.

into the atmosphere in the form of volatile halides or hydroxides (*5*, *6*). Stoiber and Rose have reported 47 minerals in about 100 different high-temperature fumaroles (*6*). They concluded that the particular composition of the fumarole incrustations depends upon the reactions of volcanic gases and volatile trace elements with the atmosphere and the fumarole wall rock. Although studies of the composition of volcanic smoke fumes are few in number (*7*, *8*), the behavior of Se and Hg from volcanoes indicates that these elements are effectively transported into the atmosphere (*9*). However, a complete picture of volcanic trace element emissions is currently not available.

In June 1973 an opportunity arose to sample atmospheric particulate matter from an active volcano on the island of Heimaey, located in the Vestmannaeyjar archipelago off the southern coast of Iceland. This island experienced an eruption in January 1973. By June all major activity had ceased, and there remained only a few small lava streams that flowed harmlessly into the sea; however, the cooling lava and ash still produced great volumes of smoke and sulfurous fumes. Deposits on the rocks surrounding the numerous active fumaroles ranged from yellow to red-orange in color and proved to contain up to 50 percent S (by weight). We collected numerous samples of lava, ash, and fumarole deposits.

Filter and cascade impactor samples were taken at two locations. Site A was located on the northeastern edge of the island only a few meters from a small lava flow. At this site hot gases, but no visible smoke, were coming from underneath the broken lava field. Site B was located on the northwestern flank of the active cone. Here there was a great amount of visible smoke and sulfurous fumes.

We collected filter samples on 47-mm filters (Nuclepore) (pore diameter, 0.45 μm), using a twin-piston vacuum pump and a portable 1-kw, gasoline-powered generator located 92 m downwind of the sampling site. We collected the cascade impactor samples using a six-stage cascade impactor (Scientific Advances) discussed in detail elsewhere (*10*).

Lava, fumarole, and aerosol samples and blanks were analyzed by nondestructive neutron activation analysis according to a procedure similar to that reported previously (*11*). All samples, blanks, and standards were irradiated in the National Bureau of Standards reactor ($\phi_{\text{thermal}} = 6 \times 10^{13}$ neutron cm^{-2} sec^{-1}). After appropriate decay periods, the γ-ray radiation from the samples was measured with Ge(Li) detectors. The photopeaks of each observed element in the resultant spectra were then integrated by computer to obtain the final concentrations.

In Table 1 we have listed the average elemental concentrations and standard deviations of three lava-ash samples and five fumarole deposits. Also presented are the elemental concentrations and analytical errors for two aerosol samples, one from site A and one from site B. Those elements listed for which no aerosol concentrations are given were found to be present in concentrations not significantly above those of the blanks.

Table 2. Enrichment factors relative to crustal material.

Element	Site A	Site B
Th	0.27	0.20
La		0.43
Sc	0.88	0.81
Eu	2.74	0.90
Al	1.00	1.00
V		1.0
Fe		1.8
Ca	2.2 (0.92)*	1.9 (1.5)*
Hf	2.3	2.0
Co		3.3
Mn		3.5
Na	59 (1.00)*	17 (1.00)*
Zn		53
Sb	97	115
Cl	17,700*	4,660*
Br	5,100 (1,690)*	9,900 (8,910)*
Se	6,200	21,600

*Enrichment factors after correction for the oceanic component, with Na used as the reference element. See text for explanation.

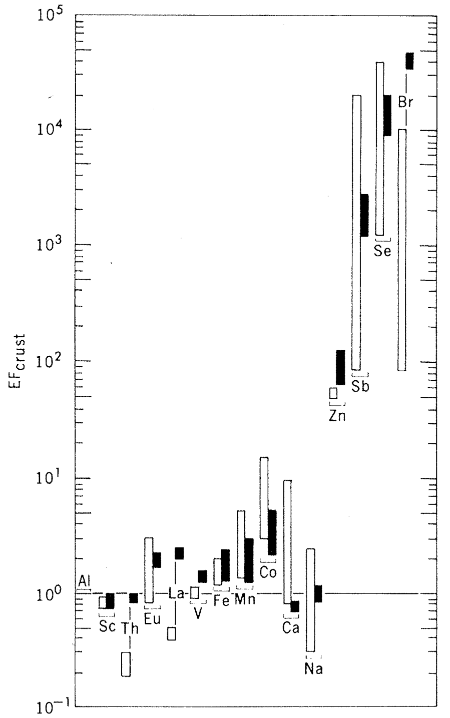

Fig. 2. Enrichment factors for atmospheric particulate matter from volcanic sources (open bars) and remote regions (the South Pole and North Atlantic Ocean) (closed bars). We know of no values from the North Atlantic for Th, Eu, and La. Values for V, Na, Ca, and Br from the North Atlantic are not included because V concentrations are highly influenced by pollution from the East Coast and Na, Ca, and Br concentrations are determined largely by oceanic rather than crustal abundances (*1*).

In order to draw some conclusions about the significance of volcanic activity as a source of atmospheric particulate matter, the various samples of lava-ash, fumarole deposits, and aerosol must be compared on a common basis. This can be done in the following way. First, one compares the composition of the lava-ash samples to that of average crustal material by taking the ratio of the concentration of the element of interest in the sample to the concentration of a reference element, in this case Al (chosen for its high concentration and its inertness in the atmosphere). This ratio is then compared with the corresponding ratio observed in average crustal material (*12*). These considerations result in the calculation of an enrichment factor which has the form

$$EF_{\text{crust}} = \frac{(\text{X/Al})_{\text{lava}}}{(\text{X/Al})_{\text{crust}}}$$

where X is the concentration of the element of interest (*1*, *2*). These same calculations can then be carried out with the elemental composition of the fumarole deposits and aerosol samples.

The results of the calculations described above are shown in Fig. 1. If the concentration of any given element in a particular sample is the same as that in average crustal material, the enrichment factor will be unity. Because the composition of the crust may show large variations from one locale to another, variations in the enrichment factors from unity can be expected. Indeed, variations of up to an order of magnitude may still be consistent with an essentially crustal elemental distribution. Most of the elements (Sc, Eu, Hf, V, Fe, Mn, Co, Ca, and Na) have enrichments close to unity for both lava-ash samples and fumarole deposits. The elements Th, La, and Ba appear to be depleted, but this is the result of the normalization to crustal abundances. Lava is typically basaltic, and most basalts exhibit lower concentrations of Th, La, and Ba than the crust [which includes not only basalts but also granites and sediments (*12*)]. Both Zn and Sb have a crustal distribution in the lava-ash samples but show great variability in the fumarole deposits. For Se there is a slight enrichment in the lava-ash samples but much higher enrichment in the fumarole deposits; Br and Cl show no enrichment in the lava-ash samples but high enrichment in the fumarole deposits.

In Table 2 we present EF_{crust} values for the two aerosol samples listed in Table 1. The elements Na, Ca, Cl, and Br have the sea as a major source. The numbers in parentheses represent the enrichment after correction has been made for the oceanic component. In this correction it is assumed that Na in excess of the amount predicted from its crustal abundance originates from the bulk transport of nonfractionated seawater into the atmosphere and that Ca, Cl, and Br are injected into the atmosphere according to their relative oceanic abundances. At site A and site B crustal Na accounted for about 2 and 5 percent, respectively, of the total Na concentration. The element Cl shows no enrichment after the oceanic component is subtracted because, within analytical errors, the oceanic contribution of Cl was equivalent to the observed Cl concentration.

In Fig. 2 we present the ranges of enrichment factors for atmospheric particulate material from two volcanic areas, Heimaey and Kilauea, Hawaii (*8*), and also from the South Pole and the North Atlantic Ocean (*1, 2*). Since the data from Kilauea, reported by Cadle *et al.* (*8*), did not include Al concentrations, we have chosen to normalize their data to reported Si concentrations. Elements reported by both Cadle *et al.* and ourselves have similar enrichments. This suggests that the Si/Al ratio is about the same for particles from the two volcanoes and, furthermore, that this ratio is close to that of crustal material. Of particular interest are the elements that show high enrichments in both volcanic and remote regions, namely, Zn, Sb, Se, and Br. Table 3 shows a comparison of the enrichment factors for these four elements. The enrichment factors for Zn and Se at the volcanic sites are remarkably similar to those from the South Pole and the North Atlantic. The enrichment for particulate Sb at Heimaey is much lower than that found at either the South Pole or the North Atlantic, but the enrichment for Sb at Kilauea is much higher. This suggests that the relative amounts of enriched elements injected into the atmosphere may vary widely from volcano to volcano, depending on magma composition and eruption characteristics. The enrichment for particulate Br at the South Pole is consistently higher than the enrichment at either of the volcanic sites. But much of the Br emitted by volcanoes is initially in the gaseous phase. Some Br may even be lost from particles to the gaseous phase upon aging of the aerosol. The wide range of enrichments for Br indicates that volcanoes may still account for some of the enrichment observed at remote regions. At Kilauea both As and Hg show high enrichments of 200 and 35,000, respectively (*8*), but there are no other data for comparison. We can be fairly certain that the Heimaey samples represent a volcanic aerosol because of the much higher concentrations observed for many elements at this site when compared with concentrations observed in the open ocean and continental areas (*13*).

Table 3. Elements showing high enrichments at both volcanic and remote sites.

Element	Heimaey	Kilauea	South Pole	North Atlantic
Zn	53		69	110
Sb	97 to 115	17,000	1,300	2,300
Se	6,200 to 21,600	1,400 to 36,000	18,000	10,000
Br	1,690 to 8,910	94 to 2,500	40,000	

The values of EF_{crust} for Zn, Sb, Br, and Se are much higher in the fumarole deposits and aerosol samples than in the lava-ash samples. Cascade impactor samples taken at site B, though incomplete, show Se, Sb, and Br to be concentrated on the smaller particles (Zn concentrations on samples from site B were not significantly above that of the blanks), whereas other elements such as Na, Ca, and Al are associated with predominantly larger particles. This suggests that the enriched elements are being volatilized out of the magma, possibly in the form of volatile halides. Although some portions of the vapors condense on the rocks surrounding the fumaroles, much of this vapor escapes into the atmosphere to form, upon condensation and coagulation, small particles. But these particles are probably removed from the troposphere by precipitation processes within, at most, a few weeks. To be of global significance the volcanic emissions should reach the lower stratosphere where worldwide transport can be accomplished by means of the zonal and meridional winds.

We have shown that enrichments for certain volatile elements (Zn, Sb, Se, and Br) in atmospheric aerosols from active volcanic regions closely parallel enrichments observed in aerosols from remote regions. These same elements are found to have similar enrichments in urban areas (*14*); however, the chemical composition and magnitude of all natural and man-made aerosol sources is not yet well enough characterized to permit any explanation for the observed enrichments of these elements in remote areas. The data presented here suggest that volcanoes may be a significant global source of these enriched elements. But the evaluation of volcanoes as a source will ultimately depend on detailed chemical measurements downwind and at high altitudes.

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Tetrahymena: Growth Without Phagocytosis

Abstract. *We have succeeded in growing a* Tetrahymena *mutant without food vacuoles in growth media supplemented with vitamins and heavy-metal salts. This finding implies the existence of adequate alternative routes of entry for every required nutrient, and clearly indicates that the food vacuole in* Tetrahymena *is a dispensable cellular organelle. The growth of the mutant without food vacuoles makes available a valuable experimental tool.*

Tetrahymena cells can take up particulate nutrients by phagocytosis, that is, the formation of food vacuoles, at a single, specialized location on the cell surface, the oral apparatus. The role of the food vacuole has posed a problem since the introduction of defined growth media composed of soluble nutrients. Carrier-mediated transport systems have been demonstrated in *Tetrahymena* (*1*). At least some of these systems are thought to be located at sites other than the food vacuole membrane (*2, 3*), possibly in the plasma membrane.

In the nutrient media commonly used to grow *Tetrahymena*, food vacuole formation appears to be essential (*3, 4*). However, in the presence of glucose and high concentrations of nucleosides, cells of strain GL of *T. pyriformis* can grow while forming vacuoles at a very low rate (*5*). This has led to the hypothesis that *Tetrahymena* cells can take up adequate amounts of all essential nutrients through a route or routes other than the food vacuole.

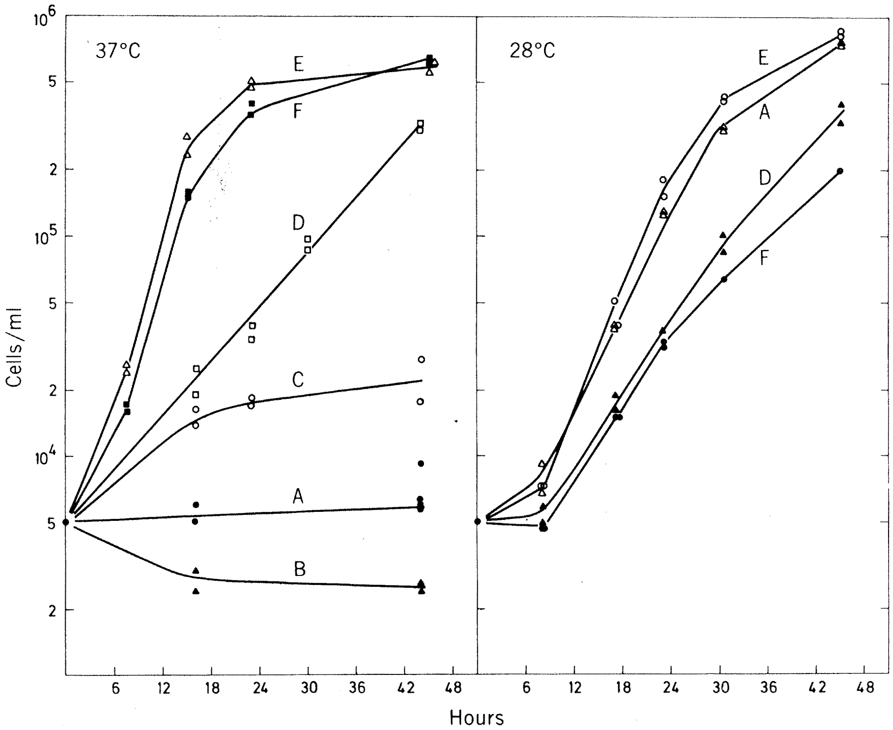

Fig. 1. Growth of mutant and wild type strains at 37°C (left panel) and 28°C (right panel) in defined media. The "basal" defined medium (BDM) has the composition described in table 1 of (*3*). The VIT solution adds 1 mg/ml of each of the nine vitamins already present in the medium (*11*). The HM solution adds each of the six heavy-metal salts already in the medium, at 25 times higher concentration (*12*). Curve A, mutant in BDM; B, mutant in BDM + VIT; C, mutant in BDM + HM; D, mutant in BDM + VIT + HM; E, wild type in BDM; F, wild type in BDM + VIT + HM. Duplicate cultures were incubated without shaking in 125-ml erlenmeyer flasks containing 10 ml of medium, and were inoculated from early stationary-phase cultures grown as follows: mutant at 37°C: BDM + VIT + HM at 37°C; all others: BDM at the corresponding temperature.

With the isolation of a mutant of *T. pyriformis* with a heat-sensitive capacity to form food vacuoles (*6*), it has become possible to test rigorously whether or not alternative routes of nutrient uptake exist and how important they are. This mutant grows and forms food vacuoles at normal rates at 30°C, but at 37°C the mutant cells are unable to form a functional oral apparatus, do not form food vacuoles, and stop growing in the commonly used growth media.

We have now succeeded in growing the mutant at 37°C in a 2 percent proteose peptone medium, supplemented with the high concentrations of vitamins and heavy-metal salts described in the legend of Fig. 1. Under these conditions, we have observed generation times as short as 3.5 hours for the mutant, and about 2 hours for the wild-type parental strain. One culture of the mutant has been maintained continuously under these conditions for an estimated 350 generations (by daily subculture) without a decrease in the growth rate. The metals in the medium precipitate at these high concentrations, but precipitate formation can be greatly diminished, if not eliminated, by the prior addition of 2 m*M* Na citrate, without any effect on the growth rate of the cells.

The same supplements enable the mutant cells to grow at 37°C in a chemically defined medium. Growth curves of the mutant at 37°C and the appropriate controls are shown in Fig. 1. Some of the cells in the medium show morphological abnormalities, and this medium may still be susceptible of improvement.

We have repeatedly verified that the mutant cells growing at 37°C in either medium do not form food vacuoles, both by direct observation under phase-contrast microscopy and by the addition of particles of India ink, as previously described (*6*). The mutant cells grown at 37°C also still show the morphological abnormalities of the oral apparatus revealed by silver impregnation (*6*). Thus the cells that grow are not revertants that have regained the capacity to form food vacuoles at 37°C. Such revertants, which can be easily detected by these tests, can be induced with nitrosoguanidine (*7*), and have very infrequently arisen spontaneously in the course of this study.

We assume that the mutation which affects the development of the oral apparatus at 37°C has not coincidentally increased nutrient-uptake capacities in the mutant. Thus we assume that the points discussed below apply equally well to the wild-type strains.