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THE POTENTIAL IMPACTS ON AQUATIC ECOSYSTEMS FROM THE
RELEASE OF TRACE ELEMENTS IN GEOTHERMAL FLUIDS^{1,2}

⁴²R. M. Cushman, ⁴²S. G. Hildebrand, and ⁴²R. W. Brocksen

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ABSTRACT

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Geothermal energy will likely constitute an increasing percentage of our nation's future energy "mix," both for electrical and nonelectrical uses. Associated with the exploitation of geothermal resources is the handling and disposal of fluids which contain a wide variety of potentially toxic trace elements. We present analyses of 14 trace elements found in hydrothermal fluids from various geothermal reservoirs in the western United States. The concentrations of these elements vary over orders of magnitude between reservoirs. Potential impacts are conservatively assessed on the basis of (1) toxicity to freshwater biota, and (2) bioaccumulation in food fish to the point where consumption might be hazardous to human health. Trace element concentrations generally range from benign levels to levels which might prove toxic to freshwater biota and contaminate food fisheries. We stress the need for site-specific analyses and careful handling of geothermal fluids in order to minimize potential impacts.

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INTRODUCTION

Recently, increased attention has been given to the potential utilization of geothermal energy for a variety of purposes, both in the generation of electrical power as well as a variety of nonelectrical uses. Economic and theoretical estimates of the potential capabilities of geothermal utilization vary widely. In the area of electrical production alone, projections of geothermally produced electrical capacity for the United States within the next 50 years vary from 1000 MW to 440,000 MW (Berman, 1975), representing 0.05% to 22% of the Nation's 2,000,000-MW total electrical capacity projected for the year 2000 (Beall et al., 1974). Geothermal generation of electricity is seen as attractive from the standpoint of economics, because the costs of capital equipment and "fuel" are lower than with many other forms of production. In comparison with nuclear or coal, where mining, processing, and generation occur at widely separated sites, environmental protection appears to be more easily assumed because the "fuel cycle" is confined to the site. In addition, public acceptability appears more likely than for most other technologies because geothermal energy is commonly regarded as clean, and apparently does not elicit the concerns for safety which accompany nuclear energy (Small, 1973).

Process heat uses of geothermal fluids (as well as the direct application of the fluids) for irrigation, aquaculture, and hydroponics are among the diverse nonelectrical uses suggested for geothermal energy (Table 1). Peterson and El-Ramly (1976) have estimated that nonelectrical uses presently account for less than 4% of exploited

Table 1. Potential nonelectric uses of geothermal energy

1. Residential and Commercial Climate Control	b) Chemical processing
a) Heating	1) Synthetic rubber
1) District space heating (central control)	2) Paper manufacturing
2) Space heating (single unit)	3) Viscose rayon manufacturing
3) Hot-water service	4) Metallurgical processes
(all of above for homes, schools, hotels,	5) Sulfur Frasch mining
hospitals, factories, clinics, farm	
buildings, etc.)	c) Food related products
b) Cooling	1) Protein manufacture
1) Air conditioning (homes, hotels,	2) Dry curing of tea
factories, etc.)	3) Rice parboiling
	4) Brewing and distillation
	5) Sugar processing
	6) Fermentation processes
	7) Food processing and canning
	8) Milk pasteurization
2. Agricultural and Related Uses	d) Drying and evaporation
a) Hot-water irrigation	1) Desalination of water
1) Crop spraying	2) Seaweed drying
2) Soil warming	3) Textile drying
b) Greenhouses and hothouses	4) Lumber drying and seasoning
c) Animal husbandry	5) Seed drying
1) Egg incubation	6) Peat drying
2) Poultry	
3) Swine	
4) Dairy farms	
5) Slaughterhouse operations	
d) Aquaculture	
3. Industrial Processes	4. Balneology (health resorts and spas)
a) Chemical recovery	
1) Carbon dioxide	
2) Lithium	
3) Sodium chloride	
4) Calcium chloride	
5) Borax	
6) Iodine	
7) Boric acid	
8) Bromine	
9) Hydrogen sulfide	
10) Sulfur	
11) Magnesium	
12) Magnesium sulfate	

SOURCE: Kunze and Richardson (1975)

geothermal energy within the United States, while on a world-wide basis about two-thirds of exploited geothermal energy is used for nonelectrical purposes.

The Geothermal Steam Act of 1970, the Geothermal Energy Research, Development, and Demonstration Act of 1974, and the Federal Nonnuclear Energy Research and Development Act of 1974 promote the increased exploitation of geothermal resources in the United States. It can be expected that geothermal energy will provide an increasing percentage of our future national energy "mix." Legislation such as the National Environmental Policy Act of 1969, and other Federal, state, and local statutes, provide for the protection of environmental quality. Therefore, it is useful and appropriate to consider the potential impacts on aquatic resources, such as toxicity to biota and/or contamination of food fisheries caused by trace contaminants in hydrothermal fluids released to aquatic systems.

Release of geothermal fluids to aquatic environments, either by design or accident, could occur in many ways. A variety of techniques are used for the disposal of fluids at geothermal power plants, including direct release to surface waters, holding and evaporation in sumps, and injection back into deep reservoirs. The choice of disposal method is site-specific, depending on such factors as water quality protection, geothermal reservoir maintenance, ground subsidence potential, and engineering design and cost considerations. The transportation for utilization or disposal of geothermal fluids, such

as through pipeline systems between wells and power plants or between wells and nonelectrical utilization facilities, may involve the piping of these fluids over distances of from tens of meters to tens of kilometers. In all of these processes, spills, sump overflows or dike breachings, equipment failure, or human oversight can result in the release of geothermal fluids and their constituent trace elements to streams, lakes, reservoirs, or other aquatic environments. In the Roosevelt Hot Springs (Utah) area, hydrothermal fluids were intentionally discharged into surface channels until damage to terrestrial vegetation became evident, at which point the practice was discontinued (Lenzer, Crosby, and Berge, 1977). Other situations in which the utilization design calls for surface release or use of hydrothermal fluids include land irrigation (Schmitt and Peterson, 1977), hydroponic greenhouse operations (Gutman, 1975), and aquaculture (Roberts, 1975).

Hydrothermal fluids from both liquid-dominated (hot water) and vapor-dominated (steam) reservoirs have been analyzed by several investigators and found to contain a variety of trace elements. Table 2 presents the analysis of 14 trace elements and total dissolved solids (TDS) from a selection of hydrothermal systems in the western United States and Alaska. Values of total dissolved solids range from hundreds to hundreds of thousands of milligrams per liter (mg/liter). Similarly, the concentrations of the elements in Table 2 range from less than one microgram per liter ($\mu\text{g/liter}$) to thousands of mg/liter. The concentrations of these elements vary from region to region, from different wells within a region, and even with time from single wells.

Table 2. Reported trace element constituents and total dissolved solids (TDS) in selected hydrothermal fluids of the United States (all concentrations in mg/l; nr = not reported).

Region	Salton Sea	East Mesa	Humboldt County, Nevada	West-central Alaska	Raft River	The Geysers (Condensates)	Sierra Valley	Honey Lake Valley	Surprise Valley	Modoc Plateau	Range
Reference	Marsh, Klein & Vermeulen (1975)	U.S.Bur. of Reclamation (1974)	Mariner et al. (1975)	Miller, Barnes & Patton (1975)	Kunze (1975)	Lake County (1976)	Reed (1975)	Reed (1975)	Reed (1975)	Reed (1975)	
Element											
As	12	nr	<0.01 - 0.08	nr	nr	0.002 - 0.09	nr	nr	nr	nr	0.002 - 12
B	400	2.2 - 3.3	nr	0.08 - 3.4	0.2	8.0 - 380.0	0.07 - 8.8	<0.02 - 5.5	0.61 - 7.6	0.22 - 12.8	<0.02 - 400
Ba	235	nr	nr	nr	<0.4	nr	nr	nr	nr	nr	<0.4 - 235
Br	120	nr	0.02 - 2	4 - 4.9	<2.5	nr	nr	nr	nr	nr	0.02 - 120
Cr	nr	nr	nr	nr	nr	0.00 - 1.5	nr	nr	nr	nr	0.00 - 1.5
Cu	nr	nr	<0.01 - 0.07	nr	nr	0.09 - 1.5	<0.01	<0.02	<0.02	<0.02	<0.01 - 1.5
Fe	2290	1.1 - 2.4	<0.02 - 0.22	<0.01 - 2.7	0.32	0.6 - 80.0	<0.06 - 1.43	<0.06	<0.06	<0.06	<0.01 - 2290
Hg	nr	nr	<0.0001 - 0.0040	nr	nr	0.0006 - 0.03	nr	nr	nr	nr	<0.0001 - 0.03
Mn	1400	nr	<0.02 - 0.10	nr	0.07	0.0 - 2.0	0.01 - 0.10	<0.01	<0.01 - 0.09	<0.01 - 0.012	<0.01 - 1400
Ni	nr	nr	nr	nr	nr	0.0 - 7.5	<0.04	<0.04	<0.04	<0.04	<0.04 - 7.5
Pb	102	nr	nr	nr	nr	0.0 - 1.5	<0.06	<0.1	<0.1	<0.1	<0.06 - 102
Rb	135	nr	<0.02 - 0.28	nr	nr	nr	<0.01 - 0.11	<0.01 - 0.04	<0.01 - 0.08	<0.01 - 0.06	<0.01 - 135
Tl	nr	nr	nr	nr	nr	0.0 - 0.7	nr	nr	nr	nr	0.0 - 0.7
Zn	540	nr	nr	nr	nr	0.2	<0.01	<0.005 - 0.043	<0.005 - 0.014	<0.005	<0.005 - 540
TDS	260,203	2311 - 21967	nr	nr	1715	nr	266 - 1570	233 - 1040	370 - 1210	231 - 1220	231 - 260,203

It is therefore necessary that detailed chemical analyses be performed for each geothermal reservoir utilized, and that these analyses be conducted periodically, in order to provide an accurate measure of the trace element constituents of the geothermal fluids so that an initial determination of the potential for environmental contamination can be made.

METHODS

Based on the trace element analyses reported in Table 2, we assessed two types of potential impacts which might occur if the fluids were released to aquatic environments through design or accident: toxicity to aquatic biota and contamination of food fisheries through bioaccumulation. We used the methods described for the assessment of these potential impacts from coal conversion process effluents (Hildebrand, Cushman, and Carter, 1976).

Reported concentrations of the various elements were compared with the lowest levels of these elements found to be toxic to freshwater biota. The potential toxicity of trace elements in the geothermal fluids was assessed by dividing the reported maximum and minimum concentration of each element by the lowest reported concentration found in the literature to be toxic to freshwater biota regardless of the organism or toxicity test used (Cushman, Hildebrand, Strand, and Anderson, 1977). Endpoints of toxicity included lethal (mortality) and sublethal (reproductive impairment, growth inhibition, etc.) effects. Therefore, the quotient we calculate would represent the highest

anticipated toxicity effect for each concentration, and the higher the quotient the greater the possible effect.

In order to assess the potential for hazardous contamination of foods resulting from the bioaccumulation of trace elements by freshwater fish, we calculated the threshold concentration of the elements in freshwater at which fish would concentrate the elements to levels considered excessive for human consumption. We used the following relation, obtained from Dawson (1974):

$$\text{threshold (mg/l)} = \frac{\text{DWS (mg/liter)} \times 2 \text{ (liters water/day)}}{0.06 \text{ (kg fish/day)} \times \text{BF}}, \quad (1)$$

where:

DWS = drinking water standard

BF = bioaccumulation factor for freshwater fish,

which simplifies to:

$$\text{threshold (mg/liter)} = \frac{33 \text{ DWS (mg/liter)}}{\text{BF}}. \quad (2)$$

The factor used in calculating the threshold concentration for hazardous bioaccumulation for each element is based on the assumption that the only significant source of each element to humans is 0.06 kg of fish per day in the diet (USNRC, 1976). The maximum human daily intake of the element is set at the amount of the element which would be taken in through drinking two liters of water per day (USNRC, 1976) containing the element at a concentration equal to a drinking water standard. Estimates of the bioaccumulation factors for freshwater

fish defined as $\frac{\text{concentration in fish (mg/kg wet wt)}}{\text{concentration in water (mg/liter)}}$ are available in the literature (Thompson et al., 1972; Thompson et al., 1976). Reported bioaccumulation factors for fish may vary over orders of magnitude, even in similar situations (Vanderploeg et al., 1975). The values we used, however, are conservative and provide a reasonable basis for this preliminary assessment.

Reported maximum and minimum concentrations of trace elements in the geothermal fluids were divided by the calculated threshold concentration in order to provide a ratio for assessing the potential for hazardous bioaccumulation in freshwater fish. Where the ratio of the reported concentrations divided by either the toxic concentration or bioaccumulation threshold concentration had a value of one or more, this element was interpreted as potentially hazardous, with the potential for biological impact rated as low, medium, or high if the ratio

$$\frac{\text{concentration of element in hydrothermal fluid}}{\text{toxic concentration}}$$

or

$$\frac{\text{concentration of element in hydrothermal fluid}}{\text{bioaccumulation threshold concentration}}$$

ranged between 1-100, 100-10,000, or > 10,000, respectively.

RESULTS

Our analysis of the potential toxicity and bioaccumulation hazard of the trace elements found in hydrothermal fluids, based on the range of reported concentrations from Table 2, is summarized for the 14 elements in Table 3. For most of the elements, the minimum reported

Table 3. Calculation of potential toxicity and bioaccumulation of trace elements in hydrothermal fluids. BF = bioaccumulation factor, DWS = drinking water standard.

Element	Toxic concentration ^a (mg/l)	BF for fish	DWS (mg/l)	Threshold bioaccumulation concentration (33DWS/BF) (mg/l)	Concentration of element in geothermal fluid ÷ toxic concentration	Concentration of element in geothermal fluid ÷ threshold bioaccumulation concentration
As	0.022	333 ^b	0.05 ^d	0.005	<1 - 550	<1 - 2400
B	0.69	1 ^c	1 ^e	33	<1 - 580	<1 - 12
Ba	5.3	4 ^b	1 ^d	8.25	<1 - 44	<1 - 28
Br	0.18	417 ^b	3.0 ^f	0.24	<1 - 670	<1 - 500
Cr	0.005	4000 ^b	0.05 ^d	0.0004	<1 - 300	<1 - 3750
Cu	0.0006	200 ^b	0.1 ^f	0.02	? - 2500	<1 - 75
Fe	0.2	100 ^b	0.3 ^g	0.10	<1 - 11,450	<1 - 22,900
Hg	0.0001	1000 ^b	0.002 ^d	0.0001	<1 - 300	<1 - 300
Mn	0.35	660 ^b	0.05 ^g	0.003	<1 - 4000	? - 470,000
Ni	0.03	100 ^b	0.05 ^f	0.02	? - 250	? - 375
Pb	0.007	300 ^b	0.05 ^d	0.006	? - 14,600	? - 17,000
Rb	14.0	2000 ^b	5 ^f	0.08	<1 - 9.6	<1 - 1690
Ti	2.0	1000 ^b	0.1 ^f	0.003	<1	<1 - 230
Zn	0.01	8500 ^b	5 ^g	0.02	<1 - 54,000	<1 - 27,000

^aCushman, Hildebrand, Strand, and Anderson (1977)

^bThompson et al. (1972)

^cThompson et al. (1976)

^dFederal Register (1975)

^eFederal Water Pollution Control Administration (1968)

^fDawson (1974)

^gU.S.P.H.S. (1962)

concentration was found to be below both toxic concentrations and concentrations with potential significance for contamination of food fisheries via bioaccumulation. That is, the ratios

$$\frac{\text{concentration of element in hydrothermal fluid}}{\text{toxic concentration}}$$

and

$$\frac{\text{concentration of element in hydrothermal fluid}}{\text{bioaccumulation threshold concentration}}$$

calculated and presented in Table 3 were less than one.

At the maximum reported concentrations of the elements in hydrothermal fluids, however, only one element, titanium (Ti) was observed at a concentration below the known toxic level, while the other thirteen elements were found at toxic levels, with ratios ranging from 9.6 (Rb) to 54,000 (Zn) (Table 3). All 14 elements we considered, when at maximum reported concentration, were found to present a potential bioaccumulation hazard, with ratios ranging from 12 (B) to 470,000 (Mn) (Table 3).

The assessment of the toxicological and bioaccumulation significance of nickel (Ni) and lead (Pb), the toxicological significance of copper (Cu), and the bioaccumulation significance of manganese (Mn) at their lowest concentrations was not possible because of the lack of sensitivity of the analytical chemistry methodology.

DISCUSSION

In assessing impacts on aquatic ecosystems or man's use of aquatic resources, our preliminary analysis suggests that all 14 trace elements

considered in this paper warrant attention. This will be especially true as the exploitation of geothermal resources for electrical and/or nonelectrical purposes increases in this country and elsewhere in the world. Toxicologically, Zn, Pb, and Fe appear to have the highest impact potential; As, B, Br, Cr, Cu, Hg, Mn, and Ni are of medium concern; and Ba and Rb have lower impact potential when found at their highest reported concentration (Table 4). In terms of possible bioaccumulation hazard in freshwater food fisheries, Fe, Mn, Pb, and Zn appear to have the highest impact potential, As, Br, Cr, Hg, Ni, Rb, and Ti have medium impact potential; and B, Ba, and Cu have lower impact potential (Table 4). Potential impacts of these elements at their lowest reported concentrations in hydrothermal fluids range from benign to medium, or unknown, according to our analysis (Table 4).

This analysis of potential toxicity and bioaccumulation of trace elements in hydrothermal fluids is preliminary and should not be construed as a prediction of impacts in all cases. Nevertheless, every element considered in this paper was found in concentrations which varied with time and with location, and these concentrations could be harmful in some instances. The significance and interpretation of trace element concentrations in natural waters is complex. The availability and solubility of many elements will depend on such factors as the presence of organic chelators in the water, and on the pH and oxidation-reduction potential of the water (Morel, McDuff, and Morgan, 1973). Additionally, synergistic or additive effects are possible, particularly with geothermal fluids, because of the high

Table 4. Summary of trace elements in hydrothermal fluids that have a potential for toxicity or bioaccumulation hazard in aquatic ecosystems

Element	Potential toxicity		Potential bioaccumulation hazard	
	Minimum concentration reported	Maximum concentration reported	Minimum concentration reported	Maximum concentration reported
As	NEE	Medium	NEE	Medium
B	NEE	Medium	NEE	Low
Ba	NEE	Low	NEE	Low
Br	NEE	Medium	NEE	Medium
Cr	NEE	Medium	NEE	Medium
Cu	?	Medium	NEE	Low
Fe	NEE	High	NEE	High
Hg	NEE	Medium	NEE	Medium
Mn	NEE	Medium	?	High
Ni	?	Medium	?	Medium
Pb	?	High	?	High
Rb	NEE	Low	NEE	Medium
Ti	NEE	NEE	NEE	Medium
Zn	NEE	High	NEE	High

Note: NEE = no expected effect (calculated ratio in Table 3 of <1)
 ? = potential impact not determined because of insufficient analytical data
 Low potential = calculated ratio in Table 3 of 1-100
 Medium potential = calculated ratio in Table 3 of 100-10,000
 High potential = calculated ratio in Table 3 of >10,000

salinity in some cases (concentrations of TDS range into the hundreds of thousands of mg/liter), high heat content, and possible presence of many other toxic constituents. Thus, the actual assessment of the potential environmental impact of particular geothermal fluids will involve sitespecific characterizations of not only the organisms found in the local aquatic environment and the dilution of released fluids by the receiving waters but also of the physical and chemical character of the geothermal fluids and receiving waters.

In the United States, most present and expected geothermal development is concentrated in the western states, where, in general, aquatic resources are scarce and highly valued. In all areas the geology is volcanic, and the water chemistry of surface waters is largely soft. Many trace elements have been found to be particularly toxic to aquatic biota in softer waters (Pickering and Henderson, 1964; Cairns and Scheier, 1957; Mount, 1966; Wurtz, 1962), and in such instances the potential for impact is clear. In the Geysers geothermal region in California, where electrical production from geothermal energy in the United States is currently centered, a kill of steelhead trout in Big Sulphur Creek has been attributed to a discharge of geothermal condensate. Boron, as boric acid, has been identified as a possible toxin in that situation (Axtmann and Peck, 1976).

Municipal water supplies may also be jeopardized by geothermal development. In Lake County, California, a proposed water supply, the Collayomi Reservoir, would be surrounded by planned geothermal development (Lake County, 1976). The necessity for environmental protection

in such a case, where an inadvertent discharge of geothermal fluids could have a serious effect, is obvious.

In conclusion, the trace elements found in hydrothermal fluids range in concentration from benign levels to levels capable of causing toxic effects in aquatic biota and/or contaminating food fisheries to the point where their consumption would be potentially hazardous to humans. The variation of reported concentrations is such that periodic and site-specific analyses are warranted. Our assessment of toxicity potential is based on a conservative methodology. As discussed earlier, trace element toxicity depends on a complex set of physical, chemical, and biological factors and interactions. The use of site-specific bioassays would be valuable in assessing the actual toxic characteristics of hydrothermal fluids from particular reservoirs. The integration of environmental protection measures into plans to utilize geothermal resources, whether for electrical or nonelectrical purposes, and the careful operation and maintenance of such facilities are mandated if aquatic environments are to be preserved, both as functioning and healthy ecosystems and as resources for man.

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