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Summary of Section V
Environmental Factors and Waste Disposal

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INTRODUCTION

Until fairly recently, the general attitude towards geothermal pollution has been one of *laissez-faire*. The reasons for this are not far to seek. In the first place, geothermal energy has been widely acclaimed by its enthusiasts as "clean," and it cannot be denied that, for a given scale of heat exploitation, it is generally far less a cause of pollution than fuel combustion. Secondly, Nature herself is often a polluter in unexploited thermal areas; so, it is asked, who are we to compete with Nature? Thirdly, we have tolerated for generations (and continue to tolerate) the polluting effects of fuel combustion on a vast and ever-increasing scale. Hence, one argument is that the influence upon the environment from the miniscule energy contribution made by geothermal heat has, on the whole, been slightly beneficial, so that no trouble arises. This somewhat natural tendency to sweep a problem beneath the carpet of persuasive excuses is understandable; but in recent years public awareness of the hazards of all forms of environmental pollution has belatedly been aroused, and we can no longer permit ourselves to look the other way.

Stringent antipollution laws have now been enacted in certain countries. While such laws are welcome in some respects, as a step in the right direction, it has sometimes been argued that their stringency is acting as a serious and very costly brake upon the tempo of geothermal development. It has now been virtually proved that an antidote of acceptable efficiency can be found for nearly every possible source of geothermal pollution. The more recently constructed geothermal power plants in The Geysers field, California, are models of nonpolluting exploitation in which the designers may take justifiable pride. Nevertheless, the antidotes cost money and (more important) take time to apply. It is this delaying factor, rather than the directly incurred costs, which has been the subject of some criticism, for delays are themselves extremely costly. It can be shown that every kilowatt of base-load geothermal power feeding a composite integrated power network can save about 2 tons of oil fuel per year. Thus, with oil fuel at a price of about \$75/ton, the cost of delaying the construction of No. 12 unit—106 MW (net)—at The Geysers would approach \$16 million for one year's deferment. This sum would appear as an invisible burden on the national balance of payments. If the cost of delay were expressed as about \$150/yr/kW and compared with the estimated construction cost of No. 12 unit, which according to Dan et al. (p. 1949) is \$141.3/kW, it will be seen that one year's delay would more than double the true construction cost. Nor is that the end of the sad story, for during that year, the basic construction costs will have risen in the present inflationary climate.

These figures, although specifically applying to No. 12 Geysers unit, illustrate the urgency that applies to all geothermal power construction programs in oil-importing countries. The question arises whether strict compliance with the antipollution laws may not be too high a price to pay for achieving near-perfection too quickly, and whether some temporary relaxation of the law would better serve the national interest. These are not only the views of the author. Axtmann (p. 1323) has suggested that some regulations under the antipollution laws should be eased, if not actually repealed, in order to aid the rapid expansion of geothermal development.

However, this should be a relatively short-term problem. In future installations it should be possible to synchronize the provision of the necessary pollution antidotes with the construction period of the remainder of the plant. Moreover, as pointed out by Allen and McCluer (p. 1313) and Axtmann (p. 1323), it is far cheaper to design a plant with built-in antidotes than to fix the antidotes as an afterthought to a completed installation, as has been necessary where antipollution legislation has been enacted after plants have been in service for some time. In the future, the enforcement of rigid antipollution laws probably will prove to be entirely beneficial and not unduly expensive. It may well be true that certain natural phenomena—for example, the hot springs at Yellowstone Park—are themselves "breaking the law" by polluting the environment to a greater extent than is permitted legally. But although we cannot prosecute Nature, there can be no harm in trying to improve her.

PROBLEMS

The problems of environmental pollution may best be considered one by one.

Hydrogen Sulfide

The gases accompanying geothermal fluids almost invariably contain H_2S. This noxious gas, in moderate and harmless concentrations, has a characteristic and rather unpleasant smell; but when more strongly concentrated, it paralyzes the olefactory nerves and thus becomes odorless. Therein lies its danger. When it is present in lethal quantities, it gives no warning of its presence. It is also 17.5% heavier than air at the same temperature and is therefore apt to collect in low-lying pockets. Fatalities have occurred on rare occasions in the vicinity of fumaroles, but no incidents have yet been reported from this hazard in geothermal exploitation plants. This is probably largely attributable to the care of designers in providing adequate ventilation in cellars and basements. H_2S also attacks equipment—for example, electrical contacts and commutators—and it may have adverse effects on crops and river life.

The gas can escape to the environment by all or any of the following paths: (1) from the condenser gas ejector discharge; (2) with warm vapor and air rising from cooling towers; (3) from wells discharging to waste when undergoing test or when a plant is unable to absorb all the steam from the bores connected thereto; (4) from "wild" bores; (5) from traps and drains; (6) in solution in the surplus condensate where cooling towers are used; (7) in solution in the main body of cooling water where river cooling is adopted for turbine condensers; and (8) in solution in the water phase in wet fields, when the water is discharged into rivers or streams (relatively small).

Until fairly recently, the general attitude to H_2S pollution has been that with (1), (2), (3), and (4) the combination of temperature buoyancy and, in the first two cases, a high discharge altitude ensures sufficiently wide dispersal to render the gas harmless; with (5) and (8) the quantities of gas are negligible; with (6) the fluids usually enter streams already infected naturally with H_2S from hot-spring discharges; and with (7) adequate dilution is likely to be afforded by large river flows (as at Wairakei). This tolerant attitude may have been justified in the early days of geothermal exploitation, but the scale of development has now grown so rapidly in certain fields that H_2S pollution can no longer be disregarded. Axtmann (p. 1323) has estimated that the H_2S discharged daily from Cerro Prieto (75 MW) is about 55 tons; and if 200 MW were to be developed at Broadlands, New Zealand, the daily amount would be about 30 tons. Reed and Campbell (p. 1399) give an estimate of 28 tons/day for the 500 MW now installed in The Geysers field. Such quantities cannot be ignored; and California legislation now insists on the removal of nearly all of this gas to bring the concentration down to less than the threshold of odor, so that if the gas can be smelled the law is being broken.

At The Geysers, escape paths (1), (2), (5), and (6) are being steadily and efficiently tackled by methods described by Allen and McCluer (p. 1313). The ejector gases contain sufficient combustibles for them to be burnt so as to convert the H_2S into SO_2, which is then scrubbed by the cooling-tower water. As a result of the "Claus reaction," elemental sulfur is precipitated. At the same time, a metal catalyst such as a nickel or iron salt is added to the cooling water, and this too has the effect of precipitating sulfur by oxidizing the H_2S. A certain amount of natural oxidation of this gas also occurs in the cooling towers. The elemental sulfur is filtered out as a sludge and the surplus cooling water is reinjected into the ground. As the sulfur sludge is contaminated with catalyst, rock dust, and so on, it is not at present marketable and is therefore being dumped in a disposal site pending the outcome of efforts to refine it or find a useful application for it. Traps and drains are being piped to the cooling towers where they share the same treatment as the condensate and cooling water. These methods are very effective, though there are certain corrosive side effects. Further research is being carried out to effect even greater H_2S abatement if possible and to reduce the corrosive action. Axtmann (p. 1323) proposes hybrid power and chemical plants based on the Claus reaction which could render H_2S emission control profitable. Allen and McCluer (p. 1313) suggest it might be possible to remove the H_2S from the steam before it reaches the plant.

There appears to be no answer to (3) beyond insistence that, when a plant is shut down for more than a short time, the wells should be throttled back to reduce the effluent. Nor is there a solution to (4) beyond the avoidance of "wild" bores by taking great care when drilling. It is difficult to see a simple solution to escape-path (7), where river flows are not very copious and are far from the sea, other than substituting cooling towers in place of direct river cooling. It is already being claimed that at Wairakei the fisheries and weed growth may be suffering from H_2S emission into the river. The answer to (8) could be reinjection.

Mercado (p. 1385) states that at Cerro Prieto, although reliance is mainly placed on the conventional use of high ejector stacks for wide dispersal of H_2S, additional protection against accumulation of the gas at ground level (especially on windless days) is provided by means of extraction fans and long ducting towards the settling-pond area. H_2S detection and alarms are also installed to protect personnel against dangerous local concentrations of the gas.

Carbon Dioxide

The greater part of the incondensable gases that accompany the bore fluids consists of CO_2. This can escape into the environment by the same eight paths listed above. The fact that fuel combustion usually produces far greater quantities of this gas than geothermal exploitation on the same thermal scale has generally been regarded as an excuse for inaction, particularly as the gas is not toxic. However, in certain high-gas-content fields, such as Monte Amiata, the CO_2 discharged to the atmosphere may be much greater than that from fuel-fired plants of comparable size and duty. It is believed that the growing CO_2 content of the atmosphere, mainly due to fuel combustion, may be having a gradual adverse effect on the world climate; while high CO_2 content in waters discharged into rivers can aggravate weed growth. It is undesirable that geothermal exploitation should contribute towards these effects, and suggestions have been made for the commercial extraction of CO_2 from geothermal effluents. The production of dry ice, carbonic acid for beverages, and methyl alcohol have all been considered but no commercial propositions have yet been advanced. Meanwhile the emission of large quantities of CO_2 from geothermal installations seems inevitable. The problem is not yet one of urgency, but if geothermal development grows dramatically—as it probably will in the near future—it will soon have to be tackled.

Land Erosion

At The Geysers field, heavy rains and steep slopes of incompetent rock often cause natural landslides and high erosion rates. The artificial leveling of ground for the accommodation of field works, roads, and power plants has sometimes aggravated erosion by creating steep local gradients and removing vegetation. These hazards have been stressed by Reed and Campbell (p. 1399) who state that close control, replanting shrubs and trees, more careful site selection, and improved construction methods are helping to solve this problem. Close spacing of several wells within a single leveled area, combined with directional drilling, can also help in this respect.

Waterborne Poisons

The water phase in wet geothermal fields sometimes contains poisonous elements—notably boron, arsenic, ammonia, and mercury—which, if discharged into streams or rivers, can contaminate downstream waters used for farming, fisheries, or drinking. This hazard has been emphasized by Axtmann (p. 1323), Rothbaum and Anderton (p. 1417), and by Andersen (p. 1317) who quotes actual concentrations of boron and permissible concentrations for various crops. Although not strictly "poisonous," high-salinity bore waters can also be harmful. A few suggested solutions are: reinjection; disposal into the sea (if not too remote) through ducts and channels; using evaporator ponds, as in Cerro Prieto (see Mercado, p. 1385); and storing the water during the dry season with subsequent release into rivers in spate during the wet season. Rothbaum and Anderton (p. 1417) propose to remove the arsenic simultaneously with the silica by preoxidizing it to the pentavalent state and subsequently dosing it with slaked lime. They also mention other possible chemical remedies.

Airborne Poisons

From ejector exhausts, from the upward effluents from cooling towers, from silencers, drains and traps, from discharging bores under test, from "wild" bores, and also from control vent-valves, various harmful elements sometimes escape into the air at geothermal exploitation sites. These can include H_2S (see above), mercury, and arsenic compounds and radioactive elements. Certain quantities of noxious, though not poisonous, emissions such as rock dust and silica-laden spray (see below) may also be airborne. Mercado (p. 1385) mentions that during the initial development and cleaning of bores, the vertical discharge of fluids can foul the power plant and neighboring agricultural lands with salt. Horizontal well discharge in a controlled direction is being considered as a solution to this problem. Authors in general have not alluded much to airborne poisons other than H_2S, but other toxicants are seldom of serious proportions. Nevertheless, systematic monitoring is advisable to keep a careful watch on possible future dangers.

Noise

The noise of escaping steam at high pressure can be very distressing to the ears, and workers on new wellhead sites have to wear ear plugs or muffs lest their hearing be damaged. Even after exploitation, when the bore steam normally flows fairly silently through insulated pipes to the plant, there will often be fluids escaping noisily to waste through any of the following paths: (1) newly commissioned bores or other bores undergoing test; (2) "wild" bores—fortunately rare occurrences; (3) pressurized hot water in wet fields discharged to waste and flashing in the process; (4) small quantities of steam vented to waste in order to control pressures and flows; (5) large quantities of steam vented to waste when a plant is shut down either inadvertently or for maintenance.

The last three of these noise sources can be greatly mitigated by means of effective mufflers which destroy the kinetic energy of the discharging fluids, reduce the volume of noise and deflect it skywards, and (more important) lower the pitch to a frequency level less painful to the ears. At the Wairakei Hotel, situated only a few hundred meters from some of the bores and vent valves, the noise—mostly from (3)—resembles that of a waterfall and has, it is sometimes claimed, a soporific rather than a distressing effect. The first two sources of noise are virtually incurable except by erecting temporary sound barriers, and can be mitigated only by reducing blowing times to practical minima and taking all possible precautions against the appearance of "wild" bores. The third source of noise could sometimes be overcome by reinjection. Drilling operations can also be noisy, but they do not persist for very long.

Reference to noise and its reduction is made by Mercado (p. 1394), Reed and Campbell (p. 1399), Swanberg (p. 1435), Jhaveri (p. 1375), and Andersen (p. 1317). Jhaveri and Andersen give details of comparative noise levels. Jhaveri extends his study to include vibrations and Andersen includes a study of the effects of noise upon animals.

Noise in and near power-plant buildings also occurs from machinery. This is difficult to control and is generally no worse than in conventional power plants. Control rooms and offices can be soundproofed. Legislative action against harmful noise levels has been taken in the USA and other countries, and though strict enforcement may sometimes be difficult, these laws should act as a powerful incentive to designers to overcome the nuisance.

Heat Pollution

The necessary adoption of moderate temperatures for geothermal power production results in low generating efficiencies and the emission of huge quantities of waste heat. Where cooling towers are used, this waste heat escapes into the atmosphere and into the surplus condensate; where direct river cooling is adopted, it is mostly spent in raising the temperature of the river water. In wet fields, another enormous source of heat waste can arise from the reinjection of very hot unwanted bore water into rivers and streams (as at Wairakei) or into storage ponds and thence into the atmosphere (as at Cerro Prieto). One possible way of reducing this heat waste may be the reinjection of the surplus cooling-tower water and rejected bore water into the ground. Other possible ways are to generate additional power by means of binary cycles or to establish dual or multipurpose plants which usefully extract low-grade heat from the turbine exhausts or from rejected bore waters. Where none of these practices are adopted, as at Wairakei, huge quantities of heat may be dissipated into rivers, with consequent hazards to fisheries and perhaps with encouragement to the growth of unwanted water-weeds. At Wairakei, the normal river flow is fortunately sufficiently high to dilute the hot and warm wastes so that the average river temperature rise, after complete mixing has been effected, is limited to about 1.5°C. Although there is a high local degree of heating near the point of hot-water discharge, the danger zone is confined to a comparatively small area which the fish learn to avoid.

At times of low river flows, however, temperature rises of up to 6°C may occur. Fish kills have been reported and trout hatching appears to have suffered, though it is possible this has been partly due to other influences such as H_2S. At Cerro Prieto, waste heat is dissipated in a large evaporation pond (Mercado, p. 1385).

The ill effects of heat pollution have been stressed by Swanberg (p. 1435). In the discussion, Armstead deplored the discharge of huge quantities of very hot water into rivers, as an unnecessary and "criminal" waste of heat in an energy-hungry world. Reinjection, he said, could perhaps be the answer. But alternatively, it should be possible to find a profitable market for vast quantities of free (or at least very cheap) heat. If medium-grade heat is copious enough it should always pay to ship the raw materials and labor required for an energy-intensive industry to remote sites where very cheap energy is available, even across national frontiers, and to transport the end products to the markets. The aluminum industry has proved this to be so. Moreover, the transportation of hot water (though not steam) was economic over considerable distances, as had been proved in Sweden.

Swanberg (p. 1435) also suggests that the escape of heat and moisture from cooling towers may affect local climate (to a greater extent than with highly efficient fuel-fired plants), particularly in the matter of forming fog and ice. On the other hand, he admits that the increased atmospheric humidity could sometimes have a beneficial effect.

Silica

One of the most troublesome products of wet geothermal fields is the silica content of the bore water, often in saturated solution at depth. With the temperature reductions as flashing occurs in the bores and in subsequent stages of exploitation, the silica will either precipitate immediately, or it will remain for a limited time in a state of supersaturation, according to the form and conditions in which it occurs. Axtmann (p. 1323) mentions that the chemistry and physical behavior of silica is not yet fully understood. Although silica precipitation on bore casing and in wellhead equipment is not unknown, usually it is delayed by supersaturation and comes out in discharge ducts. At Wairakei, for example, much effort and expenditure (about $26 000/yr according to Mahon) has to be spent in cleaning the silica deposits from the open bore water discharge channel from the field to the river. Mercado (p. 1385) reports that at Cerro Prieto, waste bore waters are ducted to a large evaporation/settlement pond (pending the construction of a new canal to lead the waste fluids to the large Laguna Salada, or perhaps to the Sea of Cortez), and that precipitation in the ducts to the pond is not excessive. In district heating installations, however, where the bore water remains contained for a long time within pipes and heat exchangers, silica scaling can become a serious problem, especially on galvanized surfaces, as described by Thorhallsson et al. (p. 1445). Dilution with colder fresh water has proved to be beneficial in such cases, as a less troublesome alternative to frequent cleaning with wire brushes.

The fear of subterranean silica precipitation has often acted as a deterrent to reinjection (see below), and this has been stressed by Cuellar (p. 1337). Axtmann (p. 1323) mentions the possibility of passing supersaturated silica solutions through a sand-filled fluidized bed heat exchanger, in which the fall in temperature, in combination with sand nucleation centers, should effectively precipitate and remove the silica; while Rothbaum and Anderton (p. 1417) describe a pilot plant for treating supersaturated silica solutions with slaked lime to produce useful calcium silicates. Both these proposals could perhaps effectively remove the silica from the bore water before reinjection. The Rothbaum and Anderton proposal could simultaneously remove any arsenic that might be present (see above). The resulting calcium silicates may be dried with geothermal heat and used for building materials, insulants, ceramics, and perhaps for pretreating soils. Axtell, in the discussion, asked how much enthalpy would be lost by the treatment advocated by Rothbaum and Anderton (p. 1417). Mahon, on behalf of the authors, said that a 9 and an 8°C temperature drop had been observed at Wairakei and Broadlands respectively. The use of settlement ponds, as at Cerro Prieto, can be a partial solution to the problem of precipitating silica by aging before reinjection.

Cuéllar (p. 1337) discusses the chemistry and behavior of silica and describes certain tests performed at Ahuachapán in order to ascertain the best method of waste-water disposal. It has been demonstrated that reinjection at or above 150°C can be effected without any silica deposition in the reinjection bore or in the underground fissures, but for lower temperatures encrustation will occur after a lapse of time as the water cools. This means that water separated at the wellheads at more than 150°C would have to be carried to the reinjection points through insulated pipes, or if open channels were used, periodic cleaning would be necessary. Also, if lower temperature water is rejected, silica will be precipitated in the pipes or ducts by which such water is removed. It has been found that a retention pond of adequate capacity effectively removes much of the silica by encouraging polymerization so that deposition in channels or pipes after retention would be reduced if not entirely eliminated. Further tests are to be done to study the effects of silica on reinjection at lower temperatures after retention; but it is understood that nevertheless it has been decided to construct a 70-km open channel to the sea, capable of carrying at least 1 m^3/sec by gravity.

Another nuisance from silica can be caused by the deposition of fine spray from blowing bores or field silencers on automobile windshields or windows of nearby buildings. Unless quickly wiped off, the deposit becomes very hard and difficult to remove. Spray from the same source can also kill local vegetation. Timber was thus destroyed at Wairakei, and problems arose in El Salvador from this cause, where the bores are sited among coffee plantations. Damage of this sort is usually confined to relatively small areas and must be accepted as inevitable. The payment of compensation to landowners may sometimes be necessary but this should form a negligible fraction of the production costs.

Subsidence

The withdrawal of large quantities of subterranean water from a wet field can cause substantial ground subsidence. This can cause tilting and stressing of pipelines and surface structures, and perhaps could lead to serious damage or even disaster, though large local differential movements are fortunately rare. Stilwell, Hall, and Tawhai (p. 1427) mention vertical movements having been observed of up to 4.5 m in 10 years at Wairakei and 6 m since 1962. In addition, horizontal movements of up to 0.225 m have been detected in 8 years, these movements being towards the area of maximum subsidence, which does not necessarily coincide with the area of maximum fluid discharge. Damage at Wairakei has been confined to fractures in the main bore water drainage channel. The power plant itself is fortunately sited well away from the area of maximum subsidence. Dry fields appear to be immune from this trouble (except for tectonic subsidence).

Where wet fields are exploited it is important at the very outset to establish an accurate reference grid of bench-marks and triangulation, extending well into undisturbed areas, so that all ground movements within the exploited area may be carefully monitored. Swanberg (p. 1435) states that as an alternative check to direct mensuration, gravity surveys offer an approximate indication of water-depleted zones. He also mentions that extensometers are being used in the Imperial Valley, California, to differentiate between deep-seated and shallow movements arising from aquifer depletion and ground-water pumping respectively. Stilwell, Hall, and Tawhai (p. 1427) say that the introduction of extensometers in New Zealand is proposed in order to detect rock strains. In the discussion, Dominguez asked Stilwell whether distinction could be made in wet fields between tectonic and water-removal subsidence; but the speaker said this was not yet possible.

One theoretical remedy to ground movement, proposed by Swanberg (p. 1435), would be to install downhole heat exchangers instead of extracting the natural thermal fluids. This would seem to pose underground circulation problems, and in any case an economic solution is not easily foreseen. Another more obvious remedy would be to recharge the field, partly by reinjecting the thermal water after flashing, and partly by means of supplementary water to make good the deficit lost in steam. It has been observed that a discharging field (for example, Broadlands, New Zealand) after "resting" will "rebound" to a large extent as a result of natural recharge, so that this method would almost certainly be effective. In a built-up area it could well be mandatory. In the discussion, Barnea asked Stilwell whether the New Zealand authorities had been deterred from reinjection by the hope that the field would ultimately yield dry steam. The speaker replied that owing to conflicting opinions as to the efficacy of reinjection there had been reluctance to risk spoiling the performance of the field.

Seismicity

Fears have sometimes been expressed that prolonged geothermal exploitation could trigger earthquakes, especially if reinjection is practiced in zones of high shear stress where fairly large temperature differentials could occur. These fears arise because all existing geothermal exploitations are in naturally seismic areas, and it could be that any interference with nature could precipitate seismic shocks. Swanberg (p. 1435) cites examples in Colorado where fairly big shocks have been induced by the reinjection of waste fluids. Conversely, he says, withdrawal of fluids from an aquifer is likely to have the reverse effect of reducing seismic activity. Cameli and Carabelli (p. 1329) report a controlled experiment, performed in Italy over a period of 40 days of reinjection, in which careful seismic and microseismic measurements were taken before and during reinjection. No effects were observed.

Ridley and Taylor (p. 1411) give warning that the extraction of heat from artificially fractured hot rocks by injecting cold water could well cause seismic activity. On the other hand, the main purport of their paper is conversely orientated; that is to say, it stresses the dangers of natural seismicity to geothermal installations and warns that detailed seismic studies should always precede exploitation and that all possible precautions should be taken for the protection of plant, pipelines, and other surface equipment.

Reinjection (see below) is a comparatively new practice which seems likely to become more widespread, and further experience on this potentially important matter is likely to be gained. Looking to the more remote future when vast quantities of deep-seated heat will probably be exploited by new techniques, it is possible that the risks of seismic effects could become more serious. Incredibly large quantities of heat could be won by cooling the planet through a miniscule average temperature drop. But the tiniest average temperature drop could be achieved only by fairly large local temperature drops at the points of exploitation; and this could give rise to high local stresses, perhaps with unfortunate seismic results. Although this is a long-term problem, it should be carefully studied well in advance.

Escaping Steam

As already mentioned above, the escape of moisture from cooling towers could sometimes cause fog. Of more serious impact can be the huge volumes of flash steam escaping from hot bore water rejected from silencers and from flow control vent valves, as at Wairakei. Dense fogs can result from these discharges, which may drift across nearby roads and cause traffic hazards. Traffic warning signs and diversionary routes can of course mitigate the trouble, but the best palliative is to use the hot bore water productively or to reinject it into the ground. A similar problem arises where bores, newly opened or under test, have to be blown directly into the atmosphere. This is unavoidable at times, but in a well-exploited field the proportion of openly discharging bores will be small and the hazard not serious.

Scenery Spoliation

Thermal areas often occur in natural beauty spots, highly valued by the local population and frequented by tourists. Conservationists may sometimes oppose geothermal development on the grounds that scenic amenities are thereby destroyed. This could be an exaggeration, though it is true that man-made engineering works can seldom compete with natural scenic beauty. Certainly the power plants at The Geysers, California, have been most tastefully camouflaged. The pipelines have been colored to blend in with the background; scarcely a puff of steam is visible; the power plants are inconspicuous; and the dry climate quickly absorbs the plumes of vapor rising from the cooling towers. In New Zealand, where the scarred ground surface has been rehabilitated by careful "landscaping" and damaged trees have been removed so that only the healthy forest is visible, visitors flock to see the geothermal development in greater numbers than those who frequented the area before exploitation. In fact, the Wairakei scene can claim a certain majesty of its own. Even the billowing steam from the wellhead silencers—itself a form of "pollution"—contributes an aesthetic quality.

It is true that geothermal development can interfere with natural surface thermal manifestations. In New Zealand, for instance, the activity of the geysers and hot springs in the once-famous Geyser Valley (close to Wairakei) has virtually ceased. The question of scenic amenities is one that can only be judged subjectively on a balance of considerations, by weighing the value of energy against that of tourist attractions and national heritage. This judgment must be an emotional one and cannot be strictly quantitative. The declaration of an area such as Yellowstone Park, as a zone of outstanding beauty and interest, not to be exploited for energy development, would be a value judgment: there can be no absolute standards in such matters. However, it is only fair to say that a geothermal power plant which produces no smoke, has no unsightly chimney stacks, no ungainly coal- or ash-handling equipment, no coal storage yards or oil storage tanks, and no boiler house can be far more pleasing to the eye than a fuel-fired plant of the same capacity. For similar reasons, industrial establishments using geothermal heat are likely to be far less obtrusive than those that rely upon fuels. On balance, it may justly be claimed that geothermal exploitation is far less a cause of scenery spoliation than fuel combustion, and we must have electricity and industry.

This question has briefly been referred to by Swanberg (p. 1435), whose comments are generally in conformity with what has been said here.

Ecology

There remains one other aspect of the environment that could perhaps be disturbed by geothermal development, though it has scarcely been mentioned by the authors apart from a passing reference by Mercado (p. 1385) and an implication by Andersen (p. 1317). That aspect is the ecological balance of local flora and fauna. This has been the subject of study in New Zealand, and no doubt elsewhere. The discharge of chemicals into the air, streams, and rivers and thence into the ground water, small but appreciable changes of local temperature and humidity, noise, and a degree of deforestation: all those factors could, and probably do, disturb the natural balance of nature prevailing before exploitation. Protectors of wildlife and of fisheries would do well to encourage more intensive research in this direction.

REINJECTION

Reinjection of fluids into the ground has been repeatedly mentioned, either as a proposal for overcoming some particular pollution problem, or as a practice already being adopted. There can be little doubt that the successful reinjection of cooling tower effluents and of rejected bore waters could provide answers to several of the problems discussed. This fact has been recognized for many years, but there was a timidity of approach towards reinjection. Would the introduction of cooler waters into the permeable substrata interfere with the useful output of heat from the producing wells? Would excessive power be absorbed in forcing the unwanted fluids into the permeable substrata? Would the underground permeability be destroyed by chemical deposition? Would reinjected waters outcrop elsewhere, thus simply transferring the pollution problem from one place to another? Would reinjection trigger seismic shocks?

At the UN Geothermal Symposium at Pisa in 1970, reinjection was mooted as a subject worthy of study. By 1975 quite a valuable amount of empirical data had been gained. The "pros" and the "cons" of reinjection cannot yet be established beyond all doubt, but practical experience now offers promising evidence that reinjection could often be an excellent solution to environmental problems, though clearly there may be occasions where local conditions would render it impractical—at least without prior chemical treatment or settling facilities.

Einarsson, Vides, and Cuéllar (p. 1349) describe successful experiments performed in 1970 and 1971 at the Ahuachapán field in El Salvador, where the most serious environmental problem was how to dispose of bore water from a wet field containing boron. These waters could not be discharged into riverbeds without contaminating downstream farming and drinking water supplies. During the experiment, 2 million m^3 of water at 153°C were reinjected into a bore 952 m deep at rates of up to 164 l/sec without recourse to pumping (the substrata being very permeable), simply by making use of gravity and vapor pressure. No scaling problems were observed, nor was any significant interference detected (by means of tracers) between the reinjected water and the producing bores or ground-water wells. The author recommends that reinjection bores should be about 1.5 km or more from producing bores—at least for Ahuachapán conditions. The total cost of reinjection at this site has been estimated by Einarsson at about 1 US mill/kWh. In view of the success of this experiment, it is not clear why the 70-km open channel to the sea, referred to by Cuéllar (p. 1337), is considered necessary unless large quantities of cooler bore water have to be disposed of. In any case, it would seem wise to await the outcome of the reinjection tests after retention before embarking on the construction of this costly channel which is understood to cost about $10 million, representing $333/kW if borne fully by the first 30-MW installation and $50/kW even if the field were ultimately developed to 200-MW capacity. Moreover, since Ahuachapán is situated 800 m above sea level, it seems that an opportunity has been missed—that of generating 5 or 6 MW of base-load hydro power, or considerably more peak load if storage with or without pumping were also used.

Kubota and Aosaki (p. 1379) describe how 8 million tons of hot bore water have been reinjected into the aquifer at Otake since March 1972, through three injection wells. The present rate of reinjection is about 400 t/hr. The reason for doing this is to avoid thermal and chemical pollution. The distances of the reinjection wells from the nearest production bores range from 150 to 800 m. No fall in temperature or in output of the producing wells has been observed, no contamination of the ground water has been detected, and no seismic effects have been noticed. On the other hand, the authors claim that the performance of the producing wells has improved. The station output, which declined from 11 to 8.7 MW before reinjection was initiated, has since recovered to 10 MW. The only adverse occurrence has been the deposition of silica on the walls of the reinjection wells (and perhaps in the subterranean fissures) which has reduced the disposal capacity of these wells.

Gringarten and Sauty (p. 1370) refer to the exploitation in France of normal temperature gradients for space heating, as described by Coulbois and Herault (p. 2099) and as mentioned in the Rapporteur's report on Section IX. Surface disposal of the thermal waters after use is precluded because of chemical and heat pollution. Reinjection overcomes these problems and at the same time enables subterranean pressures to be maintained and ground subsidence to be limited; it also provides a means of recharge of both water and heat. Nevertheless, since heat is continually being removed from the aquifer, exhaustion of the exploited zone must ultimately occur, and care must be taken so to space the reinjection and production wells as to give a maximum useful life to the zone. The authors examine the problem mathematically, under certain assumed properties of the aquifer, and deduce a series of curves showing the number of years taken for the reinjected water to reach the production bores by different streamline paths for assumed well spacing, and the expected rate of temperature decline in terms of time.

Chasteen (p. 1335) reports on reinjection experience in three American fields. (There are discrepancies between the figures quoted in his summary and in his paper. Here the paper is assumed to be correct.) The author states that the purposes of reinjection are partly to recover rock heat and partly to dispose of unwanted bore waters or surplus condensate in a manner that avoids polluting surface water courses. Reinjection has been and is being practiced at The Geysers and Imperial Valley, California, and also at Valles Caldera, New Mexico. At the vapor-dominated field of The Geysers, 4.2×10^9 US gal of liquid have been reinjected since 1969. With the present plant installation of about 500 MW, 4.7 million US gal are being injected daily. The liquid contains some ammonia, boron, and some suspended solids. The flow is held up for a short time in concrete settling tanks with wooden baffles for the precipitation of the insolubles, and the fluid is then distributed to six reinjection bores, and is deaerated before entering them so as to avoid casing corrosion. The flow is metered. The wells used were originally steam producers. Slotted liners are provided where the reinjected fluid passes through the injection zone so as to prevent wall collapse when wet. The liquid descends the bores by gravity without pumping. Reinjection bores are placed as far as possible from and are sunk deeper than the production bores (to 5380 ft). In five years no interference has yet been detected between the two classes of bore. Some difficulty was experienced with declining injectivity due to the clogging of the fractured zone with elemental sulfur, but this was simply overcome by shutting in the bore and allowing the temperature to rise. As sulfur melts at 238°F and the reservoir temperature is 475°F, this soon removed the obstruction. Seismicity and subsidence effects are constantly being monitored but none have been observed. At Valles Caldera and in the Imperial Valley, both of which are liquid-dominated fields, 100 million U.S. gal have been reinjected during more than a year of testing in the former case, and 126 million U.S. gal in one year (1964/65) in the latter case. In the Imperial Valley, the pressure of a static well was about 200 psig. This at first had to be overcome by pumping, but after a while, the column of cooler liquid enabled gravity to take charge. Reinjection at the Imperial Valley has been at a rate of 600 US gal/min. No loss of injectivity or reservoir response has been observed at either of these fields.

Reinjection is understood also to have been successfully practiced at Larderello. In no case of practiced reinjection has pumping been necessary except initially in the Imperial Valley, as reported above. The case for reinjection cannot perhaps yet be regarded as fully proven, but there is much promising evidence in its favor. Silica would seem to be the commonest obstacle: it could mean that the life of reinjection bores could be uneconomically short, or even that underground permeability could be destroyed. Chemical treatment—preferably on a profitable basis, as proposed by Rothbaum and Anderton (p. 1417)—or settling ponds and filtration could cure or at least mitigate this problem. Of the other doubts expressed earlier in this section, the most important is the avoidance of short-circuiting between the reinjection points and the production bores. Clearly, reinjection close to the producing horizons of service bores would sooner or later cause a drop in temperature of the bore fluid (though experience in Otake has been encouraging in this respect). On the other hand, reinjection at a strategic distance from the producing bores could well increase the field life by imposing a warm barrier against the ingress of cold waters from outside the field. Again, reinjection at great depth could perhaps displace deep thermal waters upwards, thus "sweeping" the aquifer of most of its original hot-water content, at the same time extracting heat from the hot rock up through which the reinjected water must flow. In short, while reinjection could have its dangers, it could also prove to be a valuable tool for good field management by recycling both water and heat. More extended experience is needed before proper judgment can be given.

OTHER ASPECTS

Axtmann (p. 1323) rightly points out that when comparing the environmental effects of geothermal development with those of other forms of energy exploitation, account should be taken of all related activities. Thus when comparing a geothermal power plant with a nuclear plant of the same useful capacity, the environmental effects of uranium mining, fuel enrichment and reprocessing, and radioactive waste disposal should all be considered in addition to the actual power plant. Geothermal plants, having no such remotely situated sister activities, then appear at a relative advantage. However, the author goes on to point out that when assessing the polluting aspects of a geothermal installation, we should not only consider normal operating conditions, but also those during drilling, well testing, maintenance, shutdown, and the occurrence of "wild" bores, when pollution may be far worse.

Swanberg (p. 1435) states that high-enthalpy fields are generally less polluting than low-enthalpy fields. This distinction could perhaps have been better expressed as between dry and wet fields. Land subsidence, silica, heat pollution of rivers, and waterborne poisons are generally features of wet fields which, by comparison with dry fields, are of relatively low enthalpy.

Most of the authors stress the importance of monitoring—both before and after exploitation—so that a careful watch may be kept on incremental pollution and distinction made between natural and man-made pollution, and between geothermal disturbances and those arising from other human activities such as ground-water pumping. This need for monitoring applies to all of the 13 possible sources of pollution listed above except scenery spoliation, which cannot be "measured." In the discussion, Bradbury asked Axtmann whether he could quote costs for monitoring trace elements. The speaker said he could not quote actual figures but that it was less than for nuclear plants.

Several authors mention that unexploited natural thermal areas are often highly polluting; and in the discussion, Barnea suggested that this was worthy of study so that the ill effects of man-made geothermal development could be kept in proper perspective.

Certain rare trace elements can be not only a possible source of pollution but also a potential source of wealth; and in removing "poisons," valuable materials may simultaneously be won. Mercado (p. 1385) talks of the possibility of ultimately recovering chlorides of potassium and lithium from waste water. In the discussion, Barnea suggested that a total analysis be made at all developed fields with a view to studying multipurpose plants.

CONCLUSION

Since the 1960s there has been a change of mood toward the environmental aspects of geothermal development from one of unreasoning optimism to one of sober realism. Gone is the pious belief that geothermal exploitation is entirely "clean" and does not infect the environment. Nevertheless, despite a keener awareness of the dangers, there is now a well-justified belief that geothermal development is far less culpable than fuel combustion of fouling the human nest, and that an antidote can be found to almost every source of geothermal pollution. Timely legislation in certain countries has enforced attention to this very important matter even though it could have been less drastic in its pace of enforcement. The advances made in environmental studies during the last five years have been impressive, and the good work is expected to continue.