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See table of contents

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Article abstract

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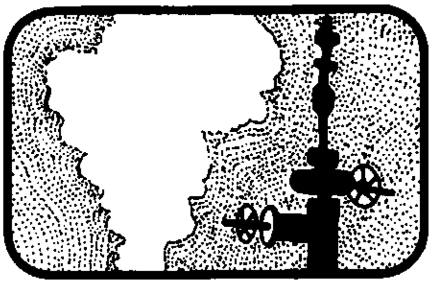

Geothermal Energy in Canada

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SUMMARY

Research in the period 1974 to 1986 showed that geothermal energy is found in a wide variety of geological settings, and that it is plentiful in Canada. Low-temperature mine water and heat pumps are being used successfully in Springhill, Nova Scotia, and have been used at Carleton University in Ottawa. Elsewhere resources of higher temperature have been demonstrated but they have not yet been used, mainly for economic reasons. As economic factors change geothermal energy will be one of the major resources to be drawn on.

RÉSUMÉ

Des recherches menées entre 1974 et 1986 ont montré qu'on trouve au Canada de grandes quantités d'énergie géothermale et que celles-ci sont situées dans des milieux géologiques très variés. Présentement, des pompes de chaleur sont utilisées avec succès et on réussi à extraire de l'énergie dans des eaux de mine de températures basses à Springhill en Nouvelle-Écosse. Ce même procédé a également été utilisé à l'Université de Carleton à Ottawa. Ailleurs au pays, des sources d'énergie thermique de hautes températures ont été localisées, mais elles n'ont pas encore été mises en valeur pour des raisons économiques. Au fur et à mesure que les conditions économiques changeront, l'énergie géothermique deviendra l'une de nos sources importantes d'énergie.

INTRODUCTION

Geothermal energy comes from the Earth in the form of heat. It has long been used for human industry, recreation and comfort in many parts of the world, particularly where its presence is obvious. The Earth's heat is a combination of the original heat resulting from formation and layering of the Earth and of the heat generated since formation by the decay of radioactive isotopes. Both of these depend on the finite amount of energy associated with the formation and original content of the Earth, and so this is not, in principle, a renewable energy resource. However, the total heat of the Earth is so great that it may be regarded, for human practical and economic purposes, as renewable. On the scale of human development and technology and of individual geothermal systems the resource is finite and renewable only at a limited rate.

Heat energy needs a carrier. In geothermal exploitation the carrier is normally the water in the ground that has collected and concentrated the heat in reservoirs. The exception to this is found in the use of hot dry rock, where water must be introduced artificially. Since the temperature of the solid Earth rises with increasing depth, geothermal energy is present below the entire surface of the continents. However, the mechanisms and economics of extraction mean that most of the Earth's energy is not useful. Conditions for use are governed by the geological setting, the physical nature, the available extraction technology and the cost compared with other energy forms. Of these, the first two are constant for any particular reservoir, the available technology improves with time, but economic conditions fluctuate. Research and exploration of geothermal energy thus focuses on the first three conditions. Exploitation depends on the level of knowledge of these three conditions and the economic conditions of the time. A more detailed description of geothermal resources and their uses may be found in Jessop (1990).

The International Geothermal Association holds a World Geothermal Congress at intervals of five years. The last was in Florence, Italy in 1995. No representatives of Canadian governments or industry were present. The proceedings of the conference include "Country Updates" and a wide variety of papers that give a summary of the current status of geothermal development (International Geothermal Association, 1995). Recent brief reviews of geothermal energy also appear in *Geotimes* (*e.g.*, Browne, 1997). The 1997 review indicated that the installed electricity generating capacity for 21 countries totals almost 7000 megawatts, not including more than 9000 megawatts of geothermal heat energy being used directly worldwide (Browne, 1997, p. 37).

TYPES OF GEOTHERMAL RESOURCES

Geothermal resources are found in various forms. Each form presents its own problems of exploitation and its own opportunities for use. The physical nature provides a division into steam, water and hot dry rock resources, and the technology of extraction divides the water resources by temperature, according to the suitability for electrical generation, direct heat use or conversion by heat pumps.

Geological setting, including the geomorphological character of the surface, may affect the ease and economic feasibility of development. Human factors, such as population density, affect the potential uses and economic situation. However, in order to describe the nature of geothermal resources the most suitable classification is by physical nature.

Geothermal reservoirs consist of water or steam trapped in porous rock. Where liquid water is above 100°C, boiling is prevented by confining pressure of impervious cap-rocks.

Dry-steam Resources

Dry-steam reservoirs, or "vapor-dominated reservoirs," consist of steam trapped in porous rocks, and covered by impermeable cap-rocks. The steam usually overlies a hot-water reservoir, with which it is in dynamic equilibrium. The temperature and pressure of dry-steam reservoirs is controlled by an enthalpy maximum of saturated steam. Maximum enthalpy occurs at a temperature of about 235°C and a pressure of about 3 MPa, and all dry-steam reservoirs have this temperature and pressure unless they contain significant quantities of contaminant gas. Either higher or lower pressure results in slight superheating, so that the reservoir is stable. At any lower temperature an increase in pressure would cause condensation (Jessop, fig. 77, p. 215, 1990). Since a hydrostatic pressure of 3 MPa implies a hydraulic depth of only about 300 m, these reservoirs are usually found within the upper 1000 m of the Earth's crust. Production wells are thus relatively short, but the difficulties and hazards of drilling into dry-steam reservoirs are great.

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A well drilled into a dry-steam reservoir normally produces a flow of steam with some contaminant gas, but with very little contaminating dissolved solid. Any grains of solid material carried in the fluid stream are removed by filters and the steam is then fed directly to turbines for the generation of electrical power. The best-known examples of exploited dry-steam systems are at Larderello, Italy (Fig.1), and The Geysers, California, USA (Fig.2). The installed generating capacity at Larderello is 460 MW, and production in 1994 was at an average rate of 292 MW (Allegrini *et al.*, 1995). At The Geysers the total generating capacity installed is 1989 MW, but some of the early plants have been closed and others are not able to maintain their rated capacity, mainly because of pressure decline in the reservoir. Production in 1993 was at the rate of 1193 MW (DiPippio, 1995). Dry-steam reservoirs are generally the cleanest and most efficiently converted of geothermal resources. Unfortunately, they are comparatively rare. They are found only in zones of active volcanism or recent tectonic disturbance. They depend on the convenient proximity of a confined aquifer to a hydrothermal circulating system and a high-temperature heat source.

Hot-water Resources

Hot-water resources, or "fluid-dominated reservoirs," are much more common than dry-steam reservoirs. The water in these reservoirs is at a high temperature, and pressure drop in a well will permit the water to evaporate partly to a mixture of saturated steam and water. In theory, any reservoir at a temperature above 100°C will produce steam, but in practice a reservoir must be above about 180°C for the steam to be economically useful for direct use in turbines. This technological limitation imposes a lower limit on the definition of hot-water resources, by association with electrical power generation through steam turbines.

There is no upper limit, but most reservoirs exploited to date are in the range 180°C to 300°C. Temperatures as high as 340°C have been recorded at Cerro Prieto, Mexico, (Banwell and Valle, 1970) where the installed generating capacity in 1995 was 698 MW (Quijano-Leon and Negrin, 1995). Such high temperatures depend on high pressures to prevent the formation of a dry-steam zone. Hot-water reservoirs may be found at any depth that is great enough or beneath any cap-rock impervious enough to provide the confining pressure required to prevent boiling. Temperature and pressure may be substantially higher than in a dry-steam reservoir, since the stability of the reservoir is not controlled by the maximum specific enthalpy on the boiling curve. This is best understood by reference to the pressure-enthalpy diagram for water (Jessop, 1990).

Figure 3 shows the well field at Wairakei, New Zealand, with steam-water separators and collector pipes.

Warm-water Resources

Warm-water reservoirs differ from hot-water reservoirs only in temperature and economic utility. This category is usually taken to include temperatures from about 50°C to about 180°C. These boundaries are set by considerations of use and have no physical significance. The upper limit is set by the lower limit of direct steam supply to turbines for electrical generation. The lower limit is determined by the application of the heat, and in space-heat-

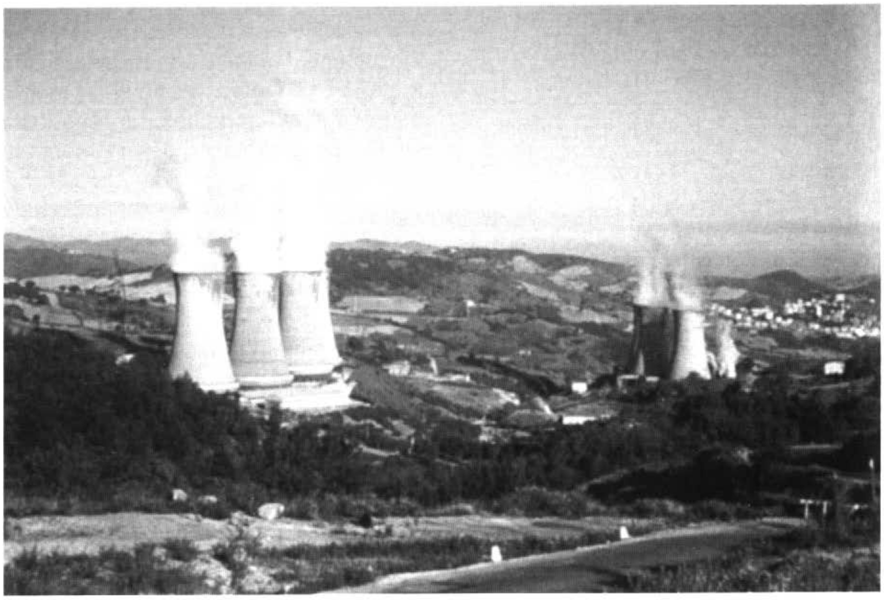

Figure 1 The cooling towers of the geothermal power stations of Larderello, Italy, where electrical power is generated from a dry-steam geothermal resource.

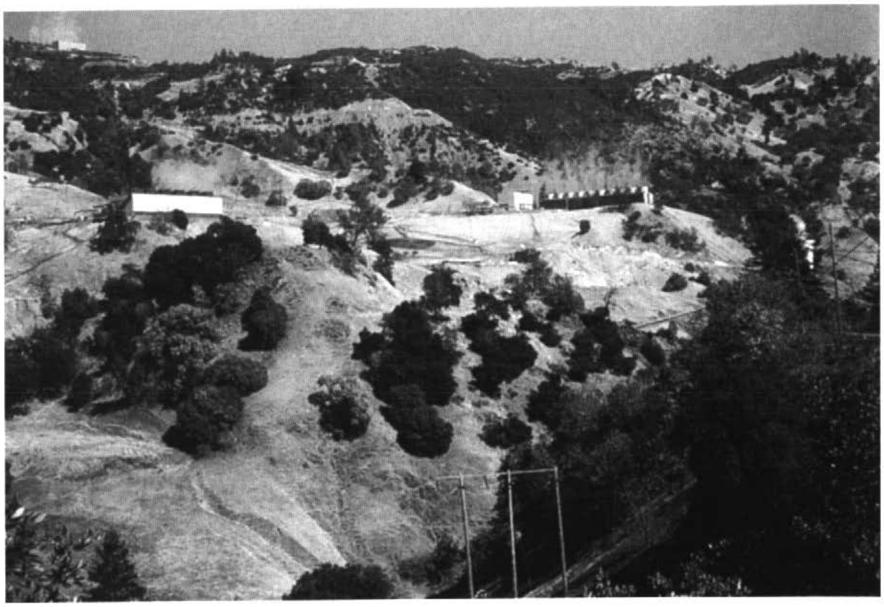

Figure 2 Three of the approximately 20 power units of The Geysers, California, USA, where electrical power is generated from a dry-steam resource.

ing this is often set by the temperature at which the use of heat pumps is needed for economic utilization.

Warm-water reservoirs are found in volcanic areas, but the most extensive reservoirs are located in the large sedimentary basins. Aquifers are found in porous sedimentary formations, of thickness of tens of metres and lateral extent of hundreds of kilometres, to depths of several kilometres. In areas of normal geothermal gradient of 20 mK·m^{-1} to 30 mK·m^{-1} (equivalent to °C·km^{-1}), these aquifers may contain water at temperatures up to 150°C or more.

Warm-water reservoirs of volcanic origin have been used extensively in Iceland, where 85% of space-heating is derived from geothermal resources (Ragnarsson, 1995). Reservoirs in sedimentary basins have been used in France, where about 200,000 housing units are heated by geothermal energy (Demange *et al.*, 1995). Figure 4 shows a group of apartment buildings in Paris and the two wells that connect with the reservoir, one for production and one for reinjection.

Figure 3 The well field at Wairakei, New Zealand, where wells have been drilled into a hot-water reservoir. The two-phase mixture is separated into its components in the separators, the small cylindrical objects. The large cylinders are noise mufflers for waste discharge.

Figure 4 Apartment blocks in Paris, France, and the associated geothermal wells. Water is produced at about 50°C to 60°C from one well, and is taken by pipe to a heat-exchanger and heat-pump system. After use, the cooled water is returned to the reservoir by the other well. The wells are directionally drilled, so that they are about 1 km apart where they intersect the reservoir.

Low-temperature Resources

The lower limit of useful temperature of a reservoir is set only by economic utility. There is no clear dividing line between systems that are generally accepted as geothermal and systems using heat pumps to extract heat from water in surficial unconsolidated material. Shallow ground water is commonly available, and may be present to depths of several hundred metres in deep valleys or areas of sedimentary accumulation.

Water in flooded coal mines has been used as a heat source in Springhill, Nova Scotia, one of the first developments of this kind anywhere in the world (Jessop *et al.,* 1995). Water at about 18°C is pumped from the mine workings and used with heat pumps to heat industrial buildings. The flooded mine workings are extensive, and the temperature of the water suggests that there is circulation within the mine. Further, some applications return more heat to the mines in summer than they extract in winter, so that the heat reservoir may last for hundreds of years (Jessop *et al.,* 1995).

Hot Dry Rock

Hot dry rock is solid rock at an unusually high temperature, but without the water needed to create a geothermal reservoir. Since heat requires a carrier in order to bring it to the surface, an artificial circulating system for water must be created. The source of the heat may be either a solidified magmatic intrusive that is sufficiently young to retain some of its initial heat, or a rock that is sufficiently high in radioactive potassium and trace-elements to generate its own heat. To provide a hot dry rock resource a magmatic intrusive must be younger than about ten million years, depending on its dimensions, and it may still have associated hydrothermal systems beyond its edges. A radioactive rock must be of substantial size and depth in order to produce the high geothermal gradient needed for hot dry rock exploitation. The levels of radioactivity required are three orders of magnitude lower than those of rocks considered to be of ore grade and the heat-producing isotopes are not mobile. Thus hot dry rock experiments pose no threat to health from harmful radioacivity.

Hot dry rock exists extensively in volcanic areas, and is the heat source for many of the hot- and warm-water reservoirs that are known. Hot dry rock is difficult to detect with the available surface survey tools, and techniques of utilisation are still being developed. Extensive experiments have been conducted in young magmatic bodies at Los Alamos, New Mexico, USA, and in Japan, and in old rock of high radioactive heat generation in the Carnmenellis Granite of Cornwall, England (Kruger, 1995). Hot dry rock is a large but substantially unknown resource, and utilization technology is in process of development.

CANADIAN RESOURCES

Research into Canadian geothermal resources was accelerated in response to the "Energy Crisis" of 1973 and following years. From 1976 to 1986 the Department of Energy, Mines and Resources, assisted by the National Research Council, made geothermal energy research one of the components of a major program of research into "Renewable Energy" sources. Most of our knowledge of Canadian geothermal resources results from that program. The locations of five of the most significant projects are shown in Figure 5.

Perhaps the most significant realization of that time, both in Canada and elsewhere, was that geothermal energy is present to some extent everywhere, and not just where hot springs and other thermal features reveal it. Thus geothermal energy may be found and used not only in countries that have volcanoes and clear evidence of geothermal activity, but in many geological and tectonic settings and in many countries that had not previously considered the possibility. This was particularly true in Canada, where recent volcanism is limited to the Pacific margin, but large sedimentary basins cover large parts of the country. Considering the types of geothermal resources described above, present knowledge of the Canadian potential may be summarized as follows.

No dry-steam reservoirs have yet been found, but their presence cannot be ruled out. Any centre of recent silicic volcanism may have one or more associated intrusive bodies capable of supporting hydrothermal systems leading to dry-steam reservoirs. Only Mount Meager in southern British Columbia (Fig. 5) has been explored. This site has been shown to have sufficiently high temperatures, but the presence of dry steam has not yet been demonstrated. A hot-water reservoir has been demonstrated at Mount Meager but the production capabilities of the reservoir have not been adequately determined (Ghomshei and Stauder, 1989). Figure 6 shows steam issuing from one of the deep wells at Mount Meager. Other reservoirs probably exist at other locations within the Mount Meager centre and at other volcanic centres in Canada.

Very large warm-water reservoirs have been shown to exist in Canada. The best known are found in the Western Canada Sedimentary Basin, in Alberta and Saskatchewan. As an energy source this geothermal resource is many times larger than the recorded reserves of oil (see resource estimate below), but economic conditions do not yet favor its development.

The low-temperature geothermal resource in Canada is also very large. Development is usually in small units, and

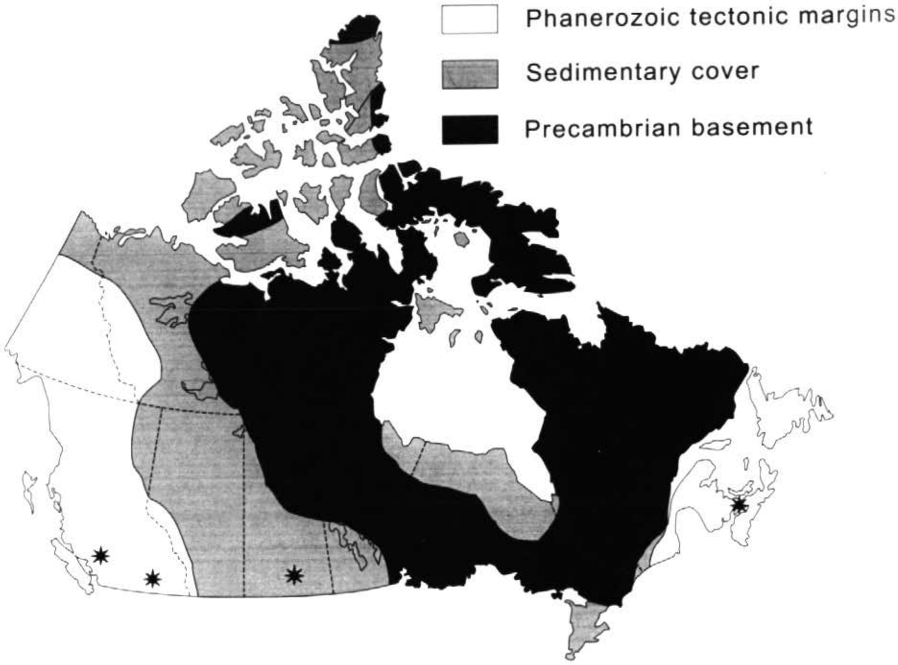

Figure 5 Locations of geothermal applications or investigations in Canada. From west to east the locations are Mount Meager, Coryell Syenite, Regina, Ottawa and Springhill.

Figure 6 One of the deep exploratory wells at Mount Meager, with steam issuing from it. Three wells were drilled in 1980-1981, and a fourth well was drilled in 1995.

depends mainly on local economic factors, such as the absence of natural gas supply and on local initiatives. Many systems have been installed to heat commercial buildings and larger private homes, particularly in British Columbia. One of the best sources of information on this type of application is found on the Internet, where there are several sites (Dandelion Geothermal Ltd., personal communication, 1998). Carleton University in Ottawa has used ground water from limestone aquifers at a temperature of about 9°C to heat and cool university buildings, as described below. It is estimated that the Carleton University system reduced the energy costs of the University by $430,000 per year (Minty, 1990). At Springhill, Nova Scotia, the use of water from the flooded coal mines for heating and cooling of industrial buildings has been a world leader, as described below. These projects have resulted in substantial savings over the use of fuel oil and conventional air-conditioning.

The hot dry rock potential of the Canadian crust is poorly known. Hot dry rock exists below Mount Meager and probably below other volcanic centres such as Mt. Cayley and Mount Edziza, all in British Columbia. Substantial bodies of intrusive rock in the interior of British Columbia are sufficiently radioactive to produce high geothermal gradients. A small drilling experiment in the Coryell Syenite, west of Lower Arrow Lake, British Columbia, has shown higher temperature gradients (Lewis *et al.*, 1979) and a probable hot dry rock potential better than that of Cornwall England, where a major development program has been undertaken.

CARLETON UNIVERSITY, OTTAWA

The Carleton University Groundwater Energy Project was originally designed for implementation in four phases (D. Allen, personal communication, 1997). Phase 1 of the Project, opened in February 1990, was constructed using standard groundwater-source heat-pump technology and was designed to provide heating and cooling for approximately 40% of the campus buildings. The original design (*i.e.*, that using heat pumps) was modified in the Commons Building such that the building could be directly cooled during the summer months and pre-heated in the winter by a heat exchanger, without the use of heat pumps. This retrofit work was undertaken in 1992-1993.

In the summer of 1996 there were two wells through which water was produced and reinjected at approximately 62 $L{\cdot}s^{-1}$. The reinjection temperature was approximately 3°C higher than that of the extracted water. The pumping well is located approximately 170 m from the reinjection well. Both wells are open boreholes and are cased through the overburden (approximately 30 m). The well diameter is 30 cm to a depth of 60 m, and 25 cm from 60 m to the completion depth of 120 m. The bedrock consists of fractured limestone, with significant fracturing along major faults that cross the campus. All wells on campus are artesian, and many are flowing artesian. Typical flow rates measured during drilling are on the order of 60-80$L{\cdot}s^{-1}$. The ambient groundwater temperature is approximately 9.5°C. Two further wells were used for cooling only, but these have since been shut down because of improper use of the aquifer (*i.e.*, it heated up). In general, the data indicate that there has been no thermal breakthrough between the reinjection well and the pumping well over a 10.5 month period (the monitoring period). The direction of operation has remained consistent, contrary to standard groundwater pumping systems which normally reverse the flow direction at the end of each heating or cooling season, *i.e.*, the production and injection wells are reversed at the end of each season to take advantage of any accumulated temperature change.

In-house studies used the Carleton aquifer test data for defining the aquifer properties and for developing a two-dimensional conceptual model of a faulted aquifer. Ultimately, this model was calibrated using the transient hydraulic test data. The model was expanded and was used to simulate the proposed Phase 2 well configuration. This configuration consisted of nine production wells, pumping and reinjecting at a rate of 265 $L{\cdot}s^{-1}$. The additional wells for Phase 2 were drilled during 1994 and were to have been incorporated with the existing five-well system of Phase 1. Unfortunately, the system has never been implemented or tested because of non-technical administrative problems.

Computer simulations of the system were carried out using the finite element method of solution (*ibid*). Two aquifer thicknesses, 6 m and 60 m, were analysed in an attempt to model both an aquifer with discretely fractured horizons and the full thickness of the aquifer, respectively. In both simulations there was no thermal breakthrough at the end of a six-month heating/cooling season. This suggested that had Carleton University gone ahead with the proposed expansion to the system (Phase 2) the system probably would have operated efficiently. The Carleton University system was a pioneer in the development of an aquifer thermal energy storage system in fractured limestones or any fractured rock. It is most unfortunate that the university chose to abandon the system, for reasons that do not seem to be related to the achieved or potential success (D. Allen, personal communication, 1997).

SPRINGHILL, NOVA SCOTIA

At Springhill, located in the Cumberland Basin of Nova Scotia (Fig. 5), the aquifer is the abandoned workings of the coal mines. The mines, which ceased operations in 1958, are flooded and contain about 4,000,000 m^3 of water which is recovered at the surface at a temperature of about 18°C. The heat in the water is derived from the normal heat of the host rocks, and temperature is controlled by naturally occurring convective mixing of the water. Water is pumped from the mines to act as the primary input to heat pumps for both heating and cooling of commercial buildings (Jessop *et al.*, 1995).

Coal mining began at Springhill in 1872 and continued as the primary industry of the town until 1958, when the last of a series of rock-bursts prompted the final closing of the mines. With the main industry removed, the town entered a period of economic readjustment and had to strive to develop new industries. The rapidly rising cost of oil-based energy from 1973 to 1980 added a major impediment to economic recovery. Happily, the use of geothermal energy from the mines since 1989 has given the town a major economic boost.

Geothermal gradient has been measured at several locations within the Cumberland Basin and is in the range 14 $mK{\cdot}m^{-1}$ to 17 $mK{\cdot}m^{-1}$. Surface temperatures, below the depth of significant seasonal variation, are in the range of 6°C to 8°C, and waters near the surface would be expected to be near this temperature.

Production and return temperatures at the Ropak Can-Am building in Springhill show that production temperature of the water is constant at 17.9°C, whereas return temperature varies from a minimum of 11.1°C in winter to a maximum of 26.7°C in summer. During the study period the maximum energy derived from the water in the winter was 9.6 GJ per day and the maximum returned in the summer was

13.7 GJ per day. In one seasonal cycle the total heat taken in winter is about 890 GJ and the heat put into the mine in summer is about 1550 GJ, for a total of about 2440 GJ exchanged and a net heat input to the mine of about 660 GJ.

The water in the mine workings acts as a large reservoir of heat that is drawn on and replenished seasonally, rather than as a depletable resource. The Ropak Can-Am application returns more heat than it takes out, but other users are a net drain on the heat content. The net annual heat exchange by Ropak Can-Am is less than the total accessible heat by a factor of about 400. These rates of heat exchange show that the Springhill resource could support this system and several others of similar magnitude for many decades.

The capital cost of the heat pump system and the two wells was $110,000, about 20% higher than the estimated cost of conventional oil furnaces at the point of installation. However, the maintenance and operating costs are considerably lower than those of conventional oil furnaces. In 1991 the company estimated that the geothermal system saves $160,000 per year over the equivalent oil-fired furnace system (Ropak Can-Am, personal communication, 1992). Thus the pay-back period of the extra capital cost was less than one year. This does not include the benefits of cooling in the summer of the plastic-moulding equipment. This cooling would have to have been provided by some other means. There are non-monetary benefits in addition to the savings in energy costs: the clean operation now permits the company to make food containers; and working conditions are much better than before, particularly in the summer.

The extraction of energy from mine water produces no combustion gas and leaves no chemical residue on the surface. This energy source, when in routine use, produces no harm to the local environment. In the event of a break in a pipe the potential damage would be limited to any damage caused by the water and any impurities. At the Springhill Museum, water pumped from the mine is discharged into the local surface drainage. Thus the potential for environmental damage by a pipe-break is limited to physical damage by the water itself.

In the winter heating season carbon dioxide emissions from a heating system based on oil that supplied 890 GJ would release about 500 tonnes of carbon dioxide. In the summer an air-conditioning system driven by electricity produced from coal, as is most electricity in Nova Scotia, implies the release of about 240 tonnes of carbon dioxide. Thus the total release of carbon dioxide for the Ropak Can-Am building, heated and cooled by conventional means, would be about 740 tonnes·a^{-1}. The emissions necessary to provide the same benefits of heating and cooling from the geothermal source are only about 370 tonnes·a^{-1}, derived from the electrical energy needed to drive the heat pumps and water pumps. The geothermal system thus results in a reduction of carbon dioxide emission by about 50%. Although this is a very small quantity in comparison with the national emission of carbon dioxide into the atmosphere, it is a contribution to environmental responsibility that is reproducible in many other locations (Jessop *et al.*, 1995)

UNIVERSITY OF REGINA, SASKATCHEWAN

In 1979 the University of Regina drilled a well on the campus to a depth of 2210 m in search of geothermal water to heat a planned sports and recreation building (Fig. 7). Although the well was successful, the sports building has not been built.

A Basal Clastic Unit, from 2029 m to 2204 m in the well, is mainly sandstone, with good porosity of 11% to 19% and permeability of 70 mD to 220 mD. Temperature at the Precambrian surface (2204 m) was 60.7°C. Formation pressures were sufficient to provide a static water level in the well at 17 m below ground surface (Jessop and Vigrass, 1989). Water density in the Winnipeg Formation aquifer (2029 m to 2078 m) aquifer was 1058 kg·m^{-3} and the salinity was about 100,000 ppm, consisting mainly of sodium chloride. Use of the well as an energy source would have required a second well at a distance of about 1 km, to act as a reinjection well. With heat exchangers and heat pumps to reduce the temperature of the water by 40°C, this system could have provided at least 3 MW of thermal energy. However, the rest of the campus was supplied with heat by a steam distribution system, and the proposed geothermal system would have been totally independent of the main campus system. The costs of two wells, about M$1.6 at that time, plus the heat exchange and circulation system, made the project uneconomic except as a feasibility study.

The well has been used for accurate temperature logging and for hydrofracture experiments to determine the orientation of principal stresses (McLennan *et al.*, 1986). It has been a valuable research facility, but it has never been used for its intended purpose.

MOUNT MEAGER, BRITISH COLUMBIA

Mount Meager is located approximately 160 km north of Vancouver, British Columbia, in a geological setting of late Tertiary to Quaternary volcanic terrains superimposed on the granodiorites of the Coast Plutonic Complex. It is the northernmost volcano of the Cascade chain, which ex-

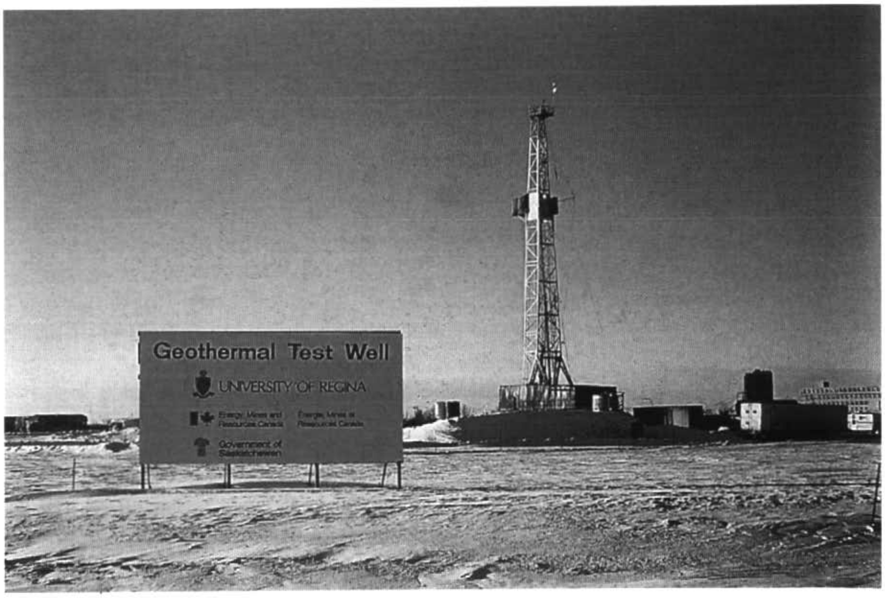

Figure 7 Geothermal test well drilled in 1979 at the University of Regina, Saskatchewan.

tends southwards to California. The Mount Meager Complex is a volcanic edifice about 16 km in diameter and rising about 2000 m above surrounding valleys. It is made up of andesite to dacite flows, pipes and fragmental rock. Eruptions started at the southern edge of the present edifice about 1.9 million years ago and progressively shifted northward, the latest being a pumice explosion about 2400 years ago (Souther, 1977). At present about 3 m of precipitation per year at higher altitudes and melting of permanent ice caps occupying higher slopes supply water to this high-relief and high-energy hydrologic regime.

Beginning in 1974, the Department of Energy, Mines and Resources and British Columbia Hydro and Power Authority sponsored extensive geochemical and geophysical surveys in the vicinity of Mount Meager, in the Meager Creek valley on the south side and in the Lillooet River valley to the east and north. Reconnaissance geophysical surveys and small-scale diamond drill projects identified and localized a potential resource area on the lower flanks of Pylon Peak, about 5 km upstream from the main vent of the Meager Creek springs (Souther, 1980). In one of the wells a temperature of 202°C was recorded at a depth of only 267 m. Major-ion and stable-isotope studies on the waters from hot springs and shallow drill-holes have suggested that high temperatures may be present at depths reached by surface-driven circulating waters. Absence of tritium, derived from hydrogen bombs, in hot springs suggests that residence time is more than 25 years (Clark *et al.*, 1982). Dipole-dipole resistivity surveys identified a large (8 km^2), low-resistivity anomaly of 10-100 ohm-metres against a background of 200-400 ohm-metres. The Meager Creek Fault, a normal fault trending east-west along the Meager Creek valley and dipping at 50° under Mount Meager, was identified as the main structure responsible for seepage of thermal waters (Lewis and Souther, 1978; Read, 1979).

Exploration culminated with the drilling of three large-diameter wells during 1980 and 1982. Reaching depths of 3000 m to 3500 m, these wells provided some of the information necessary to evaluate the targets identified in earlier studies. The first hole (MC1) proved to be capable of long-term, two-phase fluid production. Major-ion (Ghomshei *et al.*, 1986) and stable-isotope data (Ghomshei and Clark, 1993), from fluids from well MC-1, are strongly suggestive of the presence of abundant geothermal fluids resident at a depth of 2500-3000 m. A high temperature (270°C), indicated by sodium/lithium geothermometry, suggests that fluids have migrated upward from a deep, high-temperature reservoir at approximately 2500 m to a shallower reservoir at 1600 m. A major path for this migration is provided by the Meager Creek fault zone. The MC1 well discharge is from the shallow reservoir, at the intersection of the borehole with the permeable zone (Meager Creek Fault) at 1600 m. The thermal waters travelling along the Meager Creek fault zone have been thermally and chemically re-equilibrated with the wall-rocks, and so a shallow reservoir (1600 m) temperature of only 200-210°C is shown by downhole measurements and chemical geothermometers.

In a hydrothermal system, temperature is controlled by the movement of water in faults and porous zones, rather than by conduction in solid rock. The MC1 temperature profile shows an isothermal ascent of fluids from a depth of about 1600 m. This is the depth of the top of the hot reservoir in the Meager Creek fault. The hot waters rise with a constant temperature of 195°C. Near the surface the temperature drops rapidly to under 150°C. This is, to some extent, due to mixing with near-surface cold waters or to in-well boiling. It is possible that steam loss occurs at relatively deeper levels; the consequent pressure drop would then permit the invasion of cold waters at shallower levels. Wells MC2 and MC3 demonstrate similar isothermal rise but from a deeper source at 2500 m. The temperature of the rising fluids is 160-180°C, considerably lower than MC1 waters (Ghomshei and Stauder, 1989).

Despite some technical problems such as casing failure, well MC1 sustained a relatively high-enthalpy discharge to run the first, and so far the only, Canadian geothermal test generator. The well was capable of producing 27 tonnes per hour as total mass. On the basis of 10% steam fraction the total steam was about 2.7 tonnes per hour, which could produce approximately 200 kW of electricity, based on a conservative steam-conversion factor of 14 tonnes/MW. This is low for a production well, but it is encouraging for an early-stage exploration well.

Resource estimation at Meager Creek has been based mainly on analysis of the temperature profiles. Geothermal productivity, however, depends also on hydraulic conductivity of the reservoir rocks. It has been argued, from chemical and isotopic data, that hydrological properties limit the production potential at Meager Creek (Adams and Moore, 1987; Adams *et al.*, 1985), and this question remains unresolved. Comprehensive re-examination of the three existing deep wells, possible further drilling, and more detailed geochemical studies are thus warranted before proceeding to development.

The exploration program at Mount Meager revealed a permeable zone at depths of 1200 m to 1600 m, and indicated a reservoir of about 270°C at about 2500 m depth. Despite these encouraging results, the project was substantially halted in 1984, because of financial cutbacks and declining energy prices. Minor analytical work including stable-isotope studies on discharge from MC1 and meteoric waters was carried out during 1985.

The South Meager Creek geothermal energy project is now jointly owned by Crew Development Corporation and Guy F. Atkinson Holdings Ltd. A fourth exploratory well was drilled and tested in 1995. The project is now on hold pending a more favourable market for independent power producers in British Columbia.

RESOURCE ESTIMATES, WESTERN CANADA SEDIMENTARY BASIN

The Western Canada Sedimentary Basin (WCSB) contains the largest reasonably accessible geothermal resource in Canada, and it offers a simple model for resource assessment. Between the latitudes of 49°N and 60°N, the area of sedimentary cover is 1.26 x 10^6 km^2, the average depth is 1778 m, and the total volume of sediments is 2.24 x 10^{15} m^3, (Hitchon, 1968). The total pore volume has been estimated to be 265 x 10^{12} m^3 (Hitchon and Friedman, 1969), which implies an average porosity of 11.8%. Assuming a density of 1.0 Mg·m^{-3}, this means that the rocks contain about 265 x 10^{15} kg of water. Temperature data from industrial records (Sproule Assoc, 1976) indicate an average geothermal gradient of 33 mK·m^{-1}.

To calculate the geothermal resource we assume that the density of the formation water is 1.0 Mg·m^{-3}, the specific heat is 4200 J·kgK^{-1}, and that the mean surface temperature is 4°C. Two temperatures must be established for any system of exploitation. The "threshold temperature" is the temperature below which it is not economic to produce water. This may be about 60°C if a heat exchanger system is in use, but may be as low as 10°C if heat pumps are used. The "return temperature" is the temperature at which the water is rejected from the extraction system and returned to the ground. We may now calculate the total useful heat in the water of the basin, for any values of the threshold and return temperatures, and the results are shown in Figure 8. The heavy line shows the heat available when the threshold and return temperatures are equal. The return temperature will normally be lower than the threshold temperature, allowing more heat to be taken from the water. Further lines show the heat available for the return temperatures indicated.

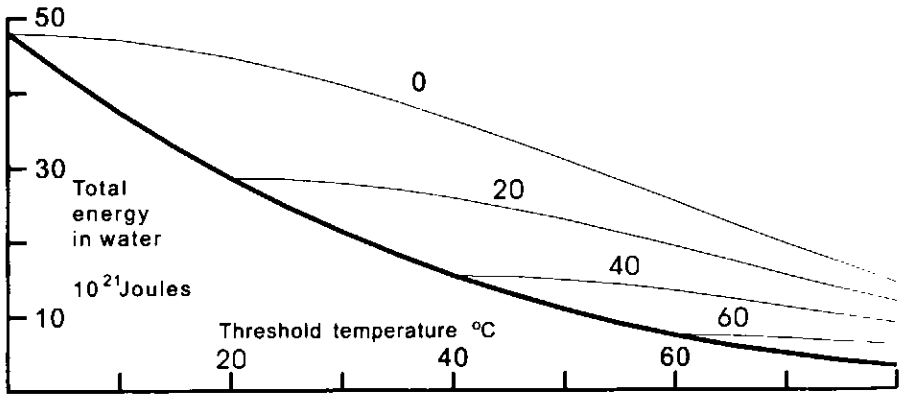

Figure 8 The geothermal energy resource of the Western Canada Sedimentary Basin, calculated as a function of the threshold and return temperatures. The heavy line shows the energy resource if all water at temperatures above the threshold temperature is extracted and returned at the threshold temperature. The lighter lines show the resource if all water at temperatures greater than the threshold temperature is extracted and returned at the temperature indicated.

Reasonable threshold and return temperatures in geothermal systems that do not employ heat pumps are 60°C, and 40°C, respectively. For systems that include heat pumps these temperatures are reduced to 40°C and 10°C. The total heat in the water of the basin that meets or exceeds these temperature criteria is 13×10^{21} J and 31×10^{21} J, respectively.

Canadian conventional oil and gas reserves are estimated at 34×10^{18} J and 68×10^{18} J, respectively (Canadian Association of Petroleum Producers, 1996). The WCSB geothermal resource is thus larger than Canada's estimated hydrocarbon reserves by three orders of magnitude. If only 1% of the geothermal resource is capable of economic production, and so equivalent to a reserve, it is still substantially greater than the hydrocarbon reserves. However, the possible applications of chemical energy in hydrocarbons and heat energy in water are different.

GEOTHERMAL ENERGY: PRESENT AND FUTURE

Of the four major attempts to date to use geothermal resources in Canada, only the Springhill project is still active. Projects at Carleton University, University of Regina and Meager Creek await more favorable economic conditions or are abandoned. None of these three projects has failed because the resource was lacking or because of technical problems. This indicates that for successful use of geothermal energy in Canada the need is not so much for geological research and resource evaluation as for research into methods to reduce costs, particularly capital costs.

Given the magnitude of the resource and its ability to provide energy with an environmental impact significantly less than that of energy produced by combustion of fuels, geothermal energy must become a major potential source of energy for the future. Geothermal energy is not generally suitable for transport, unless through electrical power, but it has a very large capacity for space-heating, an important part of the Canadian need.

While energy prices remain low, and conventional fossil-fuel resources and conventional methods of exploitation can be used, significant industrial development of geothermal energy is unlikely to occur. In the current climate of reduction of scientific and technical research no governmental organization in Canada is supporting geothermal energy research. The Office of Energy Research and Development of Natural Resources Canada refuses even to acknowledge the existence of this large resource. If governments are ever to take seriously the questions of gaseous emissions, acid rain, climatic warming and effects on human health, energy sources with a smaller environmental impact will be urgently needed. Present inactivity in geothermal energy and other research ensures that the need will not be met in a timely manner.

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