SOQ-10337

SNC INC - RAPPORT SUR LE POTENTIEL EN ENERGIE GEOTHERMIQUE DE BASSE ENERGIE DANS LES BASSES TERRES DU ST-LAURENT - CONTRAT 4275 (SOQUIP 2078) - PREPARE POUR SOQUIP - RAPPORT #10337

RAPPORT SUR LE POTENTIEL EN ENERGIE
GEOTHERMIQUE DE BASSE ENERGIE DANS
LES BASSES TERRES DU ST-LAURENT
CONTRAT 4275 (SOQUIP 2078)

SNC

10337
EH, 1

RAPPORT SUR LE POTENTIEL EN ENERGIE GEOTHERMIQUE DE BASSE ENERGIE DANS LES BASSES TERRES DU ST-LAURENT

CONTRAT 4275 (SOQUIP 2078)

Préparé pour:

La Société Québecoise d'Initiatives Pétrolières
3340, de la Pérade, Ste-Foy, Québec G1X 2L7

SNC

Distribution:

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Préparé par:

SNC Inc.
Le 18 mai 1979

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SNC Inc.

Le 18 mai 1979

Monsieur Jacques Plante
Directeur de l'Exploration et de
la Production
SOQUIP
3340, de la Pérade
Ste-Foy, Québec
G1X 2N7

N/Réf.: Contrat 4275
SUJET : Etude géothermique en "basse énergie"

Cher Monsieur Plante,

Il nous fait plaisir de vous faire parvenir trois (3) copies du rapport sur "Le potentiel en Energie Géothermique de Basse Energie dans les Basses Terres du St-Laurent". Ce rapport synthétise les résultats de la recherche effectuée à la suite de votre lettre du 19 avril 1979 sur le projet SOPQUIP 2078.

Nous regrettons d'avoir eu à conclure que le potentiel des Basses Terres ne nous paraissait pas prometteur malgré l'intérêt scientifique du sujet.

Nous vous remercions de la confiance que vous avez accordée à notre Société et vous prions d'accepter, cher Monsieur Plante, l'expression de nos sentiments les meilleurs.

Géologue Senior

Jean-Jacques Meillon

JJM/jg

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1.0 INTRODUCTION

La crise de l'énergie a amené le développement de nouvelles sources ainsi que des essais de retour aux sources d'énergie traditionnelles. L'utilisation systématique de l'énergie géothermique à "basse énergie" a commencé en Islande où le forage de puits pour l'eau chaude destinée au chauffage urbain a commencé en 1928. Cette première utilisation employait de l'eau à 87°C. Plus récemment, le chauffage des habitations, utilisant une eau dont la température minimum est de 60°C, s'est développé en Europe et en Union Soviétique. Pour le chauffage des sols dans les serres une température de 40°C est encore acceptable et, pour le chauffage urbain, on prévoit que dans un futur proche on pourra utiliser des eaux à 51°C.

A cause de la diminution des températures exploitables dûe aux avances technologiques, la prospection, qui ne se faisait à l'origine que dans les régions volcaniques, englobe maintenant les bassins sédimentaires où la recherche de nappes artésiennes profondes est devenue courante. Dans la région de Montréal le puits d'exploration pétrolière Canac B.P. Sisque Brossard # 1 a donné une température de 56°C au fond du trou. Cette température pourrait être intéressante si les autres paramètres tels que le débit du puits, les conditions d'exploitation, le marché et la distribution de l'eau chaude étaient eux aussi favorables.

Comme SOQUIP est déjà impliquée dans l'exploration pétrolière qui utilise une technologie très voisine de la géothermie, il est naturel qu'elle ait été attirée par l'éventualité d'un programme de recherches. A cet effet, une compilation des températures de fond puits et de gradients géothermiques a été faite par M. Pierre Lefebvre pour le bassin des Basses Terres du St-Laurent.

En avril 1979, SOQUIP a chargé le service géologique de SNC Inc. de vérifier et d'analyser les données de la compilation Lefebvre ainsi que d'estimer de façon préliminaire le potentiel de la géothermie à "basse énergie" dans le sous-sol des centres urbains des Basses Terres.

2.0 RESUME

Le 16 avril 1979 le service géologique de SNC Inc. a été instruit par Monsieur Jacques Plante, Directeur de l'Exploration et de la Production de SOQUIP, d'effectuer une étude du potentiel des zones peuplées des Basses Terres du St-Laurent en ressources d'énergie géothermique, dite de "basse énergie". L'étude a été réalisée par Messieurs Marc Filion et Jacques Meillon entre le 16 avril et le 11 mai 1979.

Le but de cette recherche a été d'analyser le potentiel en eau thermale à basse énergie (— 100°C) des régions urbaines et d'en dégager des conclusions sur l'éventualité d'y engager ou non des travaux d'exploration.

L'étude bibliographique a montré que le gradient géothermique des Basses Terres est normal ou légèrement en-dessous de la moyenne. Quelques températures plus élevées, notées au fond de puits forés par des compagnies pétrolières, pourraient malheureusement être dûes à des erreurs de mesure.

Dans l'état actuel de la technologie et compte tenu du coût des énergie concurrentes, nous avons estimé que l'eau devrait avoir une température minimum de 51° pour être exploitable. Comme le gradient est normal il faudrait probablement aller à des profondeurs prohibitives pour atteindre cette température. Malgré cela deux sortes de conditions géologiques favorables pourraient ramener près de la surface des eaux chauffées en profondeur.

a) Un aquifère artésien régional perméable comme celui qui va être exploité sous Regina en Saskatchewan. Cette situation n'a pas de chance d'exister sous les Basses Terres parce que les perméabilités ne sont pas assez élevées et surtout parce que de nombreuses failles arrêtent ou dévient les nappes profondes.

b) L'autre condition, plus probable dans les Basses Terres, serait reliée à la remontée des eaux profondes le long de failles réactivées à une époque récente. Bien que cette situation puisse exister, les chances qu'une telle structure soit exploitable sont minces et des coûts de recherche en seraient très élevés.

Des travaux en cours à l'IREQ (Institut de Recherches Electriques du Québec) explorent les possibilités d'utiliser l'eau à basse température (10-15°C) des aquifères de surface pour actionner des pompes à chaleur domestiques. Cette recherche n'est pas très coûteuse et, si elle est couronnée de succès, permettra l'utilisation d'aquifères superficiels déjà connus et explorés.

2.0 RESUME (suite)

Nous concluons qu'au stade actuel des besoins des Basses Terres et de la connaissance technologique sur la géothermie à basse énergie, la recherche d'eau chaude à grande profondeur (plus de 250 m) ne vaut pas la peine d'être entreprise.

3.0 TRAVAIL EXECUTE

3.1 Bibliographie

Les listages d'ordinateurs nous ont donné 157 références sur la géothermie, dont 30 pour le Canada. Les publications se rapportant directement au sujet de ce rapport ont été photocopiées et les plus importantes y sont annexées.

Les publications du Ministère des Richesses naturelles (M.N.R.) sur les Basses Terres ont été relues en y cherchant activement les schémas favorables aux remontées d'eaux profondes.

3.2 Entrevues

Ce travail étant avant tout un travail de compilation et de synthèse, nous avons dû consulter des ingénieurs et géologues dont les compétences complétaient les nôtres. La liste qui suit montre les personnes ou organismes consultés et/ou les sujets discutés.

- SOQUIP: discussion du mandat, mesures de température, coûts de sondage.
- Direction Générale de l'Energie (M.N.R.): discussion sur les réservoirs et étude des logs et diagraphies.
- Service des Eaux Souterraines, Direction Générale des Eaux (M.R.N.): discussion sur les aquifères favorables.
- Université de Montréal et Université McGill: discussions avec le staff sur les intrusions montérégiennes.
- Pompes à chaleur: discussions avec J.-P. Guay, ingénieur en chauffage SNC Inc. et avec Y. Langhame de l'Institut de Recherches Electriques du Québec (IREQ).
- Marché de l'eau chaude: discussion avec B. Webber, ingénieur civil et économiste avec Sorès du Groupe SNC.
- Sondages: devis préliminaires obtenus des compagnies Canadian Longyear, Bradley Bros., Underwater Gas Developers et Westburn Drilling.
- Températures des eaux: cinq compagnies montréalaises qui exploitent des eaux ont été interviewées.

3.0 TRAVAIL EXECUTE (suite)

3.2 Entrevues (suite)

- Gradients géothermiques et exploitabilité: plusieurs discussions avec M. Alan Jessop du Département de l'Energie, Mines et Ressources ont eu lieu à Ottawa ou par téléphone. Le projet géothermique de Regina a été discuté avec son chef de projet M. L.W. Vigrass de l'Energy Research Unit, University of Regina.

3.3 Synthèse et rédaction

La compilation et l'analyse des données ont été effectuées conjointement par Marc Filion et Jacques Meillon.

L'analyse finale et les conclusions ont été rédigées par Jacques Meillon.

MINISTÈRE DES TERRES ET FORÊTS
DIRECTION GÉNÉRALE DU DOMAINE TERRITORIAL
DIRECTION DES RELEVÉS TECHNIQUES
SERVICE DE LA CARTOGRAPHIE

1: 9 000 000

0 100 200 300

Kilomètres

Basses Terres du St-Laurent

4.0 GEOLOGIE ECONOMIQUE

4.1 Géologie générale des Basses Terres

La province géologique des Basses Terres du St-Laurent s'étend d'Ottawa à La Malbaie, le long des vallées du St-Laurent et de l'Outaouais. Il s'agit d'un bassin de sédiments marins Cambro-Ordoviciens reposant sur le socle Précambrien de la province géologique du Grenville. La bordure orientale de ce bassin a été affectée par les orogénèses Taconique et Acadienne. Au Crétacé, le dernier événement géologique majeur a été l'intrusion d'un alignement de "plugs" cylindriques de roches alcalines (intrusions Montérégiennes) qui n'ont pratiquement pas métamorphisé les sédiments Cambro-Ordoviciens. L'alignement des collines Montérégiennes passe par le centre de Montréal.

Les glaciations Quaternaires ont modelé le relief de la région mais ont peu d'incidences sur la géothermie.

Sur la coupe SOQUIP Figure 5 ci-contre on peut voir les cinq régions structurales des Basses Terres du St-Laurent (B. Granger 1978). La zone d'influence de cette étude commence au contact avec le Bouclier Canadien et, vers le S.E., comprend la zone de plate-forme (Montréal-Trois-Rivières) ainsi qu'une partie de la zone externe.

4.2 Stratigraphie et aquifères propices

4.2.1 Stratigraphie

Avec quelques modifications mineures, le tableau et le texte suivants sont extraits de la Carte Hydrogéologique de l'Ile de Montréal et des Iles Perrot et Bizard d'André Bériault et Georges Simars 1978, publiée par le Service des Eaux Souterraines, Direction Générale des Eaux, Ministère des Richesses naturelles.

Le gradient géothermique (cf paragraphe 4.3.2) paraissant essentiellement normal dans les Basses Terres, c'est plutôt vers les formations perméables et les aquifères assez profonds pour être chauds que s'est d'abord orienté cette recherche. Les formations favorables sont déjà identifiées et ont été étudiées par le Service des Eaux Souterraines, ce qui nous permet d'utiliser tels quels leurs résultats qui, avec quelques modifications, sont valables pour le reste des Basses Terres.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.2.1 Stratigraphie (suite)

UNITE HYDROGEOLOGIQUE	PUISSANCE MAXIMALE pieds	TRANSMISSIVITE (en gallons par jour par pied)
Shales du Lorrain et de l'Utica	750	$10^1 - 10^3$
Calcaire du Trenton supérieur	400	$10^1 - 10^5$
Calcaire du Trenton inférieur, Black River et Chazy	742	$10^1 - 10^4$
Dolomies du Beekmantown	814	$10^2 - 10^4$
Grès du Potsdam	1700	$10^2 - 10^5$

Le groupe du Potsdam (Cambrien) affleure sur l'extrême pointe sud-ouest de l'Ile de Montréal et sur l'Ile Perrot. Ces roches sédimentaires très anciennes se composent de conglomérats et de grès quartzeux à ciment dolomitique. Certains bancs de grès montrent des évidences de stratification entrecroisée. On "assume" la puissance de ce groupe dans la région de Montréal à environ 1700 pieds (518 m).

Une épaisse série de strates comprenant principalement de la dolomie et des grès dolomitiques d'une puissance de 820 pieds (250 m) recouvre le Potsdam et forme le groupe de Beekmantown (Ordovicien). Vers le sommet de la séquence, les bancs de calcaire et les passées argileuses deviennent plus fréquents.

Le Beekmantown est surmonté par un ensemble de formations à dominance calcaire ayant une puissance d'environ 280 pieds (85 m), connu sous le nom de Chazy. Affleurant à l'est du groupe de Chazy, on retrouve une mince bande de 50 pieds (15 m) de calcaires et de shales du groupe Black River (formations Lowville et Leroy). Toutefois, la base du groupe est à forte composition dolomitique (formation de Pamélia).

BASSES TERRES DU ST-LAURENT

COUPE STRUCTURALE

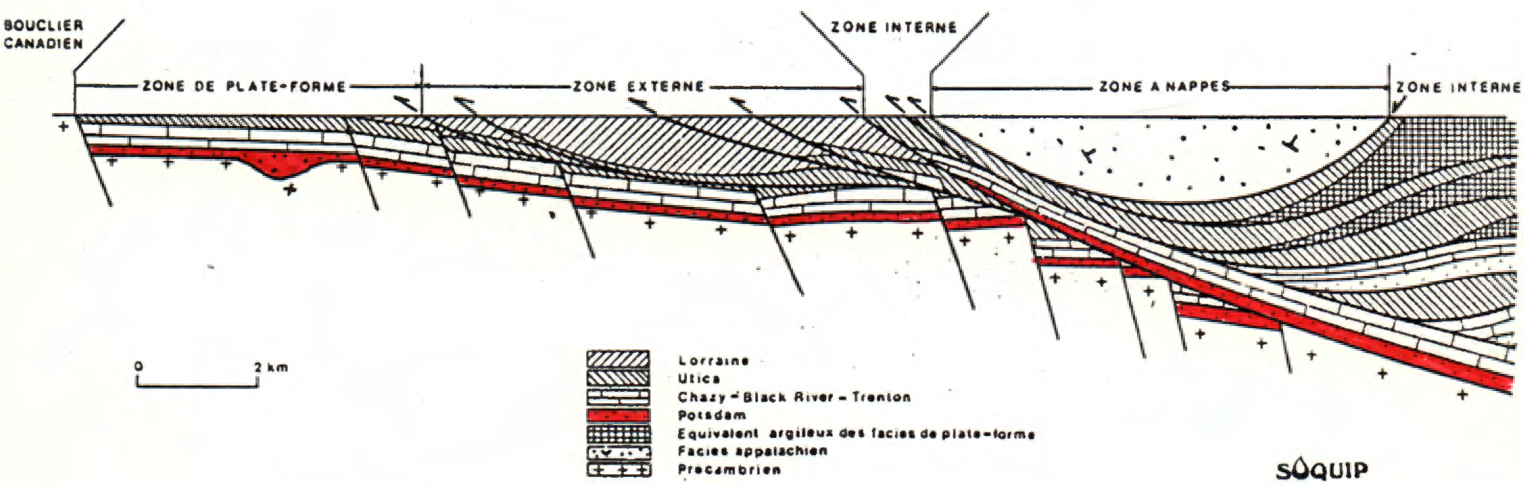


Figure 5

4.0 GEOLOGIE ECONOMIQUE (suite)

4.2.1 Stratigraphie (suite)

Des bancs de calcaires, gris bleu ou noirs, bien stratifiés, et avec des entrelits de shales noirs affleurent sur l'Ile de Montréal en une bande allant de Beaconsfield au quartier Rivière-des-Prairies. Ces roches sont associées au groupe de Trenton et peuvent atteindre une puissance de 820 pieds (250 m).

A Verdun, Lasalle, Lachine et dans la partie nord-est de l'Île, une épaisse séquence de shales et de grès argileux d'une puissance de 820 pieds (250 m) composent les groupes d'Utica et du Lorraine.

Les roches sédimentaires sont recoupées par des roches ignées, d'âge Crétacé, associées aux Montérégiennes. Ces masses intrusives se composent surtout de gabbro et de syénite. De plus, on note ici et là la présence de dykes d'alnoite et de tinguaïte et de brèches ignées.

4.2.2 Hydrogéologie

4.2.2.1 Grès cambriens du Potsdam

Avec les dolomies du Beekmantown, les grès cambriens du Potsdam sont reconnus comme étant les meilleurs aquifères du Québec. La perméabilité des grès est liée à l'existence:

1) d'une zone d'altération et de fissuration dans la partie supérieure de la roche,

2) d'un réseau de fractures profondes, et

3) occasionnellement de lits friables.

En l'absence de données sur les propriétés hydrauliques des grès cambriens de la région, le haut rendement des puits municipaux de l'Ile Perrot laisse supposer une forte perméabilité.
Remarque: aux profondeurs qui nous intéressent pour la géothermie, l'influence de l'altération superficielle est nulle et les deux autres facteurs relativement plus importants.

4.2.2.2 Dolomies du Beekmantown

Les dolomies du Beekmantown présentent une altération généralement bien développée, une fracturation profonde et, occasionnellement, des cavités de dissolution qui expliquent le haut rendement des puits se terminant dans cet horizon.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.2.2.3 Calcaires Ordoviciens des groupes de Chazy, de Black River et du Trenton inférieur

Ces calcaires qui comprennent les formations de Mile End, Deschambault et Montréal, ont également une porosité secondaire mieux développée que les calcaires du Trenton supérieur. Au début du siècle, la plupart des puits "artésiens" de l'Ile de Montréal captaient les eaux dans les calcaires du Trenton inférieur.

4.2.2.4 Calcaires et shales du Trenton non différencié et du Trenton supérieur

Les calcaires et shales du Trenton non différencié et du Trenton supérieur sont plus massifs et schisteux que les calcaires du Trenton inférieur et sont généralement moins perméables que ces derniers. Ceci est particulièrement vrai dans l'est de l'Ile de Montréal où des essais de pompage de puits terminés dans la formation de Têtreauville ont donné des transmissivités de 35 g.p.j./pi. et 58 g.p.j./pi.. Cependant au voisinage des failles Rapide-du-Cheval-Blanc, Ile Bizard, Dorval et Pointe-Claire, l'on obtient de très bons débits. Il en est de même dans le secteur de l'aéroport de Dorval où l'abaissement de la surface piézométrique et les forts débits des puits interceptant la roche en place, témoignent d'une perméabilité importante.

Les shales du Lorraine et de l'Utica sont généralement peu perméables et fournissent des débits inférieurs à 10 g.p.m..

4.2.2.5 Roches intrusives du Crétacé

Les roches intrusives Crétacé sont mal connues hydrogéologiquement. Adams et Leroy (1904) les qualifient d'imperméables. Cummings (1917) fait état d'un puits se terminant dans cette unité qui donne un "débit abondant".

4.3 Les gradients géothermiques

4.3.1 Les mesures

Les mesures de température ont été faites au fond des trous dans la boue de forage à l'occasion du "logging" des diagraphies destinées à l'exploration pétrolière. La confiance que l'on peut mettre dans ces mesures de température est assez faible parce qu'elles ont été faites avec des objectifs différents et ne sont souvent que des extrapolations (Ferti et Wichmann 1977)

4.0 GEOLOGIE ECONOMIQUE (suite)

4.3.1 Les mesures (suite)

L'interprétation est donc très aléatoire et avant d'engager de nouveaux programmes d'exploration pour la géothermie, les températures anormalement hautes devraient être vérifiées dans les trous de forages existants.

4.3.2 Le gradient

Le gradient géothermique ne peut être estimé que sur les puits assez profonds pour minimiser l'influence irrégulière des circulations d'eau près de la surface et aussi (Birch, F. 1948) parce que, près de la surface, l'influence séculaire de la dernière glaciation se fait encore sentir. Selon les instructions du laboratoire de géophysique du fédéral "les températures de surface" des roches ont été obtenues en ajoutant 3.7°C à la température moyenne annuelle météorologique. Le tableau suivant montre les gradients obtenus pour les puits de plus de 1000 m.

TABLEAU NO.

Numéro de puits	Profondeur (mètres)	°C par 100 m Gradient
65	1353	2.0
125	1270	1.8
**126	1341	2.8
152	2654	1.3 et 1.6
156	2611	1.8
**157	1449	3.2
159	1304	2.0
160	1813	1.7
161	2587	1.7
162	1876	1.2
163	3761	1.7
164	1209	2.2
165	1939	1.7
166	3804	1.3
*167	1868	0.5
168	2141	1.4
169	2500	1.3
173	2956	1.2 et 1.6
177	1812	1.5
178	1793	1.6
180	2231	1.4
183	1885	1.4

4.0 GEOLOGIE ECONOMIQUE (suite)

4.3.2 Gradient (suite)

Numéro de puits	Profondeur (mètres)	°C par 100 m Gradient
185	4277	1.4
186	1384	1.2
**187	3173	2.6
188	1409	1.5
189	2544	1.6
*190	2174	0.7

Moyenne des gradients - 1.64°C/100 m

* puits froid ** puits chaud

Sur le tableau ci-dessus l'on voit que trois puits ont des gradients anormalement élevés et deux puits ont des gradients anormalement bas.

La moyenne est de 1.64°C/100 m, ce qui situe les Basses Terres dans la moyenne des régions continentales non plissées. Ce gradient est évidemment plus bas que la moyenne globale de 2.5°C/100 m à laquelle contribuent les zones plissées, les zones océaniques et les zones volcaniques.

Des mesures détaillées de gradient faites par Butler et Doig (Annexes 1 à 3) dans quatre trous de sondage éloignés les uns des autres montrent que dans les Basses Terres le flux de chaleur varie peu d'une région à l'autre malgré les différences de géologie.

Un des trois puits chauds, le 157, est isolé; le 126 et le 197 sont entourés de puits à gradients normaux.

Les alentours des intrusions Montérégiennes ne montrent pas d'anomalies de gradient et comme, en dépit de la légère sismicité de la vallée du St-Laurent il n'y a aucune source tiède dans leur voisinage, on peut conclure que ces intrusions ont fini de cristalliser il y a très longtemps. G. Pouliot, 1962, dans sa thèse de doctorat "The thermal history of the Monteregian intrusives based on a study of the feldspar", démontre que les magmas montérégiens étaient essentiellement des magmas "secs" qui se sont refroidis très rapidement. Le complexe d'Oka, qui fait aussi partie des intrusions Montérégiennes, contient beaucoup plus d'uranium et de thorium que les roches "granitiques" normales, mais pas assez pour que la désintégration de ces éléments constitue une source de chaleur significative.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.3.2 Gradient (suite)

Comme ces intrusions sont d'âge Crétacé et de tailles modestes comparées aux intrusions batholiques tertiaires près desquelles on trouve les sources chaudes, nous pensons que la possibilité de trouver de l'eau chaude dûe à un gradient anormalement élevé doit être exclue.

4.4 Interprétation des puits chauds

4.4.1 Puits 157

Canac B.P. - Sisque Brossard # 1
Comté: Laprairie Paroisse: Laprairie de la Madeleine
Lot: 31
Latitute : 45°26'39.854"
Longitude: 73°29'27.627"

Stratigraphie		Epaisseur (en pieds)	Profondeur du contact inférieur
Recouvrement		20	20
Shale d'Utica (UTA)		558	578
Calcaire de Trenton (TRT)		818	1385
Calcaire Black River (BLR)	Sills de syénite	107	1503
Calcaire Chazy (CHZ)		327	
Grès Chazy (CHZ)		160	2005
Beekmantown (BMT)		1428	3426
Potsdam sup. (PTD)		989	
Potsdam inf. (PTD)		421 +	4754 (1449 m)

Venues d'eau à 3778' - 3958' - 4438' - 4708' - 4754' (fond)

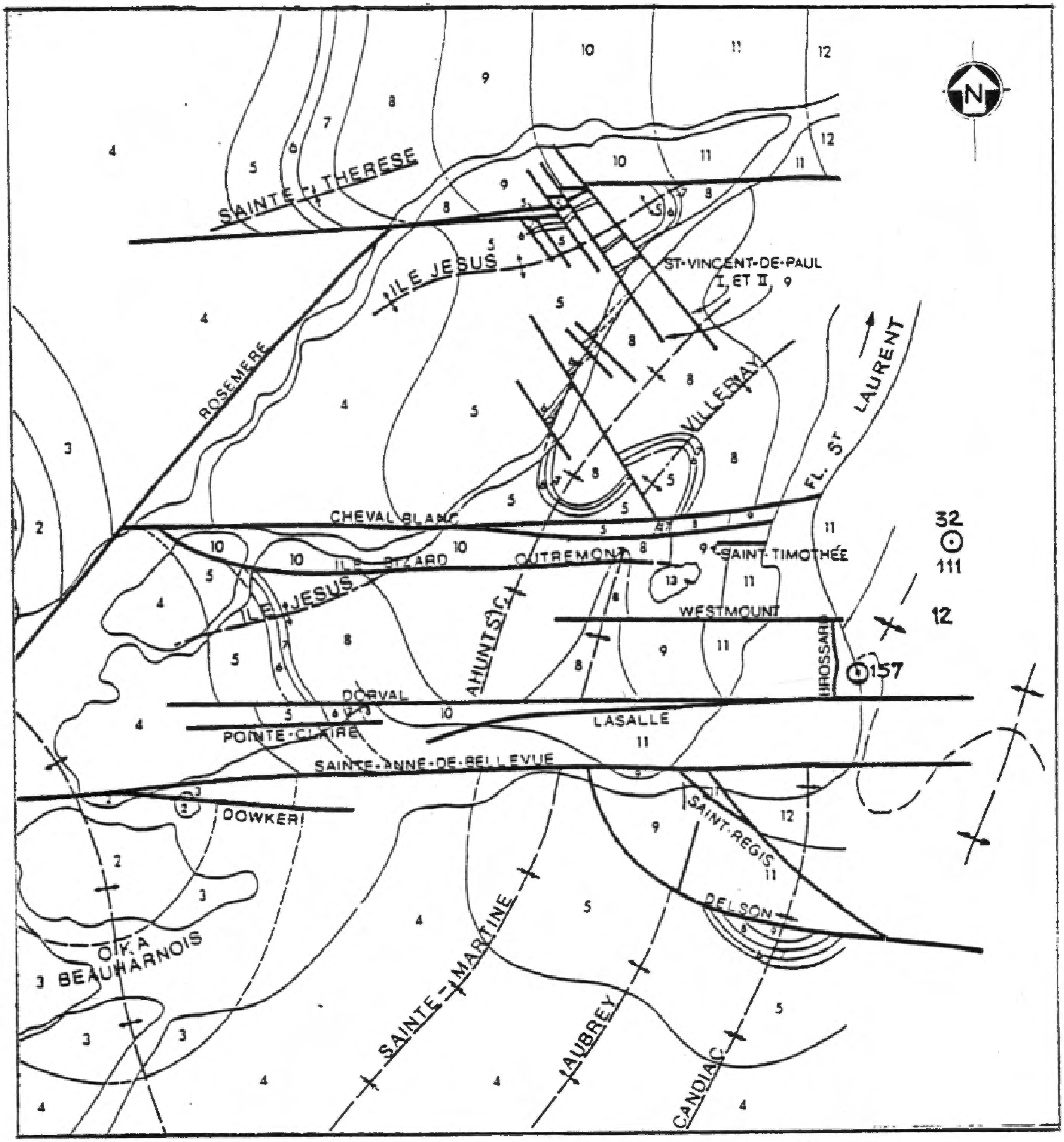
Deux venues d'eau sont dans le Beekmantown et trois dans le Potsdam, y compris la dernière qui correspond au fond du trou et à la température anormalement élevée de 56.5°C. Bien qu'en général, la fiabilité des mesures de température soit douteuse, la venue d'eau y ajoute un élément de crédibilité parce que la circulation a dû ramener plus rapidement la température du trou à celle des formations ambiantes.

En dehors d'une erreur de mesure toujours possible deux schémas géologiques peuvent expliquer cette température élevée.

FIGURE 3

GEOLOGIE DE LA REGION DE MONTREAL

Montrant la situation du puits "chaud" 157 (Canac - B.P. Sisque Brossard # 1)



6	Black River (BLR)	12	Lorraine (LRN)
5	Fm Laval (Chazy)	11	Utica (UTA)
4	Beekmantown (BMT)	10	Trenton (TRT)
3	Fm Châteauguay (PTD)	9	Trenton
2	Fm Covey Hill (PTD)	8	Trenton
1	Précambrien (PE)	7	Trenton

Echelle: Approx. 5 milles au pouce

D'après Clark 1972

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4.0 GEOLOGIE ECONOMIQUE (suite)

4.4.1 Puits 157 (suite)

Eau artésienne profonde:

On pourrait imaginer que le Potsdam est rechargé dans une région montagneuse (Appalaches) que l'eau descend à une profondeur de 4,500 m, où elle est réchauffée par le gradient normal pour ensuite remonter en suivant la stratification vers l'amont pendage. Cette situation n'est pas vraisemblable parce que, avec les pendages que nous avons dans la région, il faudrait que cette eau ait remonté le pendage sur une distance horizontale d'au moins 52 milles. Or la région est criblée de failles et, dans n'importe quelle direction, cette eau réchauffée aurait dû traverser au moins deux failles majeures. Nous rejetons ce schéma.

Remontée le long de failles:

Le puits 157 est situé dans une région de failles. La faille de Brossard de direction N-S (Figure 3) passe juste à l'ouest du puits. La continuation vers l'est de la faille Dorval-Lasalle de direction O-E passe aussi à côté du puits. Il est possible que ces failles aient fracturé le socle précambrien qui se trouve sous le Potsdam et permis des remontées d'eau chaude. Cette eau chaude pourrait se répandre dans le Potsdam qui a souvent une bonne perméabilité, spécialement dans les zones de failles où la fracturation a augmenté. Les nombreaux sills (et peut-être les dykes) de syénite montérégienne traversés par ce sondage pourraient malheureusement compliquer le trajet de l'eau chaude après sa sortie du socle. Si ce schéma est validé par des travaux ultérieurs, il posera des problèmes de tests parce que une exploitation traditionnelle avec un doublet de deux puits, l'un pour le pompage d'eau chaude vers la surface et l'autre pour la recharge d'eau refroidie, ne s'appliquera probablement pas.

Analyse:

Avec le peu de données disponibles que nous avons, il semble qu'il y a 60% des chances que l'anomalie du puits 157 soit causée par une erreur de mesure et 40% de chances qu'elle soit causée par une venue d'eau chaude remontant du socle le long de failles réactivées au cours de l'histoire géologique récente. Un essai infructueux d'assèchement à l'air comprimé de ce puits suivi, 10 heures après, d'une mesure de la remontée du niveau d'eau montrent que le puits s'est rempli à raison de 635 lites à l'heure. Comparé à 135,000 litres à l'heure produits par les puits géothermiques à basse énergie de la région parisienne, ce débit est très faible. Des structures plus ouvertes existent peut-être au voisinage et, étant donné que ce puits est dans une zone urbanisée, une éventuelle réouverture du puits pour vérification de sa température pourrait un jour être envisagée.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.4.2 Puits 126

Puits Laduboro QIG et AR # 1 Yamaska
Comté: Yamaska Paroisse: St-Antoine de la Baie du Febvre
Lot: 423 1 Concession

Formation	Profondeur (pieds)	Epaisseur (pieds)
Pas relevées	0 à 2500	
Trenton supérieur	2640	200
Trenton inf. à moyen	2840	350
Black River	3190	60
Chazy	3250	120
Beekmantown	3370	530
Potsdam	3900	485
Arène granitique (granite wash)	4385	22

Ce puits a donné une température de 48°C à 4,400 pieds dans l'arène granitique qui surmonte le socle précambrien. A 4.4 milles vers le sud-ouest un autre puits, le 159 (SOQUIP - Laduboro - Baieville # 1), a donné une température légèrement anormale dans le socle situé en-dessous de la même arène granitique. Les autres puits de la région qui ont des mesures de température, n'atteignent pas une profondeur suffisante pour permettre une comparaison valable.

L'interprétation géologique est risquée mais il se peut, qu'ici aussi, une faille ramène vers le haut des eaux chauffées à un niveau plus profond du socle.

Comme il n'y a pas de zone urbanisée dans le secteur, nous n'envisageons aucune effort supplémentaire dans la zone du puits 126.

4.4.3 Puits 187

Puits SOQUIP et Al Duchêne # 1

Ce puits est situé dans la zone Klippe sur la rive S-E du St-Laurent entre Québec et Trois-Rivières. Il se trouve à 2.8 milles au sud-est de puits 168 dont les coordonnées sont 46°27'55" et 71°54'06".

4.0 GEOLOGIE ECONOMIQUE (suite)

4.4.3 Puits 187 (suite)

Géologie	Profondeur (pieds)
Klippe	0 à 5770
Lorraine	7805
Utica	8730
Trenton - Black River	9550
Beekmantown	10200
Potsdam	10413 (3173.9 m)

La température du fond est de 98.8°C et le gradient de 2.62°C/100 m.

Les trous entourant le 187 n'atteignent pas le Potsdam mais le forage 161 situé à 4 milles au N.E. a pénétré à 4,900 pieds le Potsdam et le socle précambrien. Son gradient n'est que de 1.3°C/100 m. Il est évident qu'une faille passant entre les deux forages a déplacé le bloc de 187 vers le bas.

Il y a plusieurs sources possibles pour l'eau chaude du 187 mais comme le gradient n'est pas très élevé et que la région n'offre pas de centre urbain et de débouchés, nous n'envisageons pas de recherche supplémentaire.

4.4.4 Puits froids

Les puits 167 et 190 donnent des gradients de 0.5 et 0.7°C/100 m respectivement. Il serait séduisant d'expliquer ces températures basses par la présence d'eaux descendantes qui remonteraient ailleurs chauffées dans le circuit d'une cellule de convection; mais rien ne permet d'avancer cette hypothèse.

Plus probablement il s'agit de zones perméables où le fluide de forage est "dégurgité" par les formations longtemps après l'arrêt du pompage.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.5 Cibles possibles d'exploration géothermique

4.5.1 Aquifères artésiens profonds

Comme nous l'avons vu à propos du puits 157, les chances de trouver une nappe continue et assez profonde (3,100 m) pour être chaude sont négligeables à cause des nombreuses failles qui traversent les basses terres et provoquent un mélange des eaux. Pensant aux exemples de Régina (Sask.) et du Bassin parisien (France), c'est ce type de nappe artésienne qui nous paraissait le plus prometteur. Bien que nous abandonnions cette idée pour la plate-forme, il y a peut-être un certain potentiel dans la zone des nappes à cause de recharges naturelles possibles sur les hautes terres du S.E. (situées à droite et en dehors de la coupe schématique "SOQUIP" Figure 5). Néanmoins comme la zone des nappes est spéculative et qu'elle ne contient pas de centre urbain, nous n'y voyons aucune cible attrayante.

4.5.2 Zones de failles

Parmi les grandes failles il y a peut-être des aquifères actifs, soit parce que leurs continuations dans les terres hautes offrent des zones de recharge, soit parce que leur réseau dans le socle Précambrien est assez développé pour permettre des courants de convection. Nous avons aussi noté en 4.2.2.4 que la perméabilité des formations sédimentaires augmente fortement aux alentours des failles. Les cibles ou points de captage possibles auront probablement des formes allongées gisant le long de failles à l'endroit où ces failles passent du socle précambrien aux grès et arènes granitiques du Potsdam sus-jacent. La possibilité de trouver des failles ouvertes dans le socle grenvillien sous-jacent aux basses terres est réelle parce que d'un part la zone est encore sismique et, d'autre part, les températures ne sont pas assez élevées pour provoquer des réactions chimiques colmatant les interstices. Les venues d'eau dont nous spéculons la possibilité seraient tièdes $< 60^{\circ}C$, comme celles qui sortent de failles profondes dans les Appalaches américaines. L'exiguïté de ce genre de cible ne veut pas dire que l'on ne puisse pas y trouver des débits importants car, entre le Précambrien et l'époque actuelle, de grandes failles ont pu rejouer et rester ouvertes.

Une zone de cibles possibles serait l'extension vers l'est de la faille qui coupe les pointes nord de l'Ile Jésus et de l'Ile de Montréal pour ensuite passer par Varennes, sur la rive droite du St-Laurent, et St-Charles, sur la rivière Richelieu.

4.0 GEOLOGIE ECONOMIQUE (suite)

4.5.2 Zones de failles (suite)

La région de Varennes-Boucherville étant en train de s'urbaniser, le Potsdam des environs immédiats de cette faille pourrait-être exploré si l'aquifère du fond du puits 157 donnait de bons résultats valorisant ce genre de cible.

Une grande faille orientée N20^{o}E passe à St-Hyacinthe qui est peut-être un centre urbain assez grand pour fournir un marché à l'eau chaude éventuelle.

De plus la zone de cultures maraîchères intensives qui suit la rivière Yamaska en aval de St-Hyacinthe est parallèle à cette faille. Des serres pour le forçage des légumes, pourraient utiliser, à bon escient, une eau à 40^{o} considérée trop froide pour le chauffage des habitations. Comme pour la faille mentionnée au paragraphe précédent, il serait prudent d'attendre confirmation de la température du puits 157 avant d'envisager l'exploration de cette structure.

4.5.3 Socle précambrien - fracturation artificielle

En dehors des failles aquifères naturelles il est techniquement possible (et extrêmement coûteux) de fracturer les roches granitiques du socle à une profondeur suffisante pour exploiter le gradient géothermique normal. M.C. Smith et Al, voir article en annexe, mènent une étude à long terme sur la fracturation et l'exploitation par doublet d'un granite du Nouveau-Mexique où le gradient est élevé. Ils en sont encore au stage expérimental mais ont pu prouver que la méthode est techniquement viable. Dans les régions comme les Basses Terres où le gradient est normal, cette méthode pourrait seulement être intéressante dans un futur éloigné (tout comme la fusion nucléaire). Pour l'instant nous recommandons uniquement que les organismes directement impliqués dans les questions d'énergie suivent et gardent à jour les données émanant du groupe de M.C. Smith à Los Alamos, Nouveau-Mexique.

5.0 MARCHE DE L'EAU CHAUDE

Dans la région de Brossard (banlieue de Montréal) où se situe le puits 157, ainsi que dans les environs des autres cibles (cf 4.5.2) on doit se demander s'il existe un marché suffisant pour de l'eau chaude à 56°C. En raison des coûts minimums d'exploration et d'aménagement qui montent par paliers brutaux (voir rapport de P. Coulbois et J.-P. Herault en annexe) il faudrait se fixer un objectif minimum*, et, avant de passer à l'exploration, voir si ce marché existe; ceci pour éliminer le risque de s'engager à grands frais dans une impasse.

Deux sortes de marchés doivent être considérés:

a) marché de remplacement par lequel un certain nombre d'édifices publics, de blocs d'appartements ou d'usagers industriels pourraient et voudraient passer du chauffage aux combustibles pétroliers au chauffage à l'eau thermale;

b) un marché nouveau sur une zone s'urbanisant où, dès le départ, les ensembles pourraient être conçus en fonction du chauffage à l'eau chaude.

Des études similaires ont déjà été faites pour étudier le potentiel d'utilisation du gaz naturel dans certaines zones du Montréal métropolitain ou dans des villes secondaires susceptibles d'être branchées sur le gazoduc principal. L'expérience de ces études montre, qu'avant enquête, on ne peut préjuger un marché. Dans le cas qui nous concerne, il est estimé qu'une étude de marché comprenant la fixation d'un objectif de consommation minimum*, une enquête et des conclusions recommandant les sommes raisonnables a être affectées à un programme d'exploration, coûterait dans les $17,000.

6.0 INTERVENTIONS POSSIBLES

En supposant qu'il y ait un marché pour l'eau chaude à plus de 51°C, plusieurs interventions seraient possibles.

6.1 Vérification du puits 157

Comme il y a des doutes sérieux sur la température de 56°C mesurée au fond de ce trou, elle devrait être vérifiée en premier. Pour effectuer cette vérification il faudrait soit réouvrir le vieux puits, soit en forer un nouveau au voisinage (voir annexes 5 à 8).

6.1.1 Réouverture du sondage No. 157

En utilisant une "plate-forme de service" la réouverture et les mesures de température coûteraient environ $112,500. Si la température était effectivement élevée on devrait alors passer à des tests de pompage avec obturateurs et peut-être à un approfondissement du trou, ce qui pourrait doubler le coût de l'estimé ci-dessus.

6.1.2 Sondage d'un nouveau puits à large diamètre

Un trou de 8 7/8" de diamètre foré par un "rig" pétrolier normal coûterait dans les $930,000.

6.1.3 Sondage d'un nouveau puits de petit diamètre

L'avantage d'un puits de petit diamètre foré au diamant est que l'on aurait un carottage continu permettant une comparaison directe entre les porosités et perméabilités mesurées en laboratoire et les diagraphies. Le coût total du forage et des tests s'élèverait à $177,000.

6.2 Forages d'exploration et de production

Si les vérifications de 6.1 donnaient des résultats positifs et assez encourageants, il faudrait forer les puits de production. Pour le modèle géologique dont nous avons supposé l'existence (failles profondes) la réinjection par doublet n'est pas applicable et l'on espère que la production serait compensée par des recharges naturelles. Nous avons vu au paragraphe 4.4.1 que le débit du puits 157 est faible. Ce débit pourrait être augmenté par la fracturation, ou en multipliant les puits. A cause des complications géologiques et l'irrégularité de ce genre de cible, cette mise en production serait coûteuse et très aléatoire. Comme vu en 6.1.2, chaque puits coûterait environ un million de dollars.

6.0 INTERVENTIONS POSSIBLES (suite)

6.3 Recherches de l'IREQ

L'Institut de Recherches Electriques du Québec est en train d'étudier les possibilités d'utiliser l'eau de la nappe phréatique de surface pour activer des pompes à chaleur qui, en hiver, prendraient l'eau de la nappe à 10 - 15°C pour la réinjecter à 3°C dans la nappe. Il s'agit pour l'instant d'études sur modèle théorique mais, dès 1980, une unité expérimentale pourrait être construite à partir du modèle théorique le plus prometteur. Des études économiques basées sur l'unité expérimentale montreront si ces études pionnières pourront être applicables au chauffage collectif.

L'avantage de cette recherche est que les nappes de surfaces ou du moins peu profondes sont faciles à explorer et exploiter même si l'eau est salée. La clé du succès de ce nouveau développement se situe donc plus dans le progrès de l'utilisation des pompes à chaleur que dans la découverte d'une situation géologique exceptionnellement favorable.

7.0 CONCLUSIONS

L'étude des données disponibles a montré qu'il n'est pas sûr qu'il existe des nappes d'eau à températures anormalement élevées dans le sous-sol des Basses-Terres du St-Laurent. Cette incertitude pourrait être levée par des sondages coûteux (titre 6.0). Si ces sondages décelaient effectivement de l'eau chaude, celle-ci correspondrait presque certainement à un aquifère de "faille profonde" dont la géométrie s'opposerait à une exploration et des essais simples. Finalement, en supposant que l'exploration d'un tel aquifère soit couronnée de succès, il nous resterait encore à solutionner des problèmes de marché et d'exploitation.

Bien que nous ayons attaqué cette étude avec l'enthousiasme des "chercheurs d'or", notre exploration de toutes les avenues possibles montre que, dans l'état actuel de la technologie, un programme de sondages ou d'études supplémentaires n'est pas justifié.

Malgré l'issue négative de ce rapport nous recommandons que le dossier "Géothermie en Basse Energie" reste ouvert afin d'accueillir toutes les données nouvelles fournies, soit par l'exploration pétrolière, ou par la recherche sur les pompes à chaleur.

snc

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1

ANNEXE 1

ANNEXE 1

De: "A new study of terrestrial heat flow in the St. Lawrence lowlands of Québec".

Par: R. Doig, 1961

TABLE 6

SUMMARY OF THE HEAT FLOW RESULTS

BOREHOLE	SECTION	95% CONFIDANCE LIMITS IN dθ/dx (°C/cm)	95% CONFIDENCE LIMITS IN k (cal/°C/cm/sec)	95% CONFIDENCE LIMITS IN THE HEAT FLOW H (cal/cm²/sec)
MONTREAL # 1	800-1150'	$61.6 \pm 2.0 \times 10^{-6}$	0.0120 ± 0.0006	$0.740 \pm 0.044 \times 10^{-6}$
STE. ROSALIE # 2	500-1500'	$159.0 \pm 3.0 \times 10^{-6}$	0.00506 ± 0.00078	$0.805 \pm 0.118 \times 10^{-6}$
LOUNAN # 1 & CARTIER # 5	400-800'	$269 \pm 10 \times 10^{-6}$	0.00303 ± 0.00017	$0.815 \pm 0.056 \times 10^{-6}$

Average heat flow......$0.790 \pm 0.053 \times 10^{-6}$

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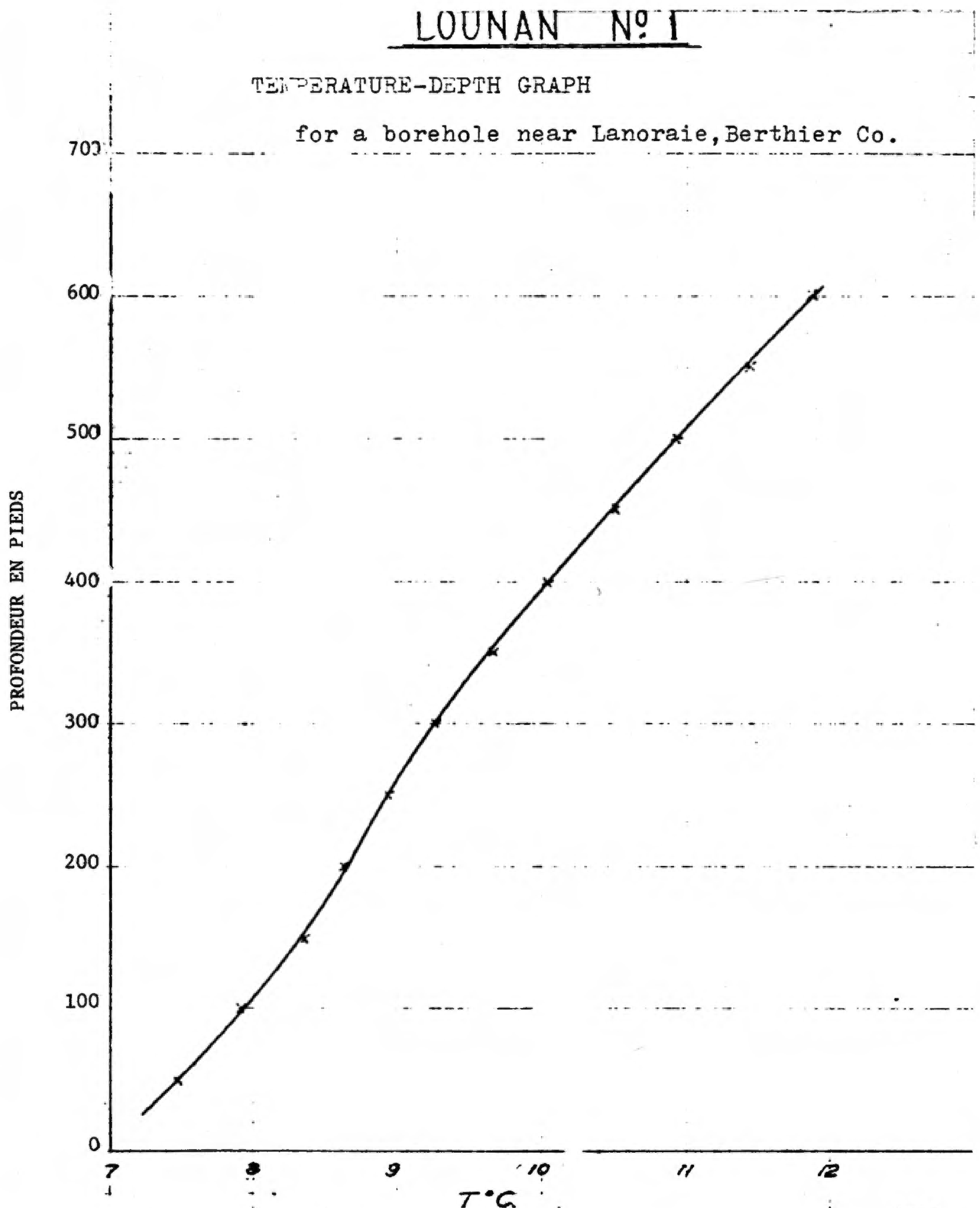
ANNEXE 2

ANNEXE 2

D'après Richard B. Butler. "Terrestrial heat flow in the St. Lawrence lowlands". M.Sc. Thesis, Mc Gill



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ANNEXE 3

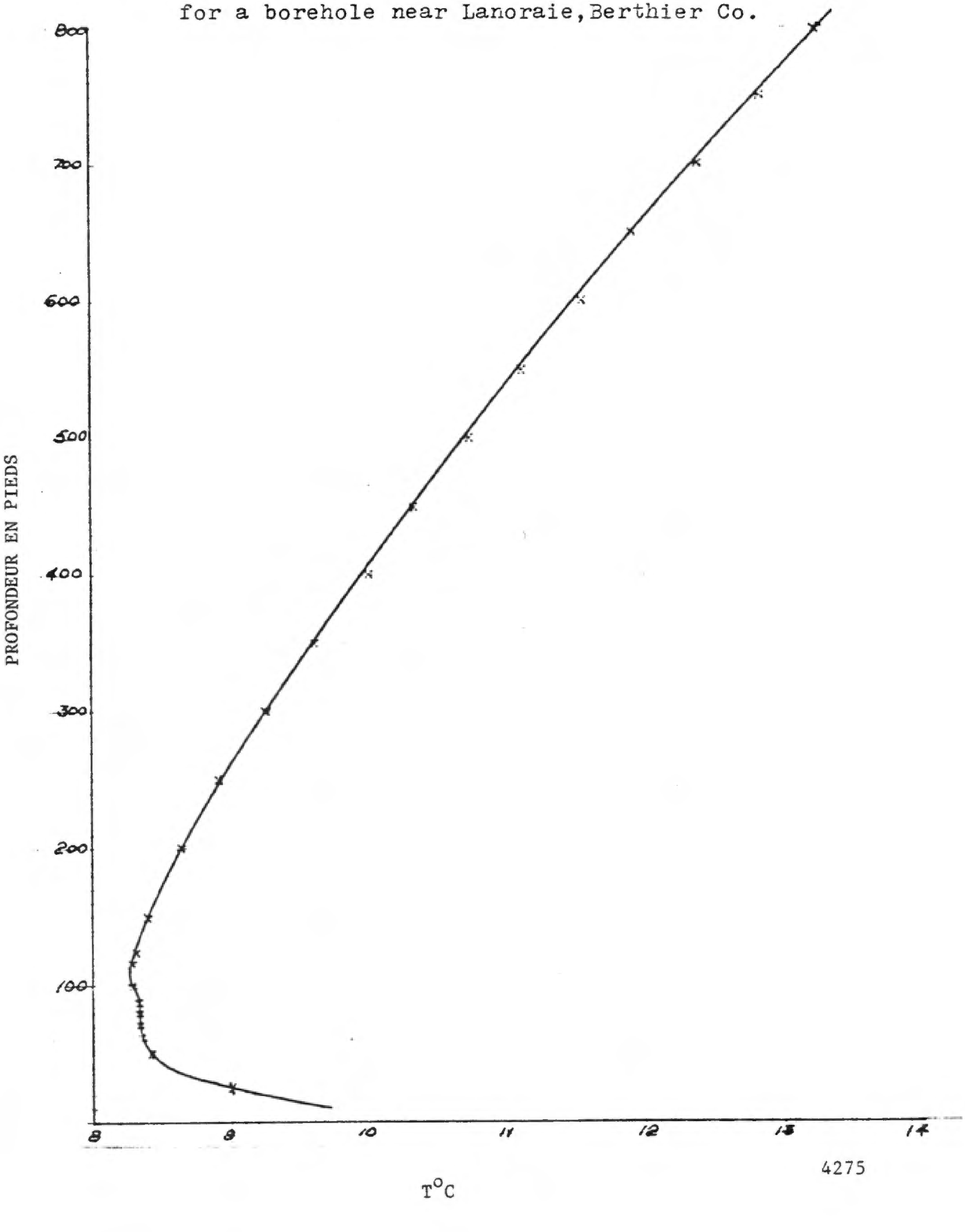
ANNEXE 3

D'après Richard B. Butler. "Terrestrial heat flow in the St. Lawrence lowlands of Quebec". M.Sc. Thesis, Mc Gill

CARTIER NATURAL GAS Nº 5

TEMPERATURE-DEPTH GRAPH

for a borehole near Lanoraie, Berthier Co.



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ANNEXE 4

76°

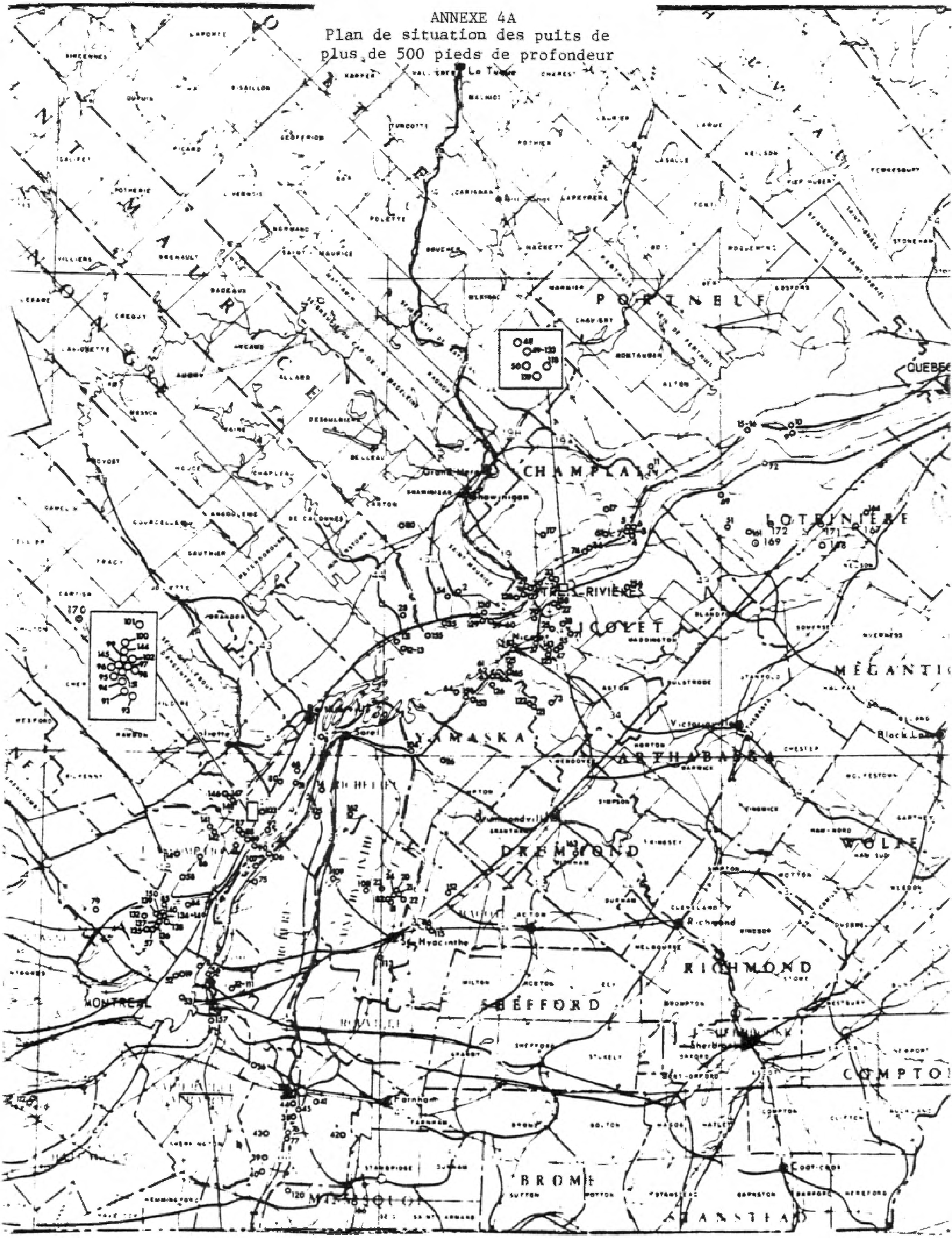
LÉGENDE LEGEND

LISTE DES PUI[illegible] DE 500 PIEDS DE PROFONDEUR
LIST OF [illegible] VER 500 FEET IN DEPTH

No	NOM DU PUITS / WELL NAME	COORDONNÉES / COORDINATES Latitude	Longitude
1	Montreal No 1	45 16 42	74 00 44
2	Yamachiche No 1	46 20 58	72 46 57
3	Bald Mountain Batiscan No 1	46 28 22	72 15 58
4	Bald Mountain Batiscan No 2	46 28 13	72 15 45
5	Bald Mountain Batiscan No 3	46 28 40	72 16 22
6	Bald Mountain-Batiscan No 4	46 28 32	72 15 48
7	Bald Mountain Batiscan No 5	46 28 21	72 16 09
8	Bald Mountain-Berthierville No 1	46 02 29	73 10 50
9	Bald Mountain-Cap Sante No 1	46 40 42	71 47 03
10	Bald Mountain Cap Sante No 2	46 41 48	71 47 17
11	Bald Mountain-La Perade No 2	46 36 29	72 12 30
12	Bald Mountain-Louiseville No 1	46 13 55	72 50 32
13	Bald Mountain-Louiseville No 2	46 13 55	72 58 32
14	Bald Mountain-St-Roch No 1	45 55 58	73 10 45
15	Bald Mountain-Portneuf No 1	46 40 59	71 55 19
16	Bald Mountain Portneuf No 2	46 40 58	71 55 18
17	Bald Mountain-Ste-Genevieve de Batiscan No 1	46 31 05	72 20 46
18	Bergeron	46 17 00	72 28 17
19	Cadbury & Fry	45 32 21	73 34 57
20	Canadian Natural Gas No 1	45 43 13	72 57 22
21	Canadian Natural Gas No 2	45 43 08	72 57 12
22	Canadian Natural Gas No 3	45 42 08	72 56 08
23	Canadian Natural Gas No 4	45 43 43	72 59 59
24	Canad[illegible] [illegible]ral Gas No 5	45 42 59	72 57 30
25	Canadian Seabord St Gregoire No 1	46 16 13	72 30 04
26	Canadian Seabord St Gerard No 1	45 59 42	72 49 23
27	Canadian Seabord Ste Angele No 1	46 19 07	72 29 10
28	Canso St-Maurice St Leon No 1	46 18 06	72 50 45
29	Caprive No 2 Trois Rivieres	46 21 30	72 34 49
30	Caprive No 3 Trois Rivieres	46 21 28	72 34 40
31	Cartier Natural Gas No 5	45 56 37	73 15 03
32	Cartier Natural Gas-St-Hubert No 1	45 30 47	73 25 58
33	Madeleine No 1	46 22 31	72 30 05
34	Madeleine No 2	46 22 28	72 29 59
35	Laduboro-Vercheres-St-Pierre No 3 Yamachiche	46 17 01	72 49 32
36	Couper No 1	45 21 02	73 22 01
37	Nicolet No 1	46 14 38	72 32 59
38	Eastern Canada No 1	45 14 44	73 15 12
39	Eastern Canada No 2	45 09 44	73 19 48
40	Eastern Canada No 3	45 07 43	73 20 05
41	Eastern Canada No 4	45 18 38	73 11 04
42	Eastern Canada No 5	45 12 32	73 06 38
43	Eastern Canada Gas & Oil No 6 Ste-Blaise	45 12 11	73 19 23
44	Eastern Canada Gas & Oil No 7 St-Jean	45 16 08	73 15 36
45	Eastern Canada Gas & Oil No 9 Ste-Anne de Sabrevois	45 15 30	73 14 06
46	Ferme Experimentale de l'Assomption	45 48 44	73 25 51
47	Forest	46 13 31	72 29 22
48	Gelinas No 2	46 21 31	72 28 17
49	Gelinas No 3	46 21 28	72 28 10
50	Gelinas No 4	46 21 25	72 28 10
51	Fortierville No 1	46 29 02	71 58 54
52	Govette	45 32 12	73 38 30
53	Lincoln No 1	45 29 35	73 15 03
54	Sweet Grass Yamachiche No 4	46 20 19	72 48 51
55	Guillemette	46 13 32	72 29 15
56	Huttes militaires de Longueuil	45 32 38	73 30 02
57	Quonto International No 1 St Vincent de Paul	45 38 46	73 39 36
58	Quonto International No 1 Mascouche	45 44 38	73 35 08
59	Canso Intercity Pointe du Lac No 1A	46 17 18	72 41 01
60	Canso Intercity Pointe-du-Lac No 1B	46 17 18	72 41 01
61	Laduboro No 1 La Baie Yamaska	46 10 16	72 40 43
62	Laduboro No 2 La Baie Yamaska	46 10 15	72 40 40
63	Laduboro No 3 La Baie Yamaska	46 10 18	72 40 40
64	Laduboro No 4 La Baie Yamaska	46 08 07	72 47 26
65	Laduboro No 5 La Baie Yamaska	46 10 14	72 40 28
66	Laduboro Seaway-Almega No 5 Champlain	46 26 16	72 23 44
67	Laduboro Seaway-Almega No 6 Champlain	46 28 11	72 20 48
68	Lounan No 1	45 58 21	73 15 07
69	Imperial Lowlands No 1	46 32 57	71 58 57
70	Imperial Lowlands No 2	46 17 42	72 33 18
71	Imperial Lowlands No 3	46 15 30	72 26 52
72	Imperial Lowlands No 4 Lotbiniere	46 38 59	71 52 04
73	Imperial Lowlands No 6 Nicolet	46 06 54	72 30 13
74	Imperial Lowlands Vercheres No 1	45 44 20	73 22 07
75	Imperial Lowlands Seaway No 1 Champlain	46 26 11	72 24 22
76	Lazo and Joseph No 1	45 12 27	73 15 40
77	Lazo and Joseph No 2	45 11 52	73 16 38
78	Maisonneuve	45 33 33	73 31 39
79	Mallet No 1	46 40 13	73 50 15
80	Mohr No 1	45 56 52	73 17 43
81	National Gas No 1	45 42 02	72 58 38
82	National Gas No 2	45 42 17	72 58 52
83	Seminaire de Nicolet	46 13 45	72 38 59
84	Okalta-Oilmont No 1	45 41 30	73 34 02
85	Okalta-Oilmont No 2	45 41 31	73 38 08
86	Oil Selections No 2	45 47 18	73 31 53
87	Oil Selections No 5	45 50 32	73 25 03
88	Oil Selections No 6	45 50 04	73 24 30
89	Oil Selections No 7	45 49 28	73 23 30
90	Oil Selections No 8	45 48 53	73 22 22
91	Oil Selections No 9	45 52 18	73 22 00
92	Oil Selections No 17	45 50 31	73 20 10
93	Oil Selections No 19	45 52 10	73 22 27
94	Oil Selections No 20	45 52 28	73 22 50
95	Oil Selections No 21	45 52 35	73 23 00
96	Oil Selections No 22	45 52 40	73 23 56
97	Oil Selections No 23	45 52 43	73 22 25
98	Oil Selections No 24	45 52 34	73 22 11
99	Oil Selections No 29	45 52 52	73 22 37
100	Oil Selections No 30	45 53 08	73 22 32
101	Oil Selections No 31	45 53 24	73 22 07
102	Oil Selections No 32	45 52 57	73 22 17
103	Oil Selections No 33	45 52 56	73 21 03
104	Quebec Fuel No 1	46 00 53	72 56 00
105	Quebec Fuel No 2	45 52 28	73 11 27
106	Quebec Fuel No 3	45 47 49	73 19 39
107	Quebec Fuel No 4	45 46 22	73 22 00
108	St Hyacinthe No 1	45 43 32	73 [illegible]
109	Richelieu Gas St Denis Nos 1 et 2	45 44 53	73 [illegible]
110	St Elie de Caxton No 2	46 29 18	72 57 04
111	St Johns Petroleum Co. St Hubert No 1	45 30 47	73 25 56
112	St Lawrence River No 1	45 16 28	74 01 06
113	Ste Madeleine No 1	45 34 55	73 00 03
114	St Philippe No 1	45 47 35	73 38 06
115	Ste Rosalie No 1	45 38 33	72 51 18
116	Ste Rosalie No 2	45 38 37	72 51 34
117	Seaway Almega No 9 St Maurice	46 28 09	72 31 46
118	Senneterre Metals Gelinas No 1 Ste Angele	46 21 25	72 28 03
119	Senneterre Metals Gelinas No 2 Ste Angele	46 21 22	72 28 07
120	Simigon No 1	45 06 33	73 16 40
121	South Shore No 1	46 06 35	72 33 36
122	South Shore No 2	46 06 39	72 33 53
123	Trudel	46 13 11	72 30 35
124	Uba No 1	45 31 28	74 08 30
125	Laduboro C.I.G. No 1 Nicolet	46 11 25	72 17 30
126	Laduboro C.I.G. No 1 Yamaska	46 09 15	72 40 42
127	Laduboro Bald Mountain Intercity No 1 Trois Rivieres	46 20 39	72 35 15
128	Laduboro Bald Mountain Intercity No 2 Trois Rivieres	46 20 08	72 36 39
129	Laduboro Bald Mountain-Intercity No 1 Pointe-du-Lac	46 17 19	72 42 24
130	Laduboro Vercheres St Pierre No 22 Pointe du Lac	46 18 24	72 41 58
131	Vercheres No 1 Louiseville	46 14 50	72 57 38
132	Que. Nat. Gas No 2 St Francois de Sales	45 39 46	73 41 36
133	Gelinas No 5	46 21 26	72 28 10
134	Que. Nat. Gas No 10 St Vincent de Paul	45 39 42	73 38 31
135	Que. Nat. Gas No 11 St Vincent de-Paul	45 38 34	73 40 09
136	Que. Nat. Gas No 12 St Vincent de Paul	45 38 52	73 39 09
137	Que. Nat. Gas No 13 St Vincent de Paul	45 39 13	73 39 00
138	Que. Nat. Gas No 14 St-Vincent de Paul	45 39 10	73 37 50
139	Que. Nat. Gas No 9 St Francois de Sales	45 39 54	73 39 21
140	Que. Nat. Gas No 10 St Francois de Sales	45 40 06	73 38 22
141	Que. Nat. Gas No 1 L Epiphanie	45 50 55	73 30 15
142	Que. Nat. Gas No 2 L Epiphanie	45 50 20	72 39 38
143	Senneterre No 2 St Gregoire	46 13 31	72 30 29
144	Louvicourt No 5 L Assomption	45 53 05	72 22 32
145	Louvicourt No 7 L Assomption	45 52 48	73 22 45
146	Que. Nat. Gas No 1 St Gerard Magella	45 54 54	73 27 28
147	Que. Nat. Gas No 2 St Gerard Magella	45 54 33	73 26 58
148	Que. Nat. Gas No 3 St-Gerard Magella	45 54 09	73 26 27
149	Que. Nat. Gas No 15 St Vincent de Paul	45 39 40	73 38 34
150	Que. Nat. Gas No 16 St Vincent de Paul	45 39 39	73 [illegible]
151	Louvicourt Metal No 8 L Assomption	45 52 46	73 [illegible]
152	Shell St Simon No 1	45 43 13	72 [illegible]
153	Laduboro No 6 La Baie Yamaska	46 07 18	72 44 01
154	Salem No 1 Dundee	45 03 32	74 25 52
155	M & G No 1 Yamachiche	46 15 26	72 52 12
156	Husky Gentilly No 1	46 21 30	72 16 48
157	Canoc BP Sisque Brossard No 1	45 26 40	73 29 27
158	Husky Bruyeres No 1	46 19 29	72 29 49
159	SOQUIP Laduboro Beieville No 1	46 07 13	72 45 16
160	CPOG Sisque SOQUIP Ile d'Orleans No 1	46 58 29	70 56 25
161	Shell Ste Francoise Romaine No 1	46 28 25	71 54 57
162	SAREP Laduboro St Ours No 1	45 52 45	73 06 30
163	Shell Bruceam No 1	45 48 04	72 25 42
164	Shell St Flavien	46 30 38	71 34 08
165	C.S. SOQUIP Laduboro No 1 & No 1A) Nicolet	46 10 42	72 37 41
166	Shell St Armand Ouest No 1	45 04 00	73 04 00
167	SOQUIP Shell Ste Croix No 1	46 37 17	71 32 16
168	SOQUIP Shell Villeroy No 1	46 27 55	71 52 16
169	SOQUIP Shell St Flavien No 1	46 29 24	71 [illegible]
170	CS SOQUIP Yamachiche No 1	46 17 27	72 [illegible]
171	SOQUIP [illegible] No 1	46 26 16	71 [illegible]
172	SOQUIP Villeroy No 2	46 23 47	71 [illegible]

47°
77°

ANNEXE 4A
Plan de situation des puits de plus de 500 pieds de profondeur



5

ANNEXE 5

ANNEXE 5

Comparaison des coûts de sondage

Compagnie A			Compagnie B
$ 15,000.	Mobilisation - démobilisation @ $1,000./j.	x 6 jours	$ 6,000.
	Installation @ $1,000./j.	x 6 jours	$ 6,000.
$ 10,000.	Désinstallation @ $1,000./j.	x 3 jours	$ 3,000.
$120,000.	0 - 4,000 pieds		$107,000.
$ 60,000.	4,000 - 5,000		$ 27,000.
$205,000.			$149,000.

$177,000.

Forage au diamant NQ-BQ, par des entrepreneurs de l'est du Canada spécialisés dans le sondage profond. Ces entrepreneurs ont également une certaine expérience pour la géothermie en Islande et au Portugal et pour le gaz au Québec.

Coût du temps d'attente:	Compagnie A	$75./hre/24 heures
	Compagnie B	$42./hre/24 heures

Coûts des tests de température estimés à $10,000.

SNC

6

ANNEXE 6

ANNEXE 6

Coût du nettoyage (estimé) du trou No. 157 par une compagnie ontarienne avec une plate-forme de service

Mobilisation - Démobilisation (incluant montage et démontage)	$ 50,000.
Sondages des bouchons de ciment - 2 j. x $5,000./j.	$ 10,000.
Si éboulis maximum: 8 jours supplémentaires @ $5,000./j.	$ 40,000.
Imprévus - 2 jours	$ 10,000.
	$110,000.

Coût du temps d'attente - $200./hre/24 heures

7

ANNEXE 7

ANNEXE 7

Estimé forage de 8 3/4" diamètre - tricorne -
par une compagnie de l'ouest du Canada

Mobilisation - Démobilisation	$250,000.
Installation et démontage ≃ 9 j. @ $4,800./j.	$ 43,200.
Forage ≃ $100./pi. x 6000 pi.	$600,000.
Extra: forêts, boues, tubage (casing)	$ 25,000.
	$918,000.

Coût du temps d'attente: $6,200./hre/24 hres

8

ANNEXE 8

ANNEXE 8

Liste des tarifs chargés par Schlumberger (Calgary)

Température, dia. min. requis 1 11/16"	$ 1.40/m.
Porosité, dia. min. requis 1 11/16" neutron	$ 1.91/m.
1 11/16" sonique	$ 1.93/m.
1 11/16" Gamma-X	idem
Résistivité - conductivité, dia. min. requis 2 5/8"	$ 2.00/m.
Densité, dia. min. requis 4 1/2"	
Diamètre du trou	$ 0.10/m.
Frais de mobilisation et démobilisation (Calgary - destination - aller-retour)	$ 0.04/mille

Coût du temps d'attente: $200 @ $300./hre

9

ANNEXE 9

Geothermal district heating

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1. Introduction

The optimum ambient temperature for human comfort is in the range of + 15-22 °C, depending on physical effort and to a certain degree on environmental factors such as relative humidity, air movement, exposure to radiation etc. The temperature of the natural environment in the inhabited parts of the earth varies, however, within the wide range of say — 35 to + 45 °C. Few parts of the earth offer the optimum temperature except for a relatively short span of the yearly cycle.

Clothing, houses and other shelters give protection against exposure to extreme cold and heat, but are insufficient for full comfort, unless the confined spaces are heated or cooled to the desired temperature. Artificial heating or cooling of houses requires expenditure of energy, which is supplied primarily by fossil fuels.

However fuels are costly, the reserves (while enormous) will ultimately be depleted, and their use pollutes the environment on a scale that is now becoming a real concern in many towns and metropolitan areas of the world.

An alternative source of energy that is eminently suited for this purpose is the geothermal energy which has been receiving increased attention in a number of countries in recent years.

Prospecting for geothermal energy is still only beginning, and accordingly estimates of the global reserves are bound to be uncertain.

The known reserves are nevertheless tremendous and growing every year as prospecting is continued. This is perhaps best illustrated by random examples.

Measurements of terrestrial heat flow in Hungary were carried out in 1954 and led to the discovery of reserves of 4,000 km^3 of hot water (60-200 °C) stored under the Hungarian plains. The recoverable heat has been estimated by Boldizsar (1970) at 2.3 × 10^{19} cal which is about 50% of the calorific value of the known petroleum reserves of the world. Important discoveries have been made in recent years in other parts of the world. It is thus claimed by Tikhonov *et al.* (1970) that thermal waters available for economic exploitation are found at depth in 50-60% of the territories of the U.S.S.R. Enormous hyperthermal areas are known in regions of recent or active volcanism in Europe, Africa and a number of countries surrounding the Pacific Ocean. The potential of the hydrothermal systems represents only a fraction of the energy reserves stored in the deep-lying rock formations of the earth's crust, provided that a suitable technology of extraction could be developed.

The utilization of geothermal energy presents as a rule minimal pollution problems, much less than those inherent to the use of fossil fuels. Most important, however, is the fact that the production cost per unit of energy is lower for geothermal energy than that of most if not all other available sources of energy.

Where geothermal energy is abundant it is in fact sufficiently economical that artificial microclimate can be created in relatively large sheltered spaces, say over scores or hundreds of hectares. This is of greatest importance for agriculture in countries with cold climates. But another obvious use for geothermal energy is the heating of houses in cold climates and cooling of houses in hot climates for increased human comfort.

The present paper will report on developments that have taken place in utilizing geothermal energy for house heating in various parts of the world, describe the technology employed and discuss some pertinent economic aspects.

2. Historical notes

(a) ICELAND

The use of geothermal energy for large-scale heating of houses was pioneered in Iceland, which is natural in as much as the country has a cold temperate climate requiring the heating of houses for about 330-340 days of a year. No fossil fuel sources are available in the country except limited reserves of peat and lignite. Hyperthermal areas are however abundant, as manifested by a multitude of hot springs and a number of major geothermal steam fields.

The first attempts at heating single farm houses were made in the beginning of the 20th century, and around 1925 hot spring water was used for the first hot houses for vegetables (Bodvarsson *et al.*, 1964; Zoëga *et al.*, 1970).

A major step forward was made when the first boreholes for hot water were drilled in the vicinity of Reykjavik in 1928, yielding 14 l/sec of 87 °C hot water. A 3 km long pipeline to the city was constructed, feeding a pilot district heating scheme comprising 70 houses, an enclosed swimming pool, an open-air swimming pool, and a public school house (Sigurdsson, 1964).

This venture was quite successful, and as a consequence more extensive drilling for hot water was started in 1933 at the Reykir thermal spring area some 18 km outside the city. This yielded about 200 l/sec of 86 °C hot water, and in the years 1939-1943 a new district heating system was constructed, serving 2,300 houses with about 30,000 people and all public buildings of the town. The system included an 18 km long transmission pipeline, pumping stations, 8,000 m^3 water storage tanks and underground distribution network in the streets of the town. This system was commissioned on 1 December 1943 and is still operating quite satisfactorily.

An extension of the system was built in 1949-50 after additional drilling had been carried out 3 km north of Reykir. A total of 72 boreholes were drilled in these two spring areas, producing a total of 330 l/sec of 86 °C water. The boreholes vary in depth from about 300 m to 770 m.

The Reykir fields have now been producing continuously for about 35 years, and the total production over this period is of the order of 300 million m^3 of water without any drop in temperature or decrease of the production rate.

A geoscientific survey of the area within the limits of the city of Reykjavik was resumed in 1954 (Bodvarsson and Palmason, 1964) and delineated a thermal area where deep drilling (700-2,200 m) was started in 1958. The steady yield of his field is now 300 l/sec of 128 °C water, and another thermal area more recently discovered and developed on the eastern periphery of the city yields about 165 l/sec water at 105 °C (Zoëga *et al.*, 1970).

The district heating system has been greatly expanded on the basis of these new thermal sources and 8,700 houses with 72,000 inhabitants were connected to the system by the end of 1969. This represents about 87% of the houses in the city, and the goal of connecting new residential quarters to the heating system as soon as they are built is nearing realization.

The city of Reykjavik has developed, owned and operated the systems from the very beginning. It has been highly sucessful, technically and economically, and is perhaps more highly regarded by the inhabitants than any other public service. This has contributed to the general concept in Iceland that, where thermal resources are available, a district heating system is a necessary and normal public service, just as much as a cold water supply, an electricity supply or a sewer system.

Developments in other parts of Iceland have been somewhat slower than in the capital, mostly because of lack of suitable financing resources for the rather capital-intensive geothermal installations.

The town of Olafsfjördur in northern Iceland with 1,000 inhabitants built its first district heating system in 1944 using hot water of only 48 °C produced by drilling in a thermal area about 3 km away. Deep drilling in 1961 yielded additional water at 56 °C. The system comprises all the houses of the town, and it has been quite successful.

The town of Selfoss (2,200 inhabitants) in southern Iceland has a district heating system which was built and operated by a local cooperative society from 1948 until 1969, when it was sold to the township. It heats the whole town comprising 154,000 m^3 of flats and 75,000 m^3 of public, commercial or industrial buildings. The water is supplied from boreholes, 1.5 km outside the town and the production is 80 l/sec water at 80 °C.

The village of Hveragerdi in southern Iceland with 820 inhabitants and a balneo-therapeutic institution for 140 patients, is one of the main hot house centres for growing flowers and vegetables. A district heating system serving all houses in the village and supplying heat to 30,000 m^2 of hot houses has been in operation since 1953. This is the only district heating system in Iceland that uses a high-temperature field (180 °C).

The town of Saudárkrókur in northern Iceland (2,000 inhabitants) has operated a district heating system for about 15 years, utilizing water at 70 °C from boreholes in the vicinity.

Since about 1930 elementary and secondary boarding schools in the rural areas of Iceland have whenever possible been sited at locations where geothermal energy is available. In these centres the school buildings and living quarters for the pupils and staff are geothermally heated. They are also as a rule equipped with a swimming pool, and are self-supplying with vegetables (tomatoes, cucumbers, cauliflowers, etc.) grown in their own hot houses. There are now many such schools in various parts of the country, and quite often they are used as tourist hotels during the summer holidays. Quite often these centres have formed the nuclei of new service communities in the rural areas.

Several new district heating schemes have been studied, and some are now under construction. A scheme for supplying the satellite towns of Reykjavik with geothermal heat from the neighbouring high-temperature areas has been studied. Feasibility studies have been made for district heating systems for Akureyri (10,000 inhabitants), Siglufjördur (2,500 inhabitants), Akranes (4,500 inhabitants), Húsavik (2,000 inhabitants), Keflavik International Airport and the neighbouring communities of Njardvik and Keflavik (about 10,000 inhabitants), Dalvik (1,000 inhabitants), Hrisey (300 inhabitants), Egilstadir (800 inhabitants), Reynihlíd at Lake Myvatn (200 inhabitants and some tourist hotels). Several of these projects are already being executed or are being seriously considered.

At the end of 1969 a total of almost 80,000 people, or 40% of the population of Iceland (200,000), lived in houses heated with geothermal energy. On the basis of the present geographical distribution, the author has estimated elsewhere that 60-70% of the population could be supplied with direct geothermal heating for their homes. Figure 1 shows the gross production of geothermal energy in Iceland since 1960 with a forecast of the growth until 1975 (Palmason and Zoëga, 1970).

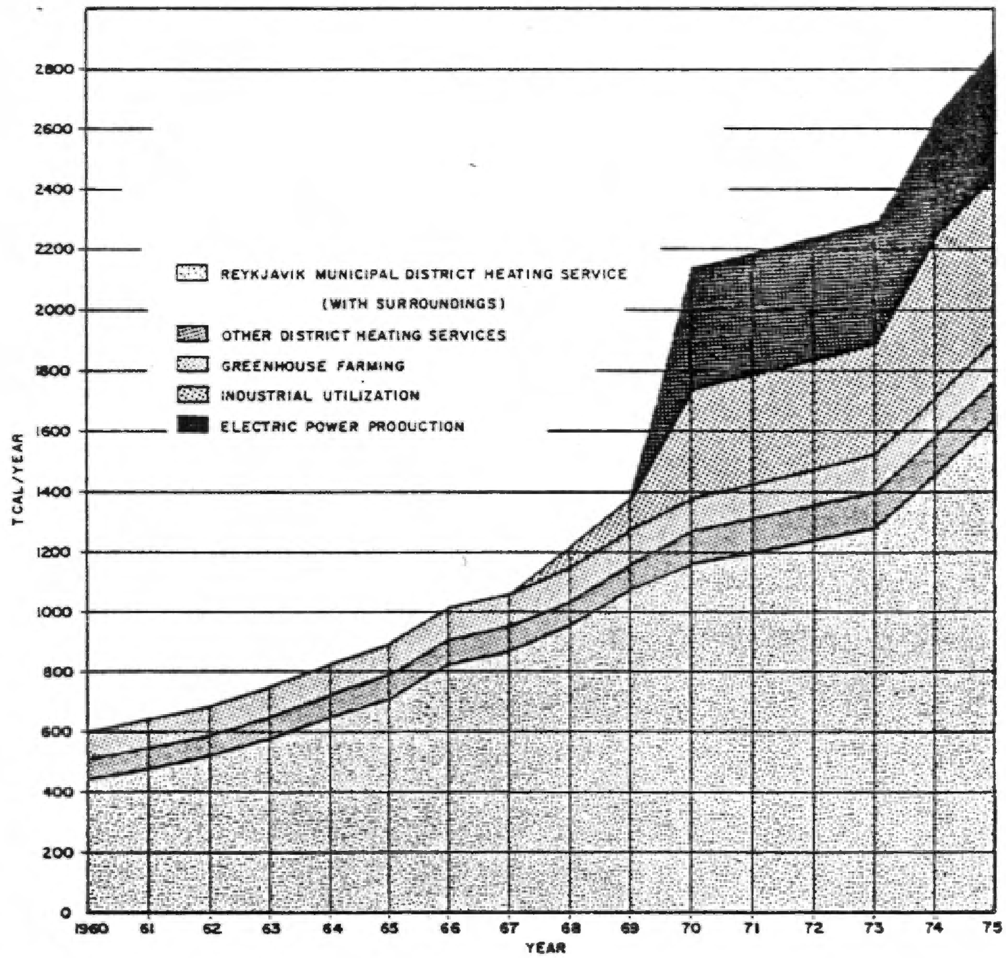

FIG. 1. Gross production of geothermal energy in Iceland (above 40 °C).

(b) HUNGARY

Following the discovery of the vast geothermal reserves of Hungary about 15 years ago, considerable interest was aroused for utilizing the energy for domestic heating. Plans were studied for constructing a geothermal district heating system for the city of Szeged around 1962. However, the drilling for hot water for this project led to the discovery of Hungary's richest oil and gas field, which resulted in the heating system being converted from geothermal energy to gas. Subsequent utilization of geothermal energy in Hungary has concentrated on agricultural applications (hot houses and animal husbandry), which have expanded extremely rapidly (400,000 m^2 hot houses by the end of 1969, expected to be doubled in 1970) (Boldizsar, 1970).

The total volume of buildings heated with geothermal energy by mid 1969 is reported as follows (Boldizsar: private communication):

Szeged 1,200 flats	120,000 m^3
Szeged University clinics	106,000 "
Hódmezövásárhely factory	160,000 "
Hódmezövásárhely Hospital	12,000 "
Makó Hospital	80,000 "
Total	478,000 m^3

The thermal waters of Hungary produced by drilling to a depth of about 2,000 m have a temperature of about 90 °C and the yield per well is of the order of 15-30 l/sec on the average.

(c) JAPAN

The traditional use of thermal springs in Japan, dating back through centuries, is for recreation and health (balneological and therapeutic uses). It is thus estimated that 100-150 million visitors enjoy annually the recreational facilities offered by the thermal springs of Japan (Komagata *et al.*, 1970).

Thermal waters have been used for hot houses for flowers since 1916, and hotels and other facilities of the recreational centres are now heated with geothermal waters.

The construction of geothermal district heating schemes involving comparatively long-distance transmission of thermal waters has been reported (Mashiko and Hirano, 1970) in the following localities:

An 11.5 km long transmission line carrying 14 l/sec of 70 °C water from the Sarukura springs to the town of Towata, was constructed in 1963.

A 12 km long transmission line in the Okawa area was built in 1963. It carries about 22 l/sec of 70 °C water and supplies 3,000 houses with heat on an area of 260 hectares.

A district heating system was built for the Ukiyama area in 1965, comprising 900 houses on 100 ha. The system is equipped with a boiler plant that can heat the water to 55 °C. The total length of pipe is 12 km.

A district heating system for the city of Aomori was constructed in 1966-67. It supplies 140 houses, including 34 hotels, and the population is 3,600. The water is supplied from the Asamushi hot spring area at a flow rate of 22 l/sec and 60 °C. The natural springs have temperatures in the range of 40-70 °C.

Attention has been given to the possibility of using waste heat from geothermal power stations for domestic heating.

(d) NEW ZEALAND

Considerable use of geothermal energy for domestic heating has been reported in the town of Rotorua (20,000 inhabitants), a tourist centre with balneo-therapeutic institutions (Kerr *et al.*, 1964; Burrows, 1970; Cooke, 1970).

The town is situated on a high-temperature area and a very large number (about 1,000) of boreholes issuing a mixture of water and steam have been drilled within the city limits. The individual boreholes are connected to single houses, groups of houses or to public building complexes, hospitals, etc., but an integrated district heating system for the whole town has not been organized. This leads apparently to rather wasteful use of the energy, and creates certain disposal problems for the excess hot water. The use of geothermal heating in Rotorua was started about 30 years ago.

A remarkable development is the recent construction of a 100-room tourist hotel in Rotorua that is not only heated with geothermal energy, but also cooled during the hot season by the use of a lithium bromide absorption unit powered with geothermal heat. This installation was commissioned in 1968 (Reynolds, 1970).

(e) U.S.S.R.

Some of the extensive hydrothermal areas of the U.S.S.R. seem to have been discovered and known for very many years as a result of drilling for oil (Tikhonov *et al.*, 1970; Sukharov *et al.*, 1970).

One such deep borehole in Makhach-Kala producing about 23 l/sec of 63 °C water has been used for 22 years for supplying dozens of dwelling houses and industrial buildings with hot water. Today several boreholes are in use supplying heat and hot water to certain districts of the town. One heat distribution station supplies districts with 15,000 inhabitants with 70 l/sec. Geothermal water is also used for hot houses and soil heating in this area.

Systematic prospecting for hyperthermal reserves and drilling for geothermal energy for its own sake did not take place until 1960.

Much attention has evidently been devoted to problems of energy utilization and the development of technically and economically sound systems, quite often involving combined schemes (Kremnjov *et al.*, 1970). A number of experimental systems have been designed and taken into use, some of which will be described later in this paper.

Besides the installations at Makhach-Kala mentioned above, the following have been reported (Lockchine and Dvorov, 1970).

Astarinsk district Azerbaidjan	15 hectares hot houses	46.5 Gcal/h
Zgoudidi town Georgia	Heating of flats, public buildings, industrial buildings, hot houses, swimming pools	50 Gcal/h
Iserbach town Daghestan	District heating for 7,500 inhabitants and industrial uses	6 Gcal/h
Caspillsk town Daghestan	District heating for 5,000 inhabitants and hot water supply	5.0 Gcal/h
Massalinski district	15 hectares hot houses	46.5 Gcal/h
Mendji Georgia	Heating of meteorologic station and agricultural uses	2.0 Gcal/h
Paratounka Kamchatka	Heating of 3 apartment houses with 48 apartments each	0.55 Gcal/h
Ternahir Kamchatka	5 hectares hot houses and soil heating of 5 hectares	19.5 Gcal/h
Zaichi Georgia	Heating of meteorologic station, hot houses and baths	2.1 Gcal/h
Cherkesk Stavropol	District heating for 18,200 inhabitants, industrial uses, hot houses	22 Gcal/h
Total		200.2 Gcal/h

3. Technical aspects

The general technology of house heating, comfort cooling and district heating using conventional sources of energy, such as fossil fuels or electricity, is well known and need not be elaborated here.

Geothermal energy, however, has certain inherent characteristics that have to be taken into account whenever a geothermal system is planned and designed.

1. The thermal fluids have a fixed temperature in each thermal area.
2. Each borehole has as a rule a constant output.
3. The unit cost of the energy produced and/or delivered to the ultimate consumer is predominantly capital costs (depreciation, return on capital, etc., similar to hydropower).
4. The chemistry of the thermal fluid must be observed.
5. The transportability of the thermal fluids is limited.
6. The unit cost of the energy produced and delivered is dependent on the capacity of the system (scale effect).

Every district heating project must be tailored to the climate of the site. The most significant characteristic of the climate in this respect is the variation of the daily mean outside temperature over the year. Due attention must also be given to the diurnal variation of the outside temperature, and the effect of such factors as wind velocity and solar radiation.

Figure 2 shows qualitatively a typical duration curve for the mean daily temperature over the year.

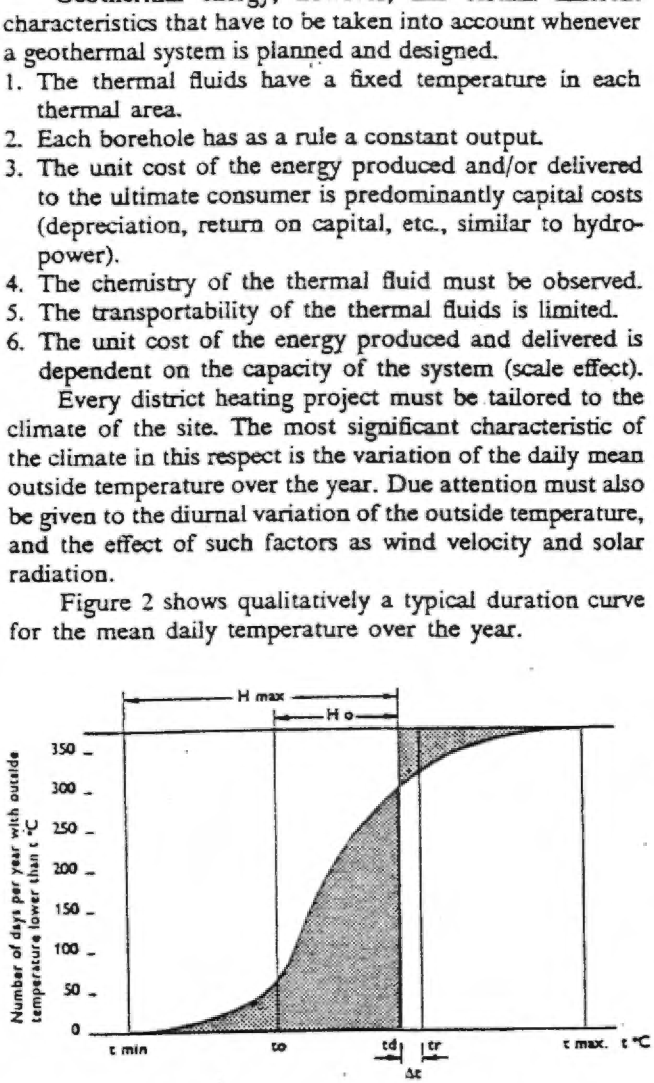

FIG. 2. Typical duration curve for the mean daily temperature over the year.

The objective is to maintain a constant optimum room temperature t_r in the heated buildings, for instance 20-22 °C for apartments. The building receives, in addition to the heat supplied by the system, a certain amount of 'free heat', i.e. heat lost by the occupants, electric lighting and appliances, solar radiation, etc. The free heat increases the room temperature by Δt °C, and accordingly the design room temperature is:

$$t_d = t_r - \Delta t \ ^\circ\text{C}$$

The power required for heating is directly proportional to the differences between the inside design temperature and the outside temperature:

$$H = k(t_d - t) \text{ kcal/h}$$

where t is the outside temperature (°C).

The shaded area in Figure 2 for $t < t_d$ represents the annual number of degreedays G_h requiring heating, and for $t > t_d$ the degreedays G_c requiring cooling in order to maintain the desired room temperature.

The annual energy demand for heating (or cooling) is directly proportional to the number of degreedays.

The unit energy cost is, as stated before, predominantly capital costs. A geothermal district heating system that has sufficient power to maintain the desired room temperature on the coldest day of the year would have a very low annual load factor, and consequently high unit energy costs. The annual load factor for heating can be defined as:

$$\eta_{min} = \frac{G_h}{365(t_d - t_{min})}$$

where G_h = degreedays for heating above t_{min},
t_d = the design room temperature °C,
t_{min} = the mean temperature of the coldest day of the year.

If the geothermal system were designed to maintain the desired temperature to a minimum outside temperature of t_0 only, where $t_0 > t_{min}$, the annual load factor would be:

$$\eta_0 = \frac{G'_h}{365(t_d - t_0)}$$

where G'_h = degreedays for heating above t_0,
t_0 = the so-called base temperature, °C, i.e. the mean temperature of the coldest day at which the geothermal system can still maintain the desired room temperature.

Reference to Figure 2 shows that this would greatly improve the annual load factor, and reduce the unit cost of the geothermal system correspondingly. The power of the geothermal system would be reduced in the proportion H_0/H_{max} (Fig. 2), and in the first approximation the unit geothermal energy costs would be reduced in the proportion:

$$\frac{e_0}{e_{max}} = \frac{\eta_{min}}{\eta_0} F \frac{(H_0)}{(H_{max})}$$

where e_0 = unit energy cost for geothermal system with base temperature t_0,
e_{max} = unit energy cost for geothermal system with base temperature t_{min},
$F \frac{(H_0)}{(H_{max})}$ is a function that defines the variation of the capital investment for the system in relation to the ratio of installed power (H_0/H_{max}).

The remaining problem is how to handle the heating demand of the relatively few days of the year that have outside temperature $t < t_0$, and days with high wind velocity at which the system may only be able to handle the load at $t > t_0$.

This problem is aggravated by the fact that the water of the geothermal system has constant temperature, and accordingly the efficiency of heat utilization in radiators decreases with increased load.

The simplest solution is to expect the consumers to accept a lowering of the room temperature on the relatively few days of the year with $t < t_0$. This can be tolerated if the cold spells are of short duration and the houses have some heat storage capacity (masonry or concrete construction), but it is not popular with the consumers.

Thermal aquifers, where the temperature allows installation of deep well pumps in the boreholes (150–180 °C or less) can sometimes yield increased production for a limited time by pumping at a considerable draw-down of the water level. This method has been used in Reykjavik, Iceland, for several years (Zoëga *et al.*, 1970).

Heat pumps utilising the heat of the waste water leaving the house systems are being used in Paratounka, Kamchatka, U.S.S.R., to supply additional heat (Lokchine *et al.*, 1970).

It has been suggested (Bodvarsson *et al.*, 1964) to store surplus hot water by injecting it into underground permeable formations if such are available in the vicinity of the system.

The most practical solution is usually to install facilities for peak heating of the water by fossil fuels or electricity as required, perhaps in combination with one or more of the above mentioned methods. This has been done in Iceland, Japan and U.S.S.R. The sum of the energy requirements of the coldest days is so small in comparison with the annual energy needs that the use of expensive peak heating is fully justified.

The selection of the base temperature t_0 for the geothermal system must be taken as a compromise in each case, with due consideration to the climatic premises and the available means of dealing with the peak load.

The demand for heat is not only subject to seasonal variation over the year as discussed above, but also to diurnal variation. Figure 3 shows the variation of the load over 24 hours on two consecutive days in one of the sub-stations of the Reykjavik District Heating System. This comprises the demand for heating and for hot tap water. The general shape of the curve (b) is typical for most days of the year; however, it is of interest to note the difference between the demand of the two days, which shows the influence of 'free heat' due to a few hours of sunshine (a).

In as much as the unit cost of energy in geothermal district heating systems is primarily capital cost, attention should be given to all available possibilities of either reducing the investment or increasing the annual load factor.

At the present state of the art, geothermal power stations operating in geothermal fields with two phase flow have a very low factor of energy utilization, which means that they supply enormous amounts of waste energy. Wherever possibilities permit this should be used for district heating, agricultural or industrial purposes. Combined schemes allowing the use of excess water for heating hot houses and especially for soil heating are practical measures for improving the annual load factor.

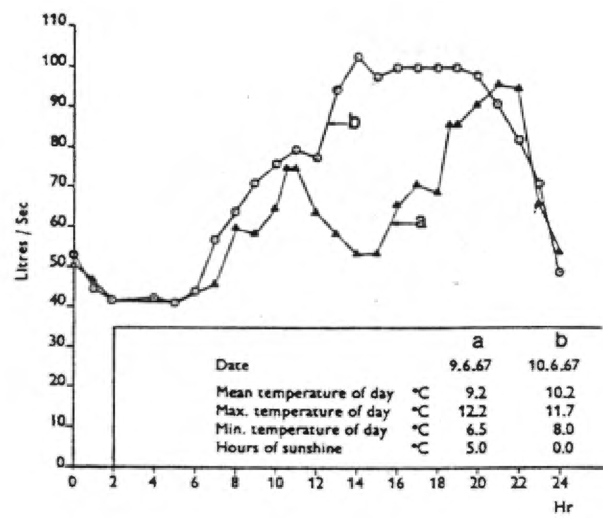

FIG. 3. Variation of the heat load over 24 hours on two consecutive days in one of the sub-stations of the Reykjavik District Heating System.

The above discussions have been concerned primarily with problems associated with the heating of homes and other buildings.

In certain climates, the cooling of premises is required for comfort. The use of absorption equipment for cooling opens up new perspectives for the utilization of geothermal energy (Reynolds, 1970).

The shaded area above for $t > t_d$ in Figure 2 represents the number of degree days G_c requiring cooling. If the energy requirements for cooling were supplied by the district heating system, its annual load factor would be:

$$\eta_0 = \frac{G'_h + xG_c}{365(t_d - t_0)}$$

where G'_h is the number of degree days for heating above base temperature t_0,

G_c is the number of degree days for cooling above the design temperature t_d,

x is the ratio of the energy requirements for each degree day of cooling and heating respectively.

The load factor is thus obviously improved.

Figure 4 shows in a similar way to Figure 2 the main characteristics of three types of climate. Figure 4*a* shows a subarctic insular climate like that of Iceland, Figure 4*b* a cold temperate continental climate, and Figure 4*c* a tropical climate. The last two figures are qualitative but they indicate, as stated above, that there should be an oppor-

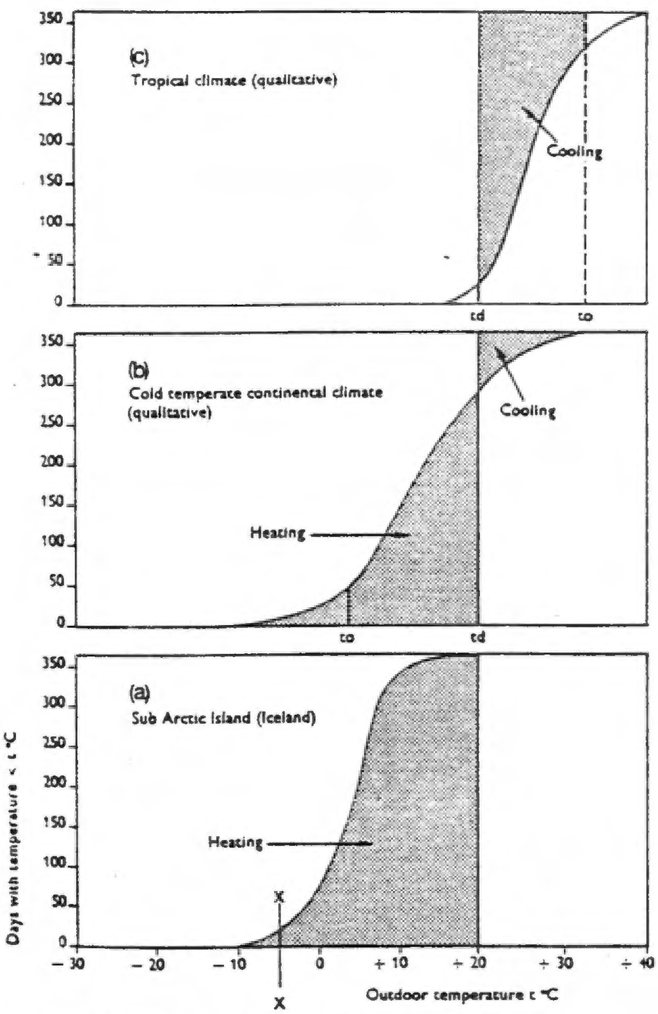

FIG. 4. Main characteristics of three types of climate.

tunity of improving the annual load factor in continental climates by the introduction of comfort cooling, and they raise the question whether an economic basis can be found for district comfort cooling systems in the tropical parts of the world. The tropical countries have an urgent need for cooling in connexion with food processing and storage, and other industrial uses for cooling and heating might be found and developed, comparable with the use of geothermal energy for soil heating and hot houses in colder climates. Combined comfort cooling and industrial schemes might therefore be feasible in the tropics.

4. Description of some geothermal district heating systems

(a) REYKJAVIK DISTRICT HEATING SYSTEM

This is the oldest and still the largest geothermal district heating system in the world.

The principal physical data of the system are summarized in the following tabulation, which is based on published data (Zoëga and Kristinsson, 1970).

1. *Climatic data*	
1.1 Mean temperature of the year	+ 5 °C
1.2 Mean temperature of the warmest month (July)	+ 11.2 °C
1.3 Mean temperature of the coldest month (Jan.)	— 0.4 °C
2. *Available heat resources (Dec. 1969)*	
2.1 Reykir geothermal area 1,000 m³/h at 80 °C	40 Gcal/h
2.2 Reykjavik geothermal area 1,700 m³/h at 119 °C (average)	135 Gcal/h
2.3 Own peak power boiler plants (oil fired)	30 Gcal/h
2.4 National Power Co. peak power boiler plant (available at electrical off-peak hours only)	20 Gcal/h
Total	225 Gcal/h
3. *Heat load*	
3.1 Volume of houses connected	10.3×10^6 m³
3.2 Number of houses connected	8,700
3.3 Heat load at — 10 °C outside and + 20 °C inside	190 Gcal/h
3.4 Specific load at — 10 °C outside and + 20 °C inside	19 kcal/h m³
4. *System data*	
4.1 Installed horsepower in pumping plants	5,115 hp.
4.2 Area served by distribution system	11.2 km²
4.3 Length of pipe lines	
4.3.1 Collecting mains	14.2 km
4.3.2 Supply mains	29.1 km
4.3.3 Street mains	125.2 km
4.3.4 House connections	120.2 km
4.4 Average density of population	643 inhabitants/km²
4.5 Average load density	17 Gcal/h km²
5. *Yearly heat production*	
5.1 Geothermal energy (1968)	960 Tcal/year
5.2 Peak power stations (1968)	80 Tcal/year
Total	1,040 Tcal/year

The development of the geothermal areas feeding the system has been described earlier in this paper.

Figure 5 shows the present system in principle. The water from the boreholes in the Reykir fields (86° C, 280 l/sec) flows by gravity into collecting tanks (1) from which it is pumped through a 15.3 km long pipeline (two 350 mm diameter pipes) to storage tanks (4), capacity 8,000 m³, on a hill within the city. The pumps are governed by air operated valves on the discharge side operated by level control in the collecting tanks. An oil-fired peak heating plant (2) can raise the temperature of the water on cold days. The water temperature in the main storage tanks is maintained at about 90 °C.

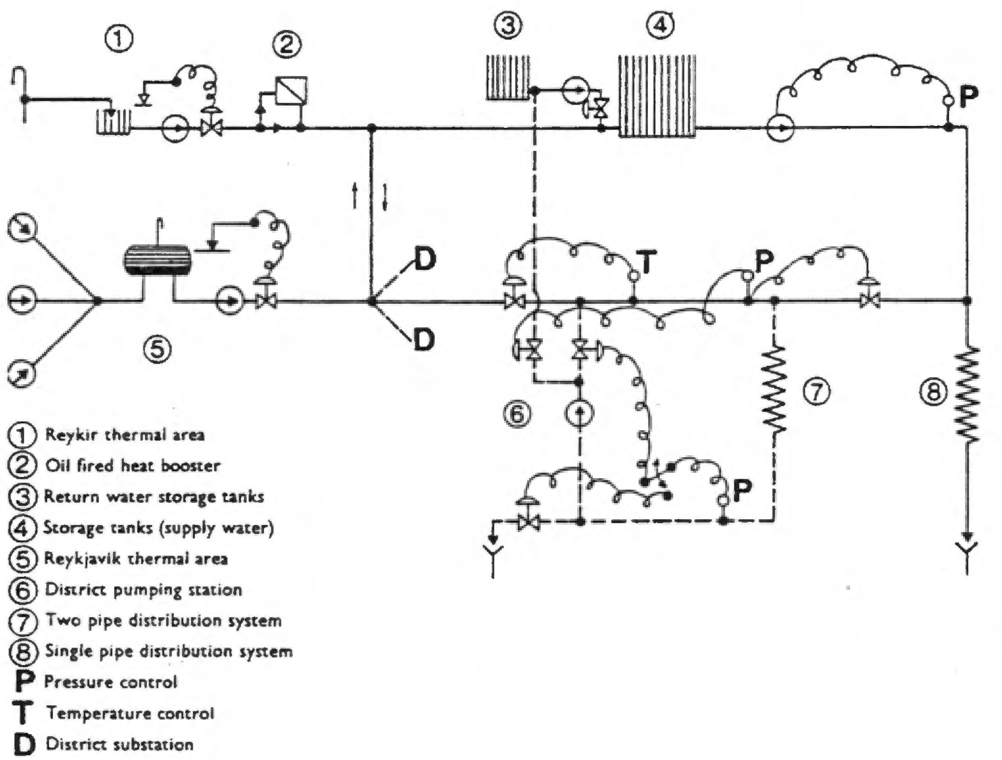

FIG. 5. Schematic diagram of system.

The boreholes of the Reykjavik fields (5) (temperature range 105-140 °C, average 119 °C, total flow 470 l/sec), are equipped with deep well pumps set at 110-120 m depth. The water in the collecting mains is thus under sufficiently high pressure to prevent flashing in the pipes to the nearest main pumping station. In the pumping stations the water passes through deaerators where controlled flashing occurs in order to remove gases (primarily nitrogen) from the water. The pumps are governed by air actuated valves controlled by the water level in the deaerators.

The temperature of the water supplied to the houses (for heating or hot tap water) is maintained at about 80 °C. In the original system based on the Reykir fields, the water was pumped from the main storage tanks (4) by pumps regulated by the pressure at a suitable point on the system through a single pipe system (8) and the water was wasted to the sewer, after passing through the house system. This system is still in use.

With the advent of the water from the Reykjavik field (temperature 100 °C) it was necessary to adopt two pipe systems (7) whereby a sufficient quantity of return water from the houses was collected in order to cool the high-temperature water (by mixing) to the desired distribution temperature. A number of sub-stations have been built which are fed with high-temperature water and serve combinations of single- and two-pipe systems (6), (7) and (8).

All pumping stations except the deep well pumps are fully automatic. An electronic controlling and monitoring system has recently been commissioned (1969) for remote supervision, data logging and certain control operations (starting and stopping of pumps) from a central control room, for all pumping stations and borehole pumps.

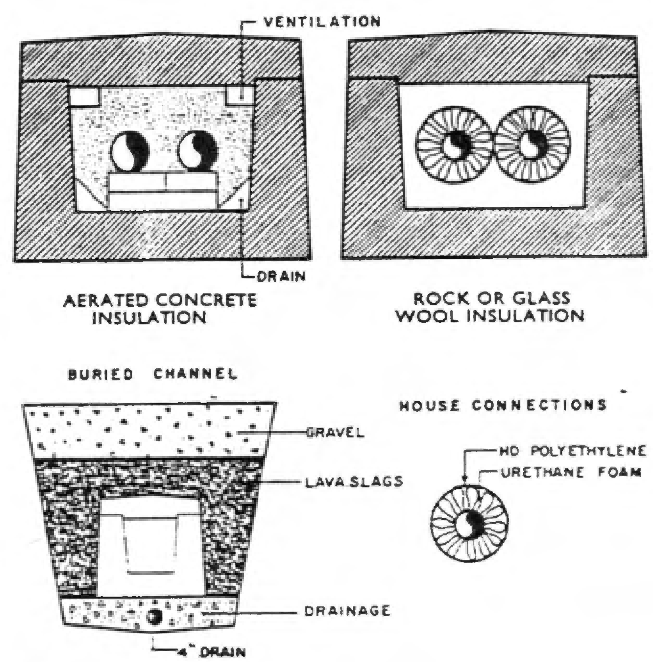

FIG. 6. Street main channels.

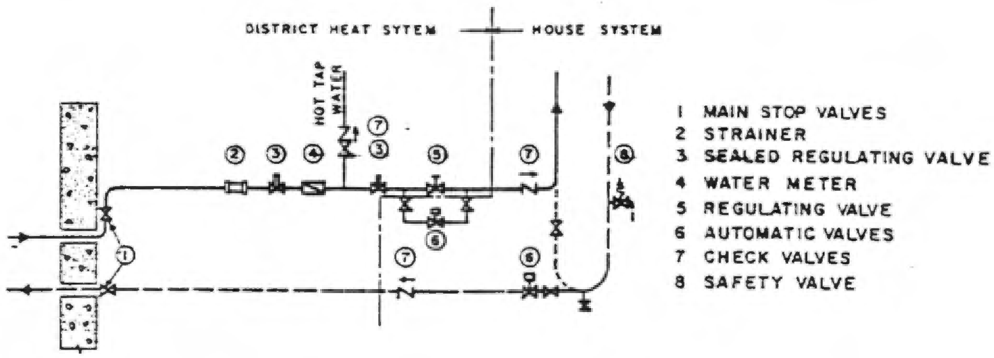

FIG. 7. House connection.

All the system pipe work is underground. It consists of welded black mild steel pipe, laid in concrete channels if the pipe diameter is 75 mm or larger and insulated with rock wool or aerated concrete. Street mains of smaller diameter as well as house connections are black steel pipes insulated with polyurethane foam in the annular space between the steel pipe and an outside protective jacket of high density polyethylene pipe. Figure 6 shows typical cross-sections of the pipes.

Figure 7 shows the standard house connections for a two-pipe system. It should be noted that the geothermal water is used directly as hot tap water. The house connection includes a sealed maximum flow regulator, (3), and an integrating water meter (4) measuring the consumption. The solenoid supply valve (6) is controlled by a room thermostat, and a high limit temperature switch controls the solenoid valve (6) in the return pipe from the radiators.

Figure 8 shows the diurnal load variation in one of

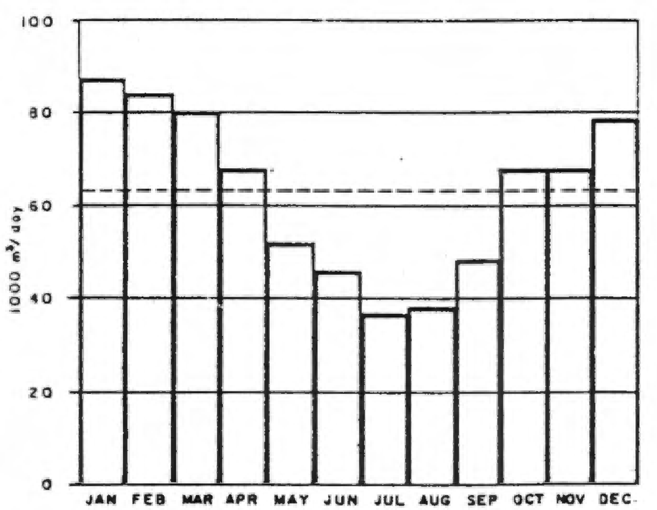

FIG. 8. Monthly water production, 1968.

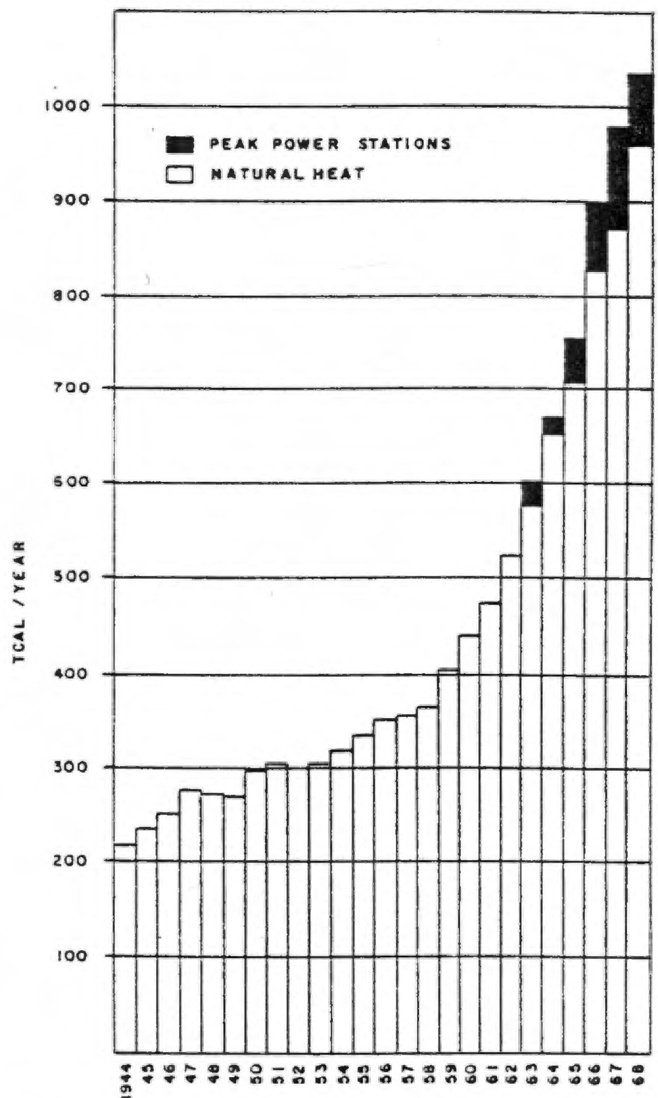

FIG. 9. Yearly heat production.

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the sub-stations. The daily peak load is generally 15-30% higher than the mean demand over the 24 hours of the day. The monthly variation of the water production is shown on Figure 8, and follows substantially the variation of the monthly mean outside temperature. The annual load factor for the whole system is quite high, corresponding to 5,000 h/yr of the full power of the system, or 57%. For the geothermal system alone the load factor corresponds to 5,800 h/yr, or 66%.

Daily load variation is generally taken care of by the storage tanks, but extreme peaks resulting from cold spells and/or high wind velocities are handled by the storage tanks in combination with peak heating by oil, and intensified pumping from Reykjavik field by the deep well pumps.

Figure 9 shows the growth of the annual heat production 1944-69, and also the portion of energy supplied by the peak heating boilers.

(b) OTHER GEOTHERMAL DISTRICT HEATING SYSTEMS

Lokchine and Dvorov (1970) describe a number of district heating systems in the U.S.S.R. ranging in power from 0.55-50 Gcal/h, using geothermal water in the temperature range 50-90 °C. The thermal waters have different degrees of mineralization. They may therefore sometimes be too aggressive to be used directly for the radiators, in which case heat exchangers are used. Apparently the hot tap water is in most cases heated indirectly by heat exchangers.

Peak heating with fossil fuel fired boilers or electricity is widely used.

Frequently hot houses and/or soil heating is combined with the district heating systems, as well as other industrial or agricultural uses of heat. In this way the annual load factor can be significantly improved especially with seasonal soil heating, which falls outside the periods of maximum demand on house heating (spring and autumn).

Considerable efforts have been made in order to

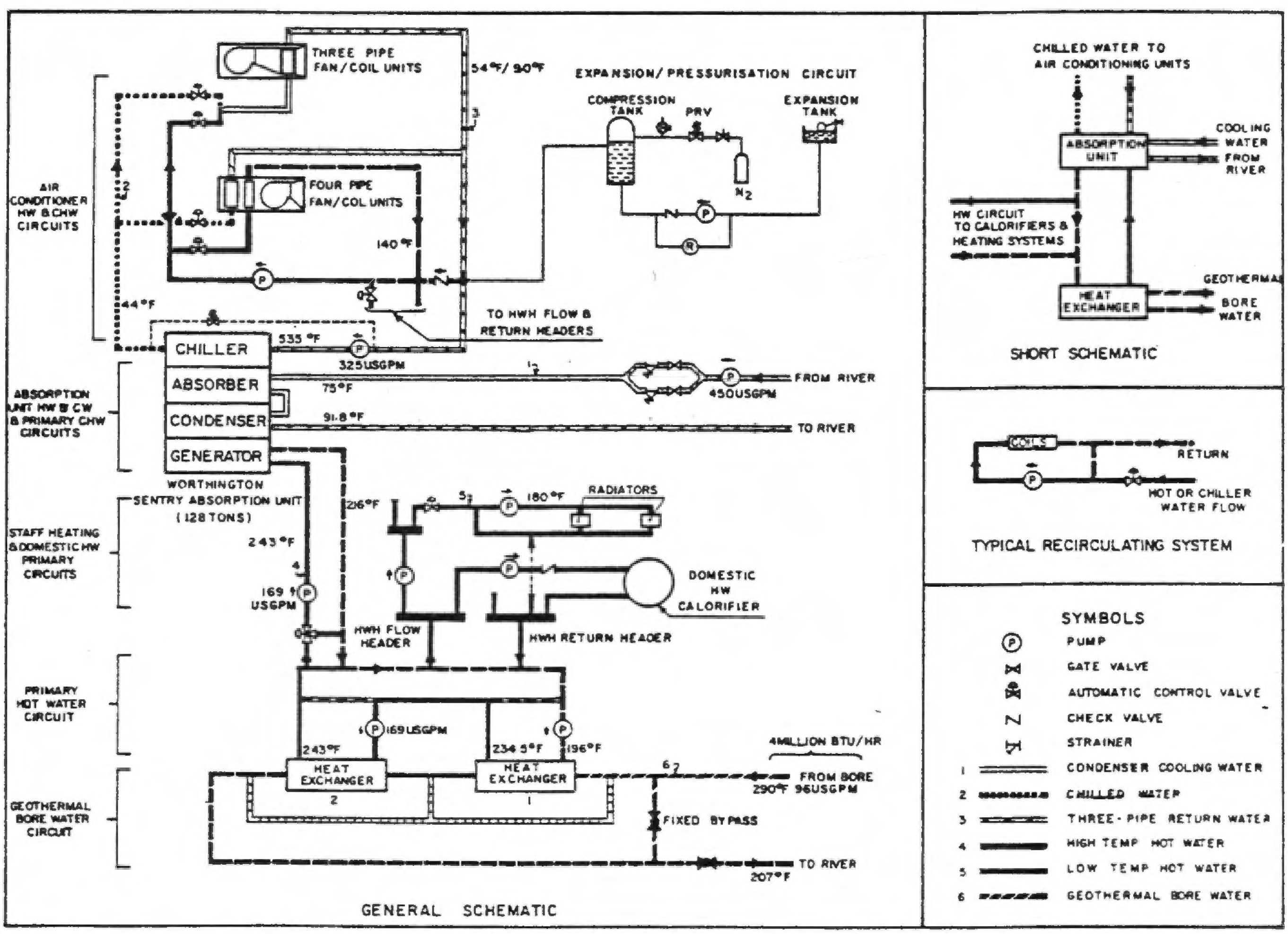

FIG. 10. Scheme of the geothermal heating and air conditioning installation in the Rotorua International Hotel, New Zealand.

increase the efficiency of energy utilization by lowering the temperature of the waste water, for instance by using two-stage heat exchangers for hot tap water, and by using two-stage heating of air.

The most interesting system is perhaps that of Paratounka, Kamchatka, (Lokchine and Dvorov, 1970). The scheme comprises three apartment houses with 48 apartments each (load 0.55 Gcal/h). Geothermal water of 80 °C is used for heating hot tap water and for heating the apartments.

The tap water is heated from + 5 °C in a heat exchanger, cooling the geothermal water to 10 °C.

The apartment houses are heated either by using a central heating system with radiators or by pipes embedded in the concrete of the floors and ceilings (radiant heating). The heating systems are designed for a temperature drop from 80 to 40 °C.

By use of a heat pump, part of the return water of 40 °C can be reheated to 60 °C by extracting heat from the remainder of the return water, which is in turn cooled to 10 °C before being wasted. The 60 °C water is mixed with the geothermal supply water of 80 °C, and the temperature of the mixture can be increased by the use of an electrical peak heating unit.

Use of the heat pump during periods of peak load counteracts the well known fact that the efficiency of heat utilization in geothermal systems using radiators decreases with increased load.

Mashiko and Hirano (1970) report on the use in Japan of various types of pipe laminated with synthetic materials instead of steel pipe in order to avoid corrosion problems associated with mineralized geothermal water.

The use of geothermal energy for cooling for industrial purposes by the use of lithium absorption equipment has been reported in the U.S.S.R. by Tikhonov and Dvorov (1970) who also point out the possibilities of using the equipment for cooling in summer and heating in winter (heat pump application) in the southern regions of the U.S.S.R. Mashiko and Hirano (1970) also mention industrial refrigeration with geothermal energy in Japan.

However, the most interesting installation in the present context is the geothermal heating and air conditioning installation in the Rotorua International Hotel, New Zealand, reported by Reynolds (1970), see Figure 10.

The system is designed for the extreme climatic temperatures of — 4 °C and + 30 °C (25 °F and 85 °F). The maximum heating load is 0.5 Gcal/h (2,000,000 BTU). Two calorifiers for the heating of tap water have a combined maximum demand of 0.5 Gcal/h, but the house heating (or cooling) has preference in the case of coincident peak demand on both systems. A 130 ton (0.39 Gcal/h) lithium bromide absorption unit supplies the cooling for the air conditioning and requires a heat input of 0.575 Gcal/h. The specific energy requirement of the absorption unit is therefore 1.47 kcal heat per 1 kcal of cooling.

The heat energy is supplied by a borehole producing at temperatures above 150 °C and a pressure of about 6 atg. The heat is transferred by heat exchanger to fresh water in closed circuits which is heated to 120 °C, and supplies heat to the radiators, tap water heaters and the absorption unit.

5. Some economic aspects

The economic feasibility of using geothermal energy for heating (or cooling) depends on whether it can compete with other available sources of energy such as fossil fuels, electricity, etc.

Such comparison should be based on the total cost to the ultimate user per unit of net energy utilized. This means comparing costs of entire systems, taking into account the desired return on invested capital of all plant used, direct operating costs, annual load factors, efficiency of energy utilization, etc.

The principal factors that affect the economic feasibility of geothermal district heating systems are the following:

1. The drilling costs per unit energy production ($/Gcal/h).
2. The temperature of the available geothermal fluids.
3. The distance from the geothermal field to the centre of gravity of the market.
4. The load density of the market (Gcal/h/km^2).
5. The annual load factor of the system.
6. The power of the system (Gcal/h).

The drilling costs per unit of energy production govern the cost of the energy ex borehole. The temperature of the fluid, the distance of transmission to the market and the load density are the main factors that influence the transport and distribution costs. The influence of the annual load factor has been discussed earlier in this paper as well as the scale effect which is related to the power of the system.

The specific drilling costs ($/Gcal/h) can differ within wide ranges. They were thus about 2,100 U.S. $/Gcal/h in one high temperature field in Iceland (Southern Hengill) and 16,700 U.S. $/Gcal/h in the Reykjavik geothermal field (low temperature area 120 °C average) (Bodvarsson *et al.*, 1964). Kremnjov *et al.* (1970) show the variation of drilling cost with depth under various geological conditions in the U.S.S.R.

The economic transportability of geothermal fluids is relative low and highly dependent on the temperature of the fluid. Several installations are in use where water of less than 100 °C is transported by pipeline over 10-20 km. Water of 150-180 °C can probably be transmitted for house heating purposes over 50-75 km, provided a large concentration market is available (more than 200 Gcal/h).

Installations are in use where the load density of the market is in the range of 10-17 Gcal/h/km^2.

The specific capital investment ($/Gcal/h) for geothermal district heating systems varies within wide ranges depending on local conditions. Zoëga *et al.*, (1970) report the average costs for the Reykjavik system, based on present day methods and equipment as follows:

Heat production	29,400 U.S. $/Gcal/h
Distribution system	58,000 "
Total	87,400 U.S. $/Gcal/h

and estimate that the replacement value of the present system (225 Gcal/h) is of the order of U.S. $17 million.

The energy price paid by the customers is 0.16 $/m^3 of water at 80 °C. Based on average utilization, this corresponds to 3.80 $/Gcal and is broken down as follows (Palmason *et al.*, 1970):

Drilling	0.73 $/Gcal
Main pipelines	0.42 "
Storage	0.15 "
Distribution	2.50 "
Total	3.80 $/Gcal

The savings in oil by the use of geothermal energ depend on the annual load factors. The following figure are reported:

Cherkest (U.S.S.R.)	680 tons oil/Gcal yea
Reykjavik (Iceland)	870 "
Paratounka (U.S.S.R.)	1,090 "
Caspillok (U.S.S.R.)	1,440 "

The Reykjavik district heating system thus saves abou 150,000 tons of oil annually that would have had to b imported, and the annual cost of heating for the customer is only 60 % of the cost of heating with oil.

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1. Published by the Istituto Internazionale per le Ricerche Geotermiche, Lungarno Pacinotti 55, Pisa, Italy.

10

ANNEXE 10

ANNEXE 10

4 - RÉPERTOIRE DES ÉTUDES ET PRESTATIONS PROPOSÉES EN GÉOTHERMIE

"Publication du B.R.G.M."

Ces études et prestations ont été divisées en deux branches :

A) basse énergie,
B) haute énergie.

Et les divers niveaux d'intervention ont été distingués :

- inventaire général des ressources
- évaluation du potentiel d'une région naturelle
- étude de faisabilité ponctuelle
- forages d'exploitation

A - GÉOTHERMIE «BASSE ÉNERGIE»

INVENTAIRE GÉNÉRAL DES RESSOURCES

Rassemblement et exploitation de documents géologiques, géographiques, géophysiques, hydrogéologiques, sismiques existants, permettant de localiser des formations aquifères profondes à l'échelle d'un pays ou d'une région.

ÉVALUATION DU POTENTIEL D'UNE RÉGION NATURELLE

Rassemblement de toutes les données (géologiques, chimiques, hydrodynamiques, essais de production) en provenance de forages ; dépouillement de ces données ; interprétation permettant de définir la profondeur, l'étendue et les caractéristiques des aquifères, ainsi que les caractéristiques chimiques du fluide.

ÉTUDE DE FAISABILITÉ PONCTUELLE

ÉTUDE GÉOLOGIQUE DÉTAILLÉE

Profondeur, épaisseur des réservoirs exploitables. Coupe stratigraphique prévisionnelle des forages - lithologie.

ÉTUDE HYDROGÉOLOGIQUE PRÉVISIONNELLE

Choix de l'aquifère ; caractéristique hydrodynamique ; évaluation de la température du réservoir.

Détermination à l'aide de modèles de simulation de l'implantation optimale des différents puits de production et de réinjection d'une installation géothermique en fonction des valeurs estimées pour les paramètres de l'aquifère.

Évaluation de la composition chimique approximative de l'eau géothermale à partir de données de puits voisins.

ÉTUDE TECHNICO-ÉCONOMIQUE

Coût prévisionnel des forages.

En fonction des besoins à l'aval (chauffage ou autres) : détermination des débits, puissances de pompage (exhaure et réinjection) nécessaires, investissements nécessaires pour la réalisation (forages, pompes, échangeurs, canalisations, génie civil, etc.) ; caractéristiques de fonctionnement (consommations d'énergie traditionnelle, d'électricité, en fonction des régimes).

Bilan prévisionnel de fonctionnement, coût de la thermie et rentabilité de l'opération par rapport à une installation traditionnelle.

FORAGES D'EXPLOITATION

ÉTABLISSEMENT DU PROGRAMME GÉNÉRAL DE FORAGE

Coupe stratigraphique prévisionnelle des terrains traversés ; programme de forage, de boues de forage, de tubage, de cimentation, de diagraphies, de stimulation du réservoir.

Définition des travaux de génie civil pour l'accès des sondes et la réalisation des plateformes de forage.

APPEL D'OFFRES

Établissement des cahiers des charges, choix des matériels. Dépouillement des offres ; réponses aux demandes d'informations techniques ; mise au point de l'offre retenue ; définition des éléments techniques devant figurer dans les documents contractuels.

Passation des marchés et des commandes ; réception du matériel.

EXÉCUTION DES TRAVAUX

Assistance technique, direction des travaux : contrôle des paramètres de forage ; choix du type d'outil ; choix du programme de boue ; contrôle des tubages et des cimentations ;

contrôle des diagraphies électriques.

Surveillance géologique des forages, contrôle des paramètres de forage ; établissement du log stratigraphique continu ; rapport de fin de sondage.

RÉCEPTION DES OUVRAGES - ESSAIS

Détermination à l'aide de tests de production des caractéristiques des puits et de celles du réservoir (autour de chaque puits : tests de courte durée ; entre les puits : tests de longue durée).

Détermination de l'enthalpie du fluide géothermal à l'aide de diagraphies de température dans les puits (au repos et en cours de production).

Évaluation du potentiel de chaque puits et du réservoir dans son ensemble (réserves).

Collecte d'échantillons du fluide produit en cours d'essais ; analyse en laboratoire de l'eau et des gaz produits par le forage ; étude des matières en suspension dans l'eau géothermale.

CONTROLE EN COURS D'EXPLOITATION

SUIVI DU RÉSERVOIR

Surveillance périodique du comportement des puits (détection des variations de production, évaluation des causes et prescription éventuelle de remèdes).

Modélisation du comportement du réservoir : calage sur l'historique de la production, optimisation du développement.

Gestion des réservoirs géothermiques.

Assistance ou conseil aux pouvoirs publics.

PROBLÈMES DE DÉGAZAGE

Détermination de la pression de bulle de l'eau thermale (seuil de pression à ne pas dépasser pour limiter les problèmes engendrés par une production trop importante de gaz).

Nature et quantité de gaz produits et utilisation possible.

CARACTÉRISTIQUES PHYSICO-CHIMIQUES ET BACTÉRIOLOGIQUES

Contrôle de l'eau thermale à la production et à la réinjection ; étude des problèmes de production par la variation des caractéristiques : entartrage, corrosion.

BILAN TECHNIQUE ET FINANCIER DE L'OPÉRATION

Comparaison avec les réalisations traditionnelles ; économie annuelle en T.E.P. (tonnes d'équivalent pétrole).

I - ÉTUDE DES RÉSERVOIRS GÉOTHERMIQUES

- Étude de l'exploitation des roches sèches : évaluation du potentiel énergétique d'un site donné à l'aide d'un modèle mathématique.
- Mise au point du programme CADOUDAL traitant le cas d'un doublet dans un aquifère en écoulement naturel, avec fuites thermiques à travers les épontes.
- Mise au point du programme METERNIQ pour l'étude du champ des températures dans un réservoir profond, homogène et isotrope, comportant un nombre quelconque de puits de production d'eau chaude et de puits d'injection d'eau froide.
- Mise au point du programme CAPRI pour déterminer les distances à respecter entre les puits d'un doublet hydrothermique et les pressions aux puits de soutirage et d'injection.
- Mise au point du programme STENDHAL pour l'étude du champ des températures dans un réservoir hétérogène, avec des conditions aux limites quelconques, utilisé pour le chauffage géothermique ou la climatisation (nombre quelconque de puits de production d'eau froide et de puits d'injection d'eau chaude).
- Mise au point du programme CAPRE pour le calcul des pressions dans un aquifère exploité pour le chauffage urbain à l'aide de doublets.
- Étude des transferts thermiques dans les milieux poreux saturés à l'aide de méthodes aux différences finies ; mise au point de programmes de gestion et de simulation de réservoirs géothermiques et extension à l'étude du stockage souterrain d'eau chaude.
  - EDITH (problèmes bi-dimensionnels)
  - ESTHER (problèmes à symétrie axiale).

II - ÉTUDE EXPÉRIMENTALE D'UN DOUBLET HYDROTHERMIQUE (SITE EXPÉRIMENTAL DU B.R.G.M. A BONNAUD - JURA)

- Réalisation d'expériences de fonctionnement en doublet, avec injection d'eau chaude et surveillance continue de la température en divers points de la nappe (1976).
- Réalisation d'expériences «à puits unique» avec injection d'eau chaude et repompage au même puits, après une période d'attente plus ou moins longue. Ces expériences ont pour but l'évaluation des caractéristiques thermiques de la nappe et des épontes (1976).
- Injection d'une masse d'eau chaude dans la nappe et surveillance de son comportement in situ au cours du temps (6 mois). Cette expérience a pour but d'évaluer l'importance des fuites thermiques (1976/77).

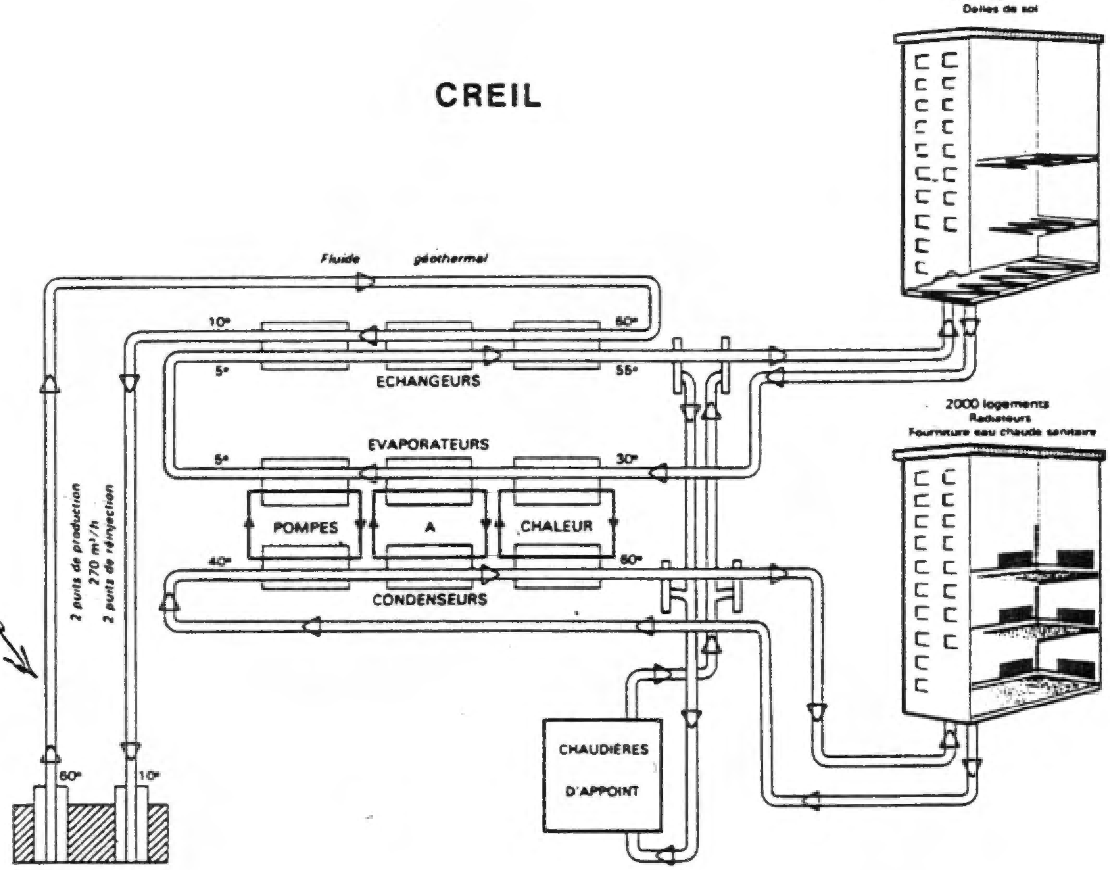
III - GÉOTHERMIE : FORAGES, ESSAIS, EXPLOITATION

- Caractéristiques des principaux appareils de forage (1973).
- Rapports de fin de sondage (Creil 1, 2, 3 et 4) - (1975/76).
- Calcul de la température en tête de puits - Influence de l'isolation des casings (1977).
- Mise au point du récapitulatif technique de fin de sondage avec sortie automatique sur ordinateur (1977).
- Étude d'essais de pompage dans les champs géothermiques (1975).
- Interprétation de pompages d'essais sur le forage géothermique de Blagnac (1975).
- Essais et mesures destinés à l'évaluation du potentiel des puits géothermiques (1975).
- Étude de l'utilisation de l'énergie géothermique en Hongrie (1972).

RÉALISATIONS - BASSE ÉNERGIE (cf. schéma Creil)

Sur le plan technique, le B.R.G.M. a réalisé l'opération géothermique la plus importante existant actuellement en France, soit quatre sondages : deux de production et deux de réinjection. Cette réalisation chauffe 4.000 habitations de la ville de Creil (Oise).

CREIL


2000 logements
Dalles de sol
Fluide géothermal
10°
60°
5°
55°
ECHANGEURS
EVAPORATEURS
5°
30°
POMPES
A
CHALEUR
40°
60°
CONDENSEURS
2000 logements
Radiateurs
Fourniture eau chaude sanitaire
2 puits de production
270 m³/h
2 puits de réinjection
CHAUDIERES
D'APPOINT
60°
10°

11

ANNEXE 11

Les Conditions de Compétitivité de la Géothermie dans le Chauffage des Habitations

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RÉSUMÉ

L'utilisation de l'énergie géothermique à basse température (55 à 80°C) rend nécessaire pour chaque opération un investissement non divisible très important (de l'ordre de 5 à 6 MF français 1974 au minimum) et en partie indépendant de la quantité de chaleur à fournir. Il est toutefois possible de faire varier la puissance calorifique de l'installation en procédant à un pompage de l'eau chaude qui entraîne des frais de fonctionnement.

La compétitivité de l'installation géothermique ne peut être réalisée que dans des fourchettes de puissance maximum et de quantité de chaleur annuelle produite variables selon la ressource (localisation, température) et les caractéristiques du dispositif secondaire de chauffage.

En fonction de ces divers paramètres, le coût de la thermie géothermique peut être calculé et comparé par conséquent au coût des moyens concurrents.

INTRODUCTION

Depuis la crise récente de l'énergie, les Pouvoirs Publics français ont décidé de promouvoir l'utilisation systématique des ressources en eau chaude mises en évidence dans les grands bassins sédimentaires français par les travaux de prospection pétrolière effectués durant les 20 dernières années. Compte tenu des caractéristiques de la ressource disponible, notamment des températures de l'eau (entre 45 et 70°C la plupart du temps), il semble que le débouché le plus important de la géothermie sera le chauffage des habitations.

On va donc se pencher dans ce qui suit sur les problèmes techniques et économiques liés à l'introduction de la géothermie dans le chauffage domestique. On fera le point des réflexions suggérées par l'étude des premières applications réalisées ou en projet en France et on proposera une méthode de travail ayant pour objet de déterminer les caractéristiques techniques d'une installation géothermique de telle manière que le coût de la calorie qu'elle produit soit le plus bas possible.

Le problème sera exposé dans sa généralité et la méthode proposée est applicable, théoriquement, à toute installation utilisant la géothermie pour le chauffage. Toutefois, on fera fréquemment référence à des exemples pris dans la région de Paris où l'on se propose de soumettre à une exploitation intensive une importante nappe, celle du Dogger, qui fournira sans doute la plus grande part de l'énergie géothermique utilisée en France. Aussi paraît-il bon de donner très rapidement quelques caractéristiques techniques essentielles de cette nappe et de ses conditions d'exploitation. Cela permettra de bien situer le cadre général dans lequel a été conduit notre travail:

1. Profondeur de la nappe dans la zone exploitée, 1500 à 1800 m.
2. Température correspondante, 55 à 70°C.
3. Salinité de l'eau, 8 à 30 g/l de NaCl, essentiellement.
4. Il s'y ajoute des traces de H_2S; de ce fait, on doit avoir recours à des échangeurs pour transférer la chaleur sur un fluide secondaire "propre" et non corrosif—de l'eau dans le cas du chauffage des habitations.
5. Réinjection obligatoire de l'eau après refroidissement pour (a) ne pas polluer les eaux de surface avec une eau saline, (b) maintenir la capacité de production du gisement, et (c) accroître la quantité de chaleur extraite du sol (la recirculation de l'eau permet de récupérer les calories contenues dans la roche magasin).
6. Production dans une zone très fortement urbanisée et industrialisée.

Avant d'aborder l'étude de la méthode proprement dite, on va examiner quelles sont les contraintes physiques qui limitent le débit que l'on peut extraire d'un puits ou d'un doublet de puits de production et de réinjection.

LES CONTRAINTES PHYSIQUES

Il faut noter tout d'abord que, pour un débit donné, l'écartement entre les puits de production et de réinjection conditionne la durée d'exploitation du système à température constante, c'est-à-dire le délai qui s'écoule entre le début de l'exploitation et le premier abaissement notable (1°C, par exemple) de température aux puits de production (Gringarten et Sauty, 1975). Mais le débit constitue lui même un des facteurs qui conditionnent cette durée d'exploitation.

En dehors des contraintes imposées par cette relation durée d'exploitation—écartement entre les puits—débit produit, d'autres éléments contribuent à déterminer la limite supérieure au delà de laquelle il n'est pas possible physiquement et économiquement de faire varier le débit:

1. La transmissivité de l'aquifère et, au bout du compte, le débit supplémentaire que l'on peut obtenir par mètre supplémentaire de rabattement.
2. La pression de fracturation qui limite la pression de réinjection. Si l'on dépasse cette pression de fracturation, on risque en effet de provoquer des communications rapides entre le puits de production et le puits de réinjection et d'acheminer très vite l'eau refroidie vers le puits de production.
3. La technologie du matériel de pompage qui n'offre qu'une gamme de matériel limitée en débit et en hauteur de refoulement.

Remarque: on admettra que les pertes de charge dans le tubage sont négligeables, ce qui est le cas dans les puits au Dogger qui sont ou seront en général tubés en 7 pouces.

La considération de l'ensemble de ces données conduit à définir, dans une situation donnée, un débit maximum Q_{max}. Dans la région de Paris, il est de l'ordre de 150 à 180 m^3/h pour la nappe du Dogger.

L'OPTIMISATION ÉCONOMIQUE

Deux voies de recherches apparaissent a priori possibles. Dans la première, on part du puits ou du doublet, donc de ses caractéristiques techniques et économiques, et on cherche à évaluer les besoins, donc, en pratique, le nombre de logements et les installations collectives annexes à desservir (centre commercial, marché, piscine, écoles, etc.) qui minimisent le coût de la calorie produite dans une installation de chauffage utilisant l'eau chaude du puits considéré.

Dans le contexte français, cette voie de recherche est irréaliste, que ce soit dans le cas de villes anciennes, de constructions neuves insérées dans un tissu urbain ancien, ou même de villes nouvelles créées de toutes pièces (ce qui est le cas de la phériphérie de Paris).

Il y a, en effet, une multitude d'autres contraintes qui l'emportent sur la géothermie pour déterminer la taille et la disposition des ensembles de logement—problèmes de l'eau, de l'évacuation des déchets, des transports, problèmes financiers et, plus simplement, le choix du parti d'aménagement sur des considérations purement urbanistes.

Dans la deuxième voie, on part des besoins exprimés au niveau d'une zone déterminée, on les confronte aux ressources géothermiques localement disponibles et on cherche à maximiser l'avantage économique d'une installation de chauffage utilisant l'eau chaude géothermale par rapport au coût d'une installation classique de chauffage à distance de même puissance.

Les besoins de la zone à chauffer et la puissance de la chaufferie varient en fonction des caractéristiques techniques de l'isolation des logements, c'est-à-dire du coefficient de déperdition calorifique $G\,(W/°C \cdot m^3\,h)$. Les normes récentes promulguées en France limitent les possibilités de variation du coefficient G dans une plage étroite pour des immeubles collectifs (de 0,8 à 1,1 dans la région parisienne) et, dans ce qui suit, on supposera G constant et égal à la valeur maximum autorisée par la norme.

On va donc se placer dans la deuxième voie de recherche et chercher tout d'abord quels sont les paramètres dont on dispose pour faire varier le coût de la calorie produite. On développera au préalable quelques considérations générales.

CONSIDÉRATIONS GÉNÉRALES

Structure du Coût des Sources Géothermiques

D'une part, la production de chaleur à partir d'eau géothermale met toujours en œuvre des investissements d'un coût plus élevé que les solutions classiques. D'autre part, l'ensemble des deux puits et des échangeurs nécessaires dans la solution géothermique constituent l'unité de base de production de chaleur et ne peuvent être divisés en unités techniques plus petites comme c'est le cas dans une chaufferie classique où l'on peut toujours fractionner la puissance entre plusieurs chaudières et, finalement, étager la puissance de manière quasi continue.

Dans le cas où l'installation nécessite plusieurs puits de production, on peut admettre que les puits d'injection ne sont pas nécessairement en nombre égal et, dans ce cas, l'unité de base indivisible n'est plus le doublet mais le puits. Quoi qu'il en soit, il s'agit toujours d'une unité de base d'un coût élevé.

Une discontinuité supplémentaire du coût intervient si l'on utilise une pompe pour accroître le débit du puits de production; mais, une fois ce seuil franchi, le coût d'investissement varie peu avec le débit extrait.

En résumé, la source géothermique se présente comme une source de coût élevé, ce coût variant par paliers très brutaux et importants comme il apparaît sur la Figure 1.

La Puissance des Sources Géothermiques

Les systèmes de chauffage classiques compensent les déperditions par les parois et les pertes par renouvellement d'air ou par le rechauffage de l'air intérieur. C'est le cas des installations utilisant des radiateurs, des convecteurs, des ventiloconvecteurs, des systèmes à dalles chauffantes, à réchauffage de l'air intérieur par passage sur batterie chaude, etc.

L'émission de chaleur de ces surfaces d'échange est fonction de l'écart entre leur température moyenne et la température intérieure que l'on s'impose de conserver constante. Il en résulte la nécessité d'élever la température moyenne des surfaces d'échange, donc la température de retour du fluide lorsque la puissance appelée augmente, c'est-à-dire lorsque la température extérieure diminue.

Or la source géothermique fournit une eau chaude à température constante proche des températures d'utilisation aux échangeurs secondaires. Si la température de retour augmente, la puissance que peut fournir la géothermie va

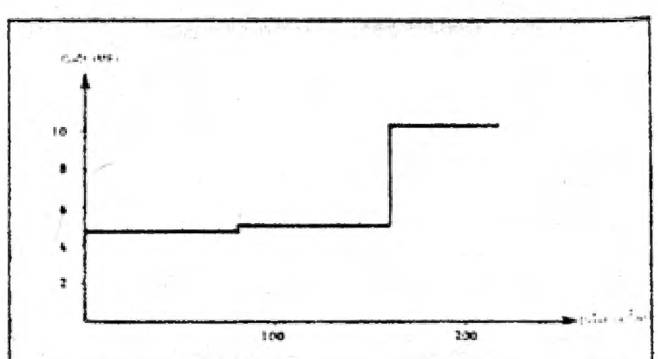

Figure 1. Coût d'investissement de l'eau géothermale en tête de puits en fonction du débit—nappe du Dogger, région parisienne.

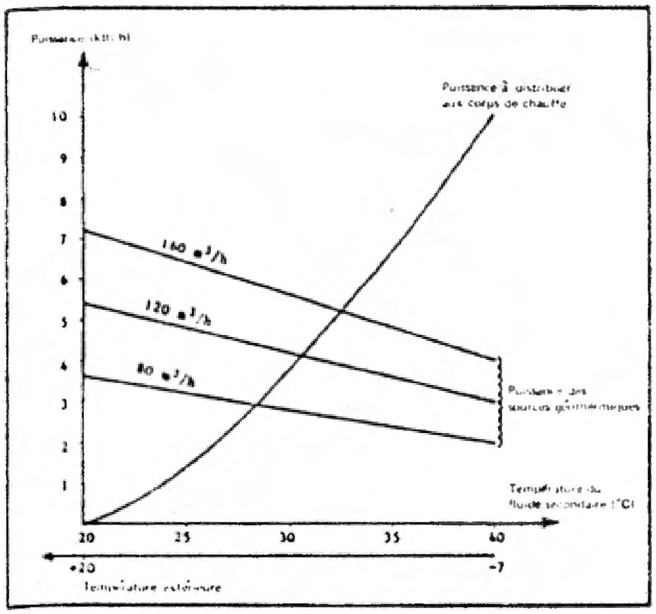

Figure 2. Puissance d'une source de chaleur géothermique en fonction de la température du fluide secondaire. Paramètres fixés: température de l'eau geothermale, 70°C; température de retour du fluide secondaire en puissance maximum, 40°C; puissance totale de l'installation, 10 kth/h.

donc diminuer. La Figure 2 illustre cette propriété pour trois sources géothermiques desservant une installation secondaire dont le retour est de 40°C en puissance maximum.

Dans les systèmes de chauffage dans lesquels l'apport d'air neuf est contrôlé, l'air neuf introduit est réchauffé par une source de chaleur alimentant un échangeur. Il est à une température d'autant plus éloignée de sa température d'introduction dans les locaux que la température extérieure est plus basse, c'est-à-dire que l'on demandera d'autant plus à une source de chaleur géothermique que la température est plus basse. La courbe des puissances géothermiques est donc inversée par rapport au cas précédent.

Dans tous les cas (et on notera que les systèmes de chauffage du second type sont relativement rares) la puissance disponible sur source géothermique varie avec la température de retour du fluide calorifère secondaire qui dépend elle-même de la température extérieure.

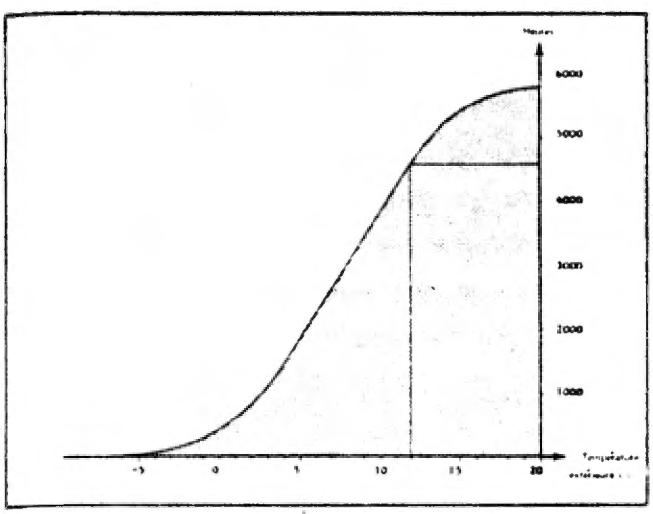

Figure 3. Courbe des fréquences cumulées des températures moyennes journalières—région parisienne, ler octobre au 31 mai. La température extérieure est en moyenne inférieure à 12°C pendant 4700 heures. L'aire de la surface en grisé donne une représentation de la consommation totale d'énergie.

Chauffage de Base et Chauffage d'Appoint

Considérons une courbe de répartition des températures extérieures (Fig. 3). La puissance appelée étant une fonction affine de la température extérieure, on voit, compte tenu de la forme de la courbe, que les puissances maxima sont utilisées un nombre d'heures très faible.

Considérons maintenant une installation de production de chaleur à deux sources: appelons source de base la source no. 1 qui sera toujours utilisée en priorité, la source no. 2 ne lui étant adjointe que si sa puissance est insuffisante pour couvrir les besoins. La Figure 4 permet de constater que, pour une part de la puissance totale installée relativement faible (par exemple 30%), la source dite de base couvre une part importante des besoins de chaleur (près de 70% dans l'exemple choisi). On voit également que la quantité de chaleur fournie par la source de base n'augmente que faiblement lorsque l'on accroît sa puissance relative. On notera toutefois que la présentation adoptée sur cette figure suppose deux sources de base et d'appoint de puissance indépendante des conditions climatiques. Si la base est une source géothermique, la courbe doit être recalculée dans chaque cas comme on le verra ci-après.

L'UTILISATION DES SOURCES

Les considérations qui précèdent font de toute évidence des sources géothermiques des sources de chaleur à affecter en base dans un système de chauffage quelconque comportant deux sources (ou plus). Le problème qui se pose est alors de déterminer la part qui revient à la géothermie dans la puissance totale installée. Mais, par ailleurs, la puissance

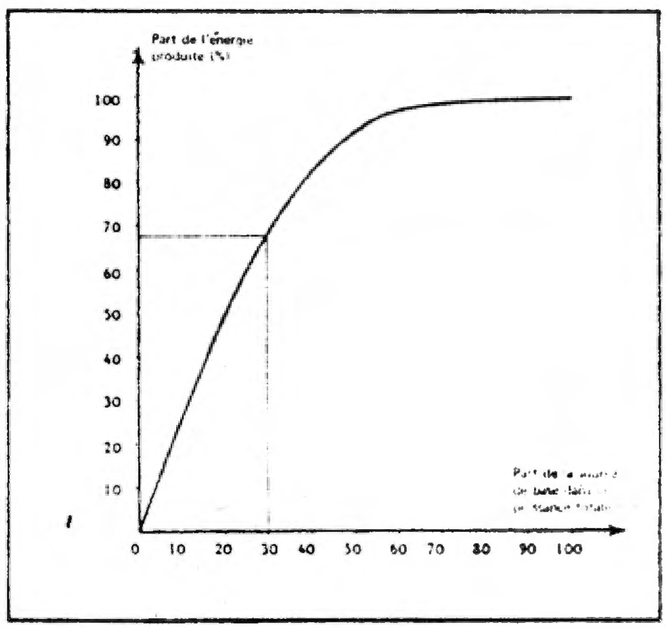

Figure 4. Proportion d'énergie produite par une source de chaleur utilisée en base, en fonction de la part de la puissance totale. Paramètres fixés: Période de chauffe, ler octobre au 31 mai; climat, région parisienne. N.B. source de base et source d'appoint ont une puissance indépendante des conditions climatiques.

installée d'une source de chaleur classique à haute température est indépendante des conditions climatiques. On a vu qu'au contraire la puissance d'une source géothermique était variable.

Il faut donc, pour définir la puissance nominale d'une source géothermique, se placer dans des conditions de fonctionnement déterminées. Par souci de simplification on définira dans ce qui suit la puissance géothermique nominale comme la puissance fournie par la géothermie lorsque les besoins en chaleur requièrent la mise en oeuvre de la puissance totale de l'installation. Cette convention repose sur le fait que la puissance de la source d'appoint doit être calculée dans les conditions du régime de pointe et qu'elle doit être égale au moins à la différence entre la puissance totale nécessaire et la puissance disponible sur la source géothermique dans ces conditions.

Ce problème étant réglé, on peut formuler clairement le problème. Soit un ensemble d'habitations dont le chauffage nécessite une puissance installée P_T. Il est possible de fournir cette puissance de deux manières: (1) une part géothermique de puissance nominale rP_T ($r < 1$) assurant la base, et un appoint classique de puissance $(1 - r)\ P_T$; et (2) une installation classique décomposable fictivement en deux parts: une base de puissance rP_T, r ayant la même valeur que dans le cas précédent; et un appoint de puissance $(1 - r)\ P_T$.

On peut admettre que le coût actualisé de l'installation d'appoint est le même dans les deux cas: le coût unitaire des investissements varie peu dans la gamme de puissance considérée et l'impact des frais de fonctionnement actualisés est prépondérant s'agissant d'une solution classique.

On est donc amené à comparer le coût des deux sources de base pour plusieurs valeurs du paramètre r. Si l'on se réfère à la notion de puissance nominale géothermique, on conçoit que l'on puisse chercher à l'accroître de plusieurs manières:

1. En jouant sur le dispositif de distribution de chaleur (en abrégé DISTCHAL) puisqu'il conditionne la température de retour du fluide calorifère en régime de puissance maximum. Plus la température de retour sera basse et plus grande sera la puissance nominale géothermique.
2. En jouant sur le système d'extraction de chaleur de l'eau géothermale, ce qui peut être accompli de deux façons: (a) S'il s'agit d'un échangeur statique, on peut en accroître la surface de manière à diminuer l'écart entre la température de retour du fluide calorifère et l'eau géothermale. L'expérience montre que le coût d'une telle augmentation s'accroît très vite, mais qu'il est possible de trouver un optimum intégrant également des considérations telles que la résistance à la corrosion, les pertes de charge dues à la circulation des fluides, etc. (b) On peut avoir recours à des échangeurs thermodynamiques du type pompe à chaleur. Ce point sera développé plus avant dans l'exposé de la méthode.

EXPOSÉ DE LA MÉTHODE PROPOSÉE

La méthode proposée se décompose en deux phases qui doivent être itérées un certain nombre de fois comme indiqué ci-dessous.

Phase 1

On se fixe une technologie de distribution de chaleur dans les logements, soit DISTCHAL$_i$. Dans la mesure du possible, on retient une technologie impliquant une température de retour basse pour tenir compte du fait que l'eau thermale est à relativement basse température. Par exemple, on fait choix d'un système de panneaux de sol avec convecteurs d'appoints à tirage naturel ou forcé.

On suppose dans la première phase que l'installation de production de chaleur géothermique est centralisée et qu'elle est à deux sources: (1) géothermie (avec transfert des calories sur le fluide secondaire exclusivement par échangeur statique); et (2) chaudière utilisant le combustible fossile le moins coûteux: fuel-oil, gaz ou charbon. Compte tenu des conditions économiques actuelles, c'est généralement le fuel-lourd.

L'installation classique de référence est constituée par une chaufferie brûlant le même combustible que la chaufferie construite en appoint à la géothermie.

Au départ, il est nécessaire de fixer arbitrairement la part r de la puissance maximum installée P_t qui est couverte par la source géothermique. Ce choix effectué, les caractéristiques de l'installation géothermique sont déterminées: on déduit immédiatement la puissance nominale de la source géothermique et, par conséquent, le débit nécessaire d'eau thermale Q_i. Il faut ensuite calculer les quantités de chaleur moyennes apportées par les deux sources compte tenu des conditions climatiques et de la température de retour déterminée par le système de distribution de chaleur DISTCHAL$_i$.

La Figure 5 montre de quelle manière s'établissent les relations entre P_T, Q et la quantité de chaleur apportée par la géothermie en fonction de la température de retour. Ce graphique a été établi en tenant compte de la variation de puissance de la source géothermique en fonction des conditions climatiques de la région parisienne.

On vérifie que Q_i est inférieur à Q_{max} défini plus haut auquel on retranche le débit Q_e nécessaire à la préparation de l'eau chaude sanitaire (voir plus bas).

On calcule alors (1) le coût actualisé de l'installation géothermique, soit $I + \Sigma f$, f étant les frais de fonctionnement et de renouvellement du matériel (pompes, échangeurs,

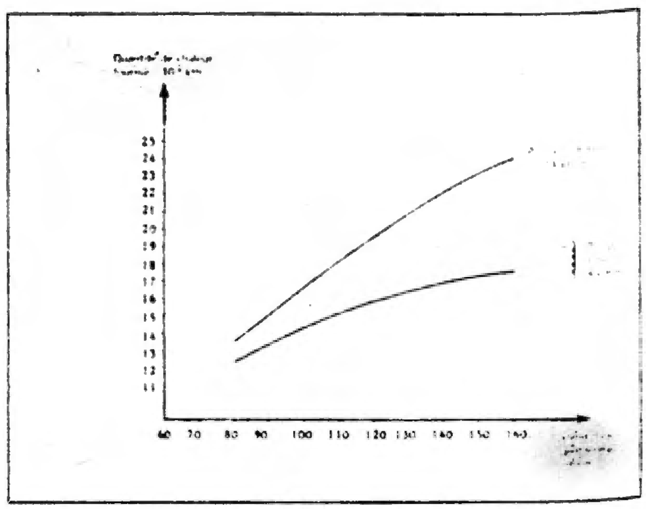

Figure 5. Quantité de chaleur produite par une source géothermique dans une installation à deux sources en fonction de la puissance totale de l'installation et du débit d'eau géothermale. Paramètres fixés: période de chauffe, 1er octobre au 31 mai; climat, région parisienne; température de l'eau géothermale, 70°C; Δt à l'échangeur, 5°C; température de retour (secondaire) en régime de pointe, 40°C. Le trait horizontal indique la quantité totale de chaleur à produire dans une installation de 8 kth/h.

etc.); et (2) le coût actualisé d'une installation de même puissance fonctionnant avec le même combustible que le chauffage d'appoint. On compare ensuite les résultats.

Il est nécessaire de faire varier r jusqu'à obtenir l'écart maximum de coût en faveur de la solution géothermique: soit r_1 la valeur correspondante de r.

Phase 2

On a vu que la puissance disponible à la source géothermique diminue en général lorsque la puissance totale appelée augmente (c'est-à-dire par temps froid). On va rechercher dans la deuxième phase à récupérer une quantité de chaleur supplémentaire en la prélevant sur l'eau géothermale avant réinjection au moyen d'un dispositif thermodynamique du type pompe à chaleur, ce qui revient à assurer une partie de la puissance d'appoint nécessaire par un apport géothermie plus une pompe à chaleur.

Pour cela, on part de la solution correspondant à r_1 précédemment définie et, disposant du coût actualisé du chauffage d'appoint dans l'hypothèse "première phase" où la puissance d'appoint de pointe est fournie exclusivement par une chaudière brûlant le combustible fossile le plus économique, on le recalcule dans l'hypothèse "deuxième phase" où la puissance d'appoint de pointe est fournie à raison de $r'\%$ par un dispositif du type pompe à chaleur.

On fait varier r' jusqu'à obtenir l'avantage maximum de la deuxième hypothèse. Pour cette valeur r'_1, la solution géothermique trouvée est celle qui fournit la calorie au prix minimum.

On pourrait objecter que ce n'est pas obligatoirement dans le cadre de la solution r_1 que se situe la solution géothermique optimum, et que l'on peut trouver celle-ci dans un couple de valeurs r et r' différant toutes deux des valeurs r_1 et r'_1 définies précédemment. Nous pensons que les écarts ne peuvent être que très faibles en raison des discontinuités observées sur les courbes de coût.

EVALUATION DE L'AVANTAGE NET

La méthode exposée ci-dessus a permis de déterminer, pour une technologie de distribution de chaleur DISTCHAL$_i$, l'avantage brut de la solution géothermique par rapport à une solution classique de chauffage à distance. On entend par avantage brut celui obtenu en ne considérant que la production de chaleur. Il convient ensuite d'évaluer l'avantage net A_i qui résulte de l'introduction de deux données supplémentaires qui n'ont pas encore été abordées.

Le Problème de l'Eau Chaude Sanitaire

Le problème de l'eau chaude sanitaire (ECS) nécessiterait une étude complète destinée à évaluer la solution technique la plus économique de fourniture de l'ECS dans le cas de la géothermie comparée à la solution la plus économique dans le cas d'un chauffage classique.

En fait, il y a peu de solutions rentables et l'étude peut être réduite à des dimensions très modestes; par exemple, étude d'un système centralisé. Pour simplifier la démarche, on considérera que tous les coûts de production de l'eau géothermale sont supportés par l' installation de chauffage, seuls intervenant donc les coûts de préparation et de distribution de l'eau chaude sanitaire. Cette simplification nous semble justifiée par la faible proportion du débit à affecter à l' ECS (15 m^3/h pour 150 m^3/h dans une installation qui desservirait 1500 logements en région parisienne) et l' importance relativement beaucoup plus grande de la quantité de chaleur ainsi produite.

La Distribution de Chaleur dans les Habitations

La solution classique au problème de la distribution de chaleur dans les habitations va généralement de pair avec une distribution par radiateur 90 / 70°C. Il faut en comparer le coût avec celui de la distribution résultant du choix de DISTCHAL$_i$. On se bornera généralement à comparer le coût des surfaces d'échange secondaires, le coût des réseaux variant très peu d'une solution à l'autre sauf si les départs en solution classique se font à des températures de plus de 110°C.

L'avantage net A_i est la somme algébrique de l'avantage brut et des avantages liés à l'ECS et à la distribution de chaleur. On peut ainsi, en répétant la démarche, évaluer une série de A_i pour toute une série de DISTCHAL$_i$ et déterminer la solution DISTCHAL qui procure l'avantage net A_i le plus élevé.

LES ÉLÉMENTS DE LA DÉCISION FINALE

Dans tout ce qui précède, on a comparé une solution géothermique du type centralisé avec des solutions classiques du type centralisé également. Or, il existe un certain nombre de solutions du type individuel ou semi-collectif qui tendent à se développer actuellement, telles que le chauffage électrique individuel, le chauffage au gaz individuel, le chauffage au gaz par chaufferie en terrasse, etc.

Si la solution classique centralisée conduit à un coût de la calorie inférieur à toutes ces solutions, il en sera de même de la solution géothermique trouvée. Si, par contre, il existe une ou plusieurs solutions du type individuel d'un coût inférieur à celui de la chaufferie centralisée classique, il faudra vérifier que la solution géothermique la plus avantageuse est également d'un coût inférieur à la moins coûteuse des solutions individuelles.

Arrivé à ce point de la méthode, on disposera en définitive d'une série importante de solutions dégageant des avantages variables dont certains sont très proches les uns des autres. On peut alors décider de la solution en prenant en considération des critères non économiques tels que l'agrément d'un mode de chauffage comparé à un autre (le chauffage par dalle de sol est souvent mal accepté), les modifications apportées au mode de construction entraînées par un type de chauffage (par exemple l'air chaud), etc.

D'une manière plus générale, la méthode proposée ne permet pas de réaliser une optimisation au sens classique du terme. Par ailleurs, aucun des phénomènes décrits ne se plie à des lois linéaires et il n'est donc pas possible d'utiliser simplement les techniques de la programmation linéaire. La méthode est donc du type itératif et se prête bien dans ce sens à l'utilisation de petits ordinateurs de bureau permettant de calculer rapidement les paramètres d'un grand nombre de solutions.

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12

ANNEXE 12

Utilization of Geothermal Water for Domestic Heating and Hot Water Supply

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ABSTRACT

A number of principal schemes for the utilization of geothermal water have been developed. There are schemes for direct and parallel utilization of geothermal water, a scheme with peak heating and compression thermo-transformer, and a scheme with combined systems of water and air heating.

The choice of the best schemes of utilization of geothermal energy is carried out according to different factors—the depth of bed, strength of rocks, yield of wells, temperature, rate of mineralization, chemical composition, climate, cost of fuel, and distance to the sites of use.

The possibilities of application of different types of systems of heating were investigated; they are panel (ceiling-floor type), convector, air heating systems, and new types of heating installations. Installations utilizing geothermal water already exist in some regions.

INTRODUCTION

The rapid increase in the demand for fuel and energy and the intensification of the mineral-fuel shortage have increased the significance of geothermal heat in the fuel and energy balance of many countries.

The USSR possesses enormous reserves of geothermal heat, but the present availability of a sufficient amount of mineral fuel and its lower cost restrain, in general, the development of geothermal energy.

However, in certain regions the strained fuel and energy balance requires the use of new sources of energy, including geothermal energy. This requires development of the technical and economic base of its application. This problem is extremely complicated due to the multitude of qualitative characteristics of geological structure: such as bedding depth; drilling conditions; outflow; physical-chemical properties; the geothermal variables such as temperature, degree of mineralization, and chemical composition; and finally the local geographic conditions such as climate, the availability of fuel energy resources, distance to the consumer, and so on.

Our work concentrates on the technical and economic part of the research. Our main task was to analyze and assess the influence of various factors that characterize the production of geothermal heat upon the economics of supply and to find the best way to determine the competitive capability of geothermal heat in comparison with traditional heating sources. Such an approach allowed us to select the problems with the highest priority.

Out of all of the schemes for geothermal heat usage that will be discussed in detail below, only one scheme was chosen. That scheme provides an indirect use of thermal springs with natural heat potential.

In our opinion, this scheme is convenient, and requires a minimum of structural elements. It does not require supplementary expenses for fuel and electrical energy, or feed water and therefore completely uses the advantages of geothermal reserves.

The scheme under consideration consists of the following main elements: the source of geothermal heat and a borehole with accessories, heat distribution ducts, sewerage for used thermal waters, and heating systems and transit heating pipelines, if the consumer is away from the output source.

The total cost of the geothermal heat supply system is a summation of all expenses of each separate scheme's elements mentioned above:

$$\Sigma C = C_{output} + C_{h\ distr} + C_{sew} + C_{heat\ s} + C_{trans}. \qquad (1)$$

Where

- C is the total expense of the geothermal heat supply system,
- C_{output} is the expenses due to the output of geothermal heat,
- $C_{h\ distr}$ is the expenses due to heat distribution ducts,
- C_{sew} is the expenses due to the sewerage system,
- $C_{heat\ s}$ is the expenses due to heating systems, and
- C_{trans} is the expenses due to transit heating pipelines.

Thereafter the structure of each component was determined and then expressed in natural indices. The analytical dependences were solved, taking into account the varieties of parameters with their limits, corresponding to the natural conditions of the major part of geothermal origins in the USSR. Relevant to the number of such parameters are the cost of drilling, the borehole outflow, the distance between them, the temperature of the geothermal spring water, the temperature change in the heating system, the water temperature intended for the hot-water supply, the number of hours in operation, the extent of transit heat mains, and the fuel cost in the region where a geothermal spring is to be developed. Different system types have been considered for heat distribution ducts, heating schemes, heating devices, and so on.

In the course of the investigation, the extent of the influence of the factors mentioned above on the cost was determined for every element of the geothermal heat supply system. The analysis of the results was done in the following manner. The sum of all expenses (1) was subdivided into two groups. One part—completely stipulated by the specific character of the geothermal heat source—is the expenses which are related to the output of geothermal springs C_{output}; and the other part represents the expenses involved in heat distribution and the consuming plants.

Without remote transportation of heat:

$$C^{I} = C_{trans} + C_{sew} + C_{heat\,s}. \qquad (2)$$

With remote transportation of heat:

$$C^{II} = C^{I} + C_{tram}. \qquad (3)$$

The results of the investigation were as follows. The dependences of the geothermal heat source were defined, and the relation was determined between the expenses C_{output} and the value of the heat load, drilling cost, and number of boreholes (the distance between them being 500 m). See Figure 1. Evaluation of costs for different distances between the boreholes is also possible by using the coefficient a (Fig. 2).

The analysis of both diagrams in Figures 1 and 2 shows that the economic indices of geothermal heat sources are improved as efficiency increases. However, the increase in efficiency is limited by the area occupied. The optimal value, as ascertained by calculations, lies between 12 and 25 to 30 Gcal/hr. The increase of the optimal efficiency helps to diminish the number of boreholes and the small distances between them (not more than 500 to 700 m).

The distance between the boreholes influences the expenses related to establishing geothermal production. This is especially noticeable for low-cost boreholes and has a natural trend to increase with an increase in the number of boreholes, as is seen from the diagram in Figure 2.

Drilling expenses have the most appreciable influence upon C_{output}. For instance, by an efficiency of 20 Gcal/hr the borehole cost is doubled and the expenses for C_{output} increase fourfold; that is, 1.4 and 3.3 times, respectively. Nevertheless, the geothermal heat source, in a series of cases, has economic advantages compared with traditional boiler houses, even with a relatively high cost of boreholes.

The analysis of summed expenses spent for the distribution and consumption of heat, C, showed that the influence of each single factor mentioned above lies in the range of 12 to 40%. For instance, a 10°C drop in the temperature of thermal water increases C^{I} by 10 to 12%. Consequently, a 10% drop in heat output increases C^{I} by 15%. A shift from south to north of one climatic region increases expenses by 10%. A complete change of a single-string system of distribution networks to a double system (head pipelines

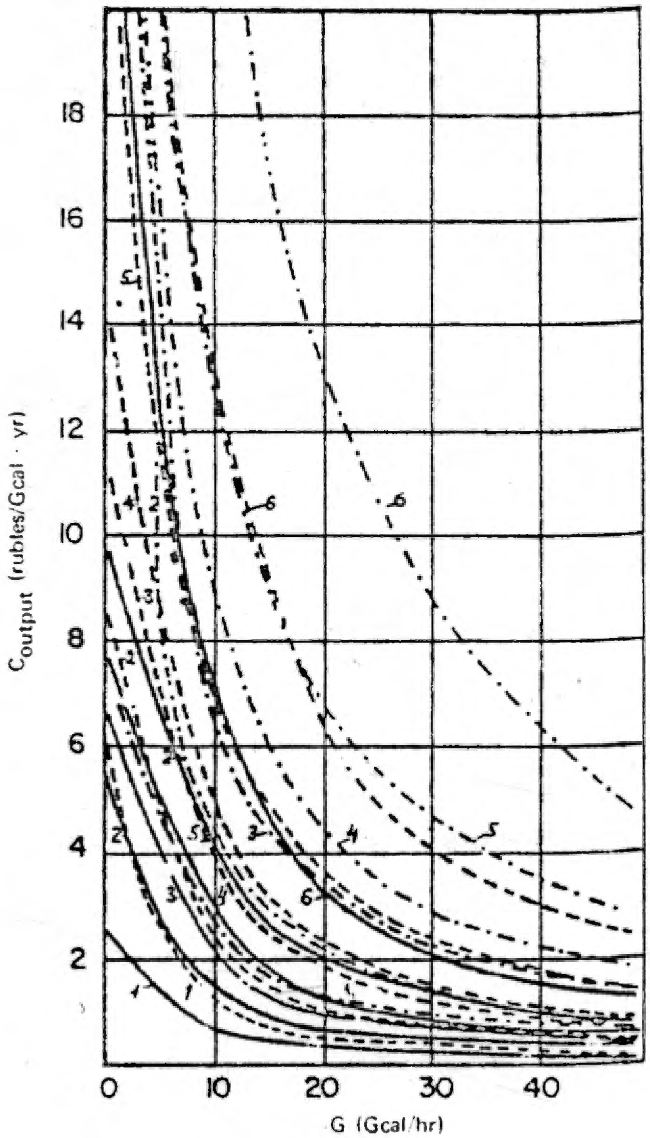

Figure 1. Change of specific reduced expenses spent in geothermal heat source under the influence of estimated load, borehole cost, and the number of boreholes (T_{max} = 3500 hr/yr, l_{bore} = 500 m); n_{bore}: 1–2, 2–4, 3–6, 4–8, 5–12, 6–22; K_{bore} (10^3 ruble/yr): ——— 50, ---- 100, ----- 200.

as single-string lines; secondary, district pipelines as double-string lines) increases expenses by 25 to 30%. An increase of the discharge distance from 0 to 10 km raises costs by 30 to 36%.

One should stress especially the significance of the correct choice of the heating system. A modern engineering development of geothermal heating systems is the enlarged surface of the heating devices. Therefore, the heating systems (even those that are most appropriate for a geothermal heat supply) have had up to now a limited rate of economy. They are, as a rule, more expensive and surpass the metal capacity of traditional systems.

Thus the double-string system with convectors does not exceed the cost of traditional systems only when the thermal springs have temperatures greater than 90°C and the temperature changes are not more than 35°C. As the temperature of the thermal water decreases and the temperature change increases, the expenses of this system rise sharply.

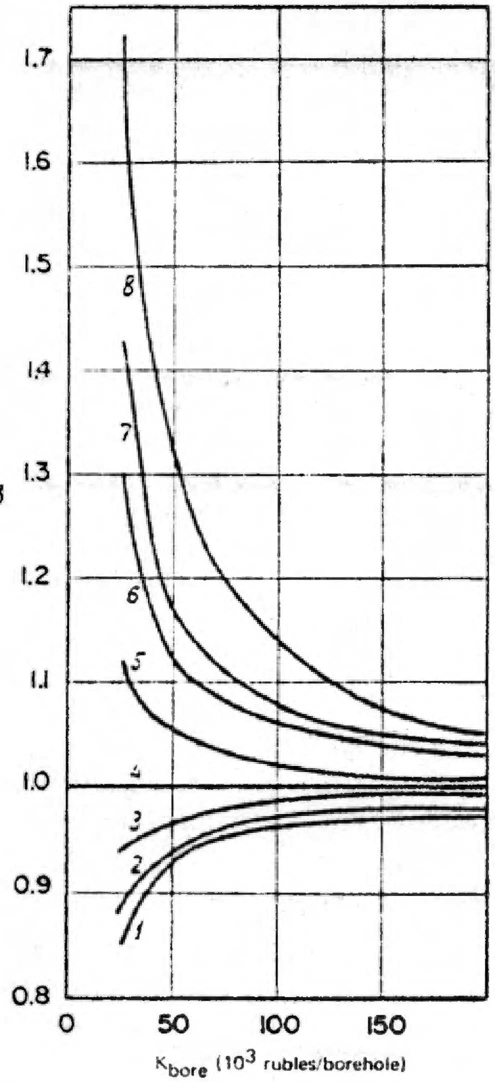

Figure 2. Auxiliary diagram for the determination of C_{output} by any distance between boreholes; l_{bore} (m): (1) 50, (2) 100, (3) 200, (4) 500, (5) 800, (6) 1000, (7) 1500, (8) 2000.

The influence of the expenses related to the heating systems upon the value of C^1 as a whole varies from 25 to 30% according to operating conditions and the type of system.

One should not neglect that the scheme efficacy of indirect application of thermal water is mainly due to the value of heat losses of the discharged water. In order to find the optimal conditions, an analysis was carried out over the scheme operating rates. These rates vary in accordance with changes in parameters, such as the primary temperature of the thermal water, the actual extent of the heat potential, the temperature of the hot-water supply system feed water, the estimated ambient outside air temperature, and the period of the heating season.

It was established that water is discharged from the heating system during the entire heating season and under all values of the above enumerated factors. However, depending on the changes, the last discharge volumes vary considerably. An appreciable decrease in the discharge volume has been observed under high values of the primary water temperature, high change, and while progressing toward the warm regions. The influence of temperature on the water that is used in the hot-water supply system is noticeable at a drop from 60 to 40°C. The combination of favorable conditions allows the minimization of heat losses related to the discharge to 3 to 4%.

As a whole, one can conclude that the costs of distributing and consuming geothermal heat in the indirect scheme without long-distance transportation do not exceed similar expenses in traditional schemes for heat supply only under very favorable conditions—when the thermal water temperature is not below 85°C, the temperature change is not more than 45°C, and the discharging distance equals up to 5 km, when located in southern regions with an estimated ambient outside air temperature not below −8°C.

The diminution of these requirements necessitates the use of more complicated, and consequently more expensive, schemes of heat distribution and consumption. The necessity of building transit heating lines and pump stations sharply increases the expense of geothermal heat supplies. The specific expenditures even with single-string heating lines in above-ground construction are considerable. They depend on efficiency, temperature change, and climate. Most noticeable is the influence of the estimated load. Thus, with efficiency increase of heating pipelines from 10 to 50 Gcal/hr under the same remaining conditions, the increase in specific expenditures is approximately three time as much. A lesser rate of influence of the temperature change has been observed, and a rate increased by 10°C reduces the specific expenditures by 8 to 10%. Shifting out of a region with an estimated ambient outside air temperature of −35°C into a region with an ambient temperature of −5°C reduces expenses by 13 to 15%.

The specific weight of the expenditures of transit heating pipelines as a whole on the summarized costs for geothermal heat supplies, depending on the above stated factors, varies over distances of 10 to 30 km by up to 50%; for 30 km, from 35 by up to 70%; and for 50 km, from 40 up to 85%.

It was interesting to compare the significant influence of all possible factors on the whole complex. For this reason, the total expenses of a geothermal heat supply were examined for two cases. The first case foresees external changes of operating conditions for the summarized value C^1; the second, for C_{output}.

The following results were obtained: From Equation (2), the sum of C^1 without long-distance transportation in the worst case surpasses by 3 to 4 times at the maximum the best case. For an existing remote single-string heat pipeline extending for 50 km, the sum of expenses is $C^1 + C_{trans}$, as in Equation (3), and, in the worse case, surpasses 10 times the expenses of the case with the best conditions. Meanwhile, the uppermost change of conditions, which defines the sum of C_{output}, can considerably increase it many times.

This means that the complex of works related to heat distribution in general is homogeneous, and the influence here of different factors in the end only changes the quantitative part, that is, the extent of pipelines, their diameter, and so on, which on the whole causes a moderate influence on the expenses.

Meanwhile the cost of the geothermal heat source is influenced considerably by qualitative data, such as bad drilling of rock, high temperature of containing rock, high pressure, and so on, which force the use of other ways of drilling, and more sophisticated equipment. A complicated chemical composition of the geothermal agent obliges us often to use costly metal grades or apply safety measures or constructions. Hence the limits of the rise in cost C_{output} become more significant than C^1 or even $C^1 + C_{trans}$.

Comparing the cases selected under worst and best conditions, permitted us to establish the most efficacious factors and to define the competitive capability of a geothermal heat supply—that is, the cost of the geothermal heat source, defined by the number of boreholes and the drilling cost, and, as one of the determining factors to a considerable extent, the distance of the consumer from the heat source.

These investigations concerning the schemes with indirect usage of geothermal heat have established that on the average they reach a level of economic equality with traditional systems in the range of borehole costs of 100 000 to 130 000 rubles per borehole and more seldom 150 000 rubles per borehole.

Looking at the capability of long-distance transportation of a geothermal heat agent, one can speak only of cheap drilling jobs, up to 50 000 rubles per borehole at a distance of 35 to 40 km. At a borehole cost of up to 80 000 to 120 000 rubles it is economically advisable to reduce the extent of a transit single-string heat pipeline up to 5 km, but under special favorable conditions (high outflow, expensive basic scheme, especially high fuel cost, and so on) it can be extended up to 8 to 10 km. At a borehole cost of 200 000 rubles, it is economically advisable to provide remote transportation of heat only if the boreholes have very high outflow, over 100 m^3/hr at a distance of not more than 3 to 5 km.

In our land, the thermal springs reserves that are suitable for indirect application are quite large: they make up around 30% of the heating potential of the reserve estimates in southern regions of the country—Krasnodarsky and Stavropolsky districts, Dagestan, Georgia, southern Kazakhstan, eastern Siberia, and the Far East. On the other hand, unfortunately the major part of the geothermal springs reserves is characterized by a high degree of mineralization. Sometimes, they contain harmful components, as for instance occurs in the springs of artesian basins of western Siberia or Armenia; or low temperatures are a problem as in Middle Asia and Kazakhstan.

PRACTICAL GEOTHERMAL PLANS

According to various characteristics of the geothermal springs, Soviet scientists have developed a series of schemes for using the hydrotherms to supply heat. Below are the characteristics of the main schemes of practical interest.

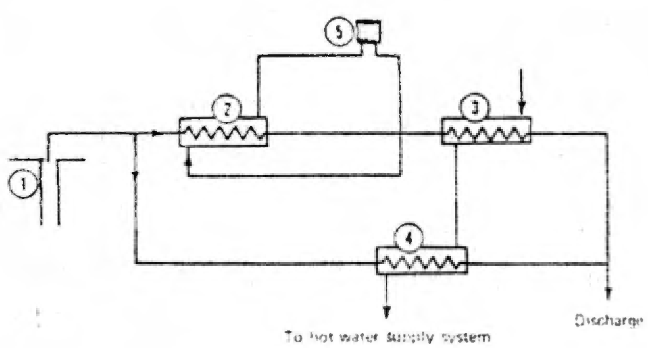

Figure 3. Principles of geothermal heat supply scheme with heat exchangers: (1) borehole, (2) heating system heat exchanger, (3) heat exchanger of the first stage in the hot-water supply system, (4) heat exchange of the second stage in the hot-water supply system, (5) heating system.

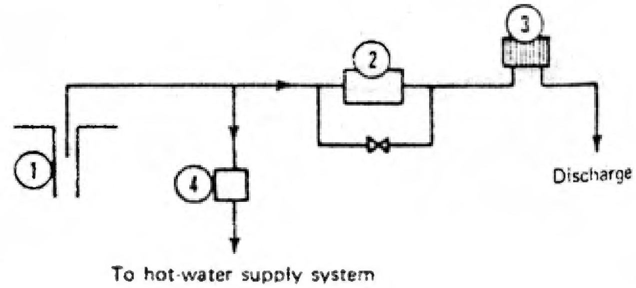

Figure 4. Principles of geothermal heat supply scheme with parallel supply of geothermal spring water to the heating and hot-water supply system and peak surplus heating water: (1) borehole, (2) peak extra heater, (3) heating system, (4) accumulator.

Case 1

The geothermal spring water has a high temperature, over 80°C, but is highly mineralized. In this case intermediate heat exchangers are needed. The principles of such a scheme are shown in Figure 3. Here the geothermal spring water from a borehole is subdivided into two parallel flows. One is directed into the heat exchanger of the heating system and then inside the heat exchanger of the first stage of surplus-water heating for the hot water supply. The second one goes into the heat exchanger of the second stage of the hot-water supply system.

Case 2

The geothermal spring water has a low degree of mineralization and a low heating potential (temperature below 80°C).

Under such conditions it is necessary to increase the geothermal spring water's heat potential. It is possible to accomplish that by various means. Consequently one can get different modified schemes. Let us consider the main ones:

1. A system with a parallel supply of geothermal spring water in the heating and hot-water supply systems and with a peak surplus heating of the feed water.
2. A system of geothermal heating without a discharge.
3. A scheme with application of heat pumps.
4. A composite system with application of heat pumps and a peak surplus heating.

Scheme 1. In the first of these systems, the geothermal spring water out of a borehole goes into the system of a hot-water supply and parallel into the peak boiler house. Here the water is additionally heated to the appropriate temperature, corresponding to the current meteorological conditions, and is fed into the heating system (Fig. 4).

While analyzing the operation of such a scheme, relationships have been found between the partial share of the boiler house in the covering of the yearly loading and the efficiency factor, η, of the geothermal heat supply system. The efficiency factor represents the ratio of the yearly amount of practically consumed geothermal heat to the total amount of heat that could be received by regular loading of the borehole during the year at full use of the heating potential of the geothermal spring water. These relationships allow us to determine the optimal temperature of the thermal spring water surplus heating for each separate case. The given scheme is advisable, especially for regions where expensive drilling is involved, so far as the peak boiler house allows us to reduce the number of boreholes. Depending on the control method, the distribution network can be assembled out of three or four strings. The greater the value of η, the greater the share of heat consumption for the hot-water supply within the total load.

Scheme 2. The second system has a more complicated arrangement than the previous one. Here the geothermal spring water coming from the borehole is additionally heated to a temperature between 160 and 200°C. The heat level depends on the climatic conditions. Such a high temperature of surplus heating allows us to achieve a balance between the needs of domestic water to feed the heating system and the hot-water supply.

Figure 5 shows a principle scheme for such a plant. Out of the borehole geothermal spring water with a temperature of t_{hwc} goes to the boiler house. Inside the boiler house the water, going through the degasifier (1) and the chemical treatment (2) passes to the water heater (3), where it is additionally heated to the temperature that ensures under estimated conditions the equality of water consumption within the heating ducts and the hot-water supply systems.

Out of the boiler house the overheated water is directed to the dwelling houses. The allotment inlet of each house is equipped with a mixer (4) wherein the domestic water is mixed with the backflow water of the heating system. The mixture of specified temperature consequently flows through the heating system (5), and then is completely consumed in the hot-water supply system (6). A possibility is provided of discharging the backflow water from the heating system into the sewerage. The installation of an accumulator (7) is also provided for a single house or for

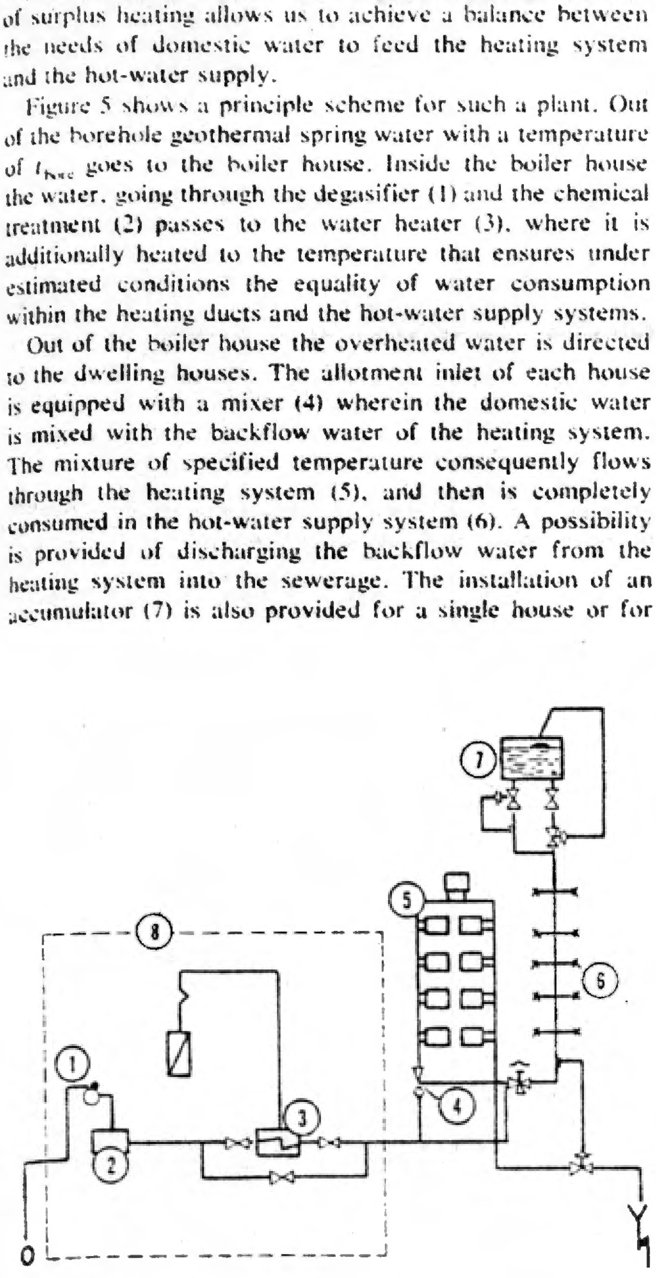

Figure 5. Principles of geothermal heat supply scheme without discharge: (0) borehole, (1) degasifier, (2) chemical treatment, (3) surplus heating, (4) mixer, (5) heating system, (6) hot-water supply system, (7) accumulator, (8) boiler house.

a group of houses. The distribution heating network is a single-string one.

With the rise of the ambient outside air temperature, the consumption of feed water at the allotment inlet remains constant, but a portion of the water is fed into the hot-water supply system, passing the heating system by means of a special branch. Here the water temperature within the hot-water supply system is kept constant during the whole heating period by means of a thermostat.

During the summer the thermal water is supplied to the hot-water supply system, bypassing the extra heater, by means of a diversion pipeline especially installed for that purpose inside the boiler house.

The realization of such a scheme permits a more efficient use of the geothermal waters, and reduces to a minimum the necessary quantity of water, and consequently the number of boreholes. This also reduces the diameter of the heating pipelines and their extent and thus minimizes the amount of metal in the heating system. However, in such a system the peak boiler house becomes a basic heat generator for the heating system and is operated during the whole period of the heating season. This leads to increased plant efficiency of the boiler house and greater fuel consumption.

It is also possible that the surplus heating temperature must not exceed 100°C, due to the danger of corrosion and boiling stone. In this case the distribution network should be a double-string line. This additional factor reduces the efficacy of the system. The factors mentioned above are critical to the given scheme, which should be chosen only by means of a scrupulous economic estimation for each case separately.

Scheme 3. This system uses low-temperature thermal springs with the help of a heat pump. In Figure 6 we see the so-called classical principles of a scheme for heat supply with the addition of a compressing heat pump. The hot water at the borehole (1) is directed to the evaporator of the heat pump (2), where its heat is given away to the rapid-acting evaporating substance. The vapors inside the evaporator are compressed by means of a compressor (3) and directed to the condenser (4). There the vapors condense by means of a higher pressure, giving away their heat to the water that circulates inside the heating system. The cooled water is discharged to the sewerage. The efficacy of the scheme is increased by the performance of the heat pump in summer as a cooling machine.

With the purpose of a more complete heat extraction from the water, a more complicated modified scheme was proposed with a heat pump.

Scheme 4. This is a complex heat supply system with a transmutation of heat from the discharge water in conjunction with its peak surplus heating and qualitative control (Fig. 7).

The spring water (1) passing through the treatment (2) is pumped over by the pumping station (3) in a quantity G through a single-string heat pipeline (4) and enters in the consumers' distribution network at a temperature t_d.

One flow of water, G, is additionally heated in the peak boiler house (5) up to the temperature of direct water t_n and goes inside the mixer (7), where it is mixed with the backflow water that is preheated inside the condensers of

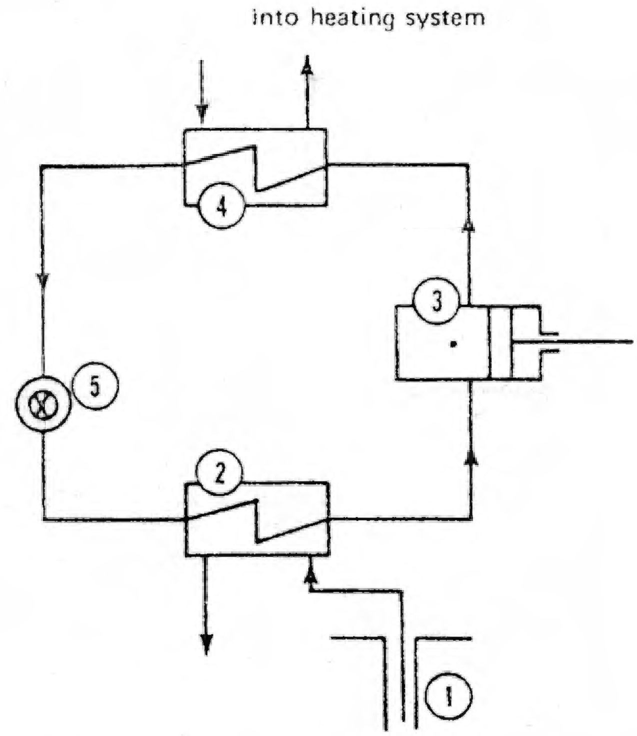

Figure 6. Principles of geothermal heat supply scheme with the application of a heat pump: (1) borehole, (2) evaporator, (3) compressor, (4) condenser, (5) control valve.

the heat pump (8) up to the temperature t_g.

The backflow water with the temperature t_0, after passing the heating system (6), diverges into three flows. One part G_1 goes to the condensers of the heat pump (8) and mixer (7). The second part of the backflow water is directed to the evaporators of the heat pump (9), where it is cooled to the temperature of t_x and then discharged. The third part is directed to the mixer (12). From the mixer the water at a temperature t_r and in a quantity of G_r goes to the

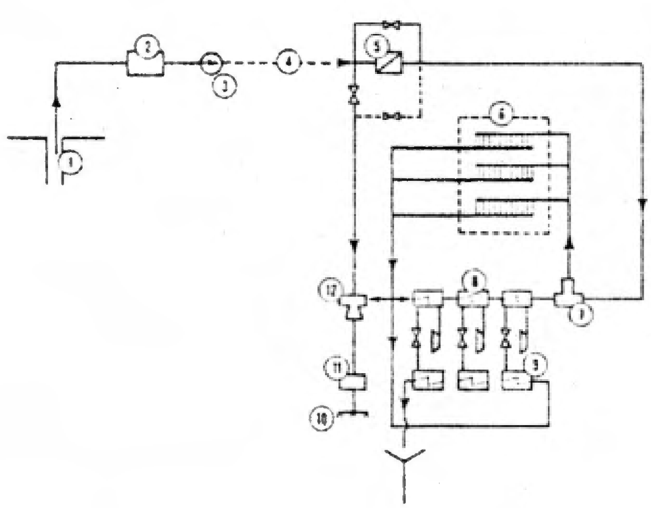

Figure 7. Complex scheme of geothermal heat supply system with the application of peak surplus heating and heat pumps: (1) borehole, (2) water treatment, (3) pumping station, (4) transit heat pipeline, (5) peak surplus heater, (6) heating system, (7) and (12) mixer, (8) condensers, (9) evaporator, (10) hot-water supply system, (11) accumulator vessel.

vessel-accumulator (11) and to the system of hot-water supply (10).

The second flow in a quantity of G_2 goes through a valve B_1 to the mixer (12) and into the hot-water supply network. If the temperature of the geothermal spring water is lower than t_r, then the water is additionally heated to t_r at the boiler house (5) and then goes through the valve B_2 into the hot-water supply system in a quantity G_r.

With the purpose of increasing the heating factor and ensuring a more versatile control, the heat pump units are connected to the heating supply system in a serial counter-flow circuit. This means that the heating of the water in the condenser (8) and the cooling of the discharged water from the evaporators (9) is done in several steps.

With a change in ambient outside air temperature, the qualitative control is made by the peak boiler house, while the heat efficiency of the heat pump and the consumption of borehole water remains constant. After disconnecting the peak boiler house, the quantitative control is done by the heat pump. This performance ensures a regular schedule of borehole water consumption throughout the year.

In this system the share of heat usage of geothermal spring water is greater, the lower the estimated temperature within the heating system equipped with convectors or panels, where the estimated temperature is 40 to 45°C.

A comparison of this system with the system without discharging shows that the specific flow of geothermal spring water in the scheme with thermo-transformers exceeds almost twice the flow in the system without discharging. Meanwhile the efficiency factor was several times higher.

The summarized share of fuel-consuming plants in a year's heat balance makes up a minimum. This fact provides the prerequisites to use that scheme in regions where the transportation expenses for fuel may exceed the expenses for drilling a large number of boreholes.

Limited Supply of Electricity

The operation of compressing heat pumps means considerable electrical energy consumption, and consequently, is limited by the electricity supply conditions of the region in question. In such cases there is a more perspective application of heat-consuming absorption machines, where as acting bodies and heat-generating engine solutions are used. The latter are selected in such a way that one of the components in a pure form serves as a cooling agent, and the other serves as a good heat absorber. A considerable interest has been shown in the application of lithium bromide in water, which serves as cooling agent.

The lithium bromide unit (Fig. 8) is set together out of two drums, the upper one (2) is a block generator-condenser, the bottom one (1) is an absorber-evaporator. The source of low temperature (steam or warm water) is used to evaporate the solution inside the generator. The steam formed in this way condenses inside the condenser and flows into the evaporator. The cold is achieved with the help of condensing the boiling agent under vacuum; and as a result, the water that circulates through the coils of the evaporator is cooled. The boiling process is maintained in the evaporator by the absorption of water vapors by the solution that enters the absorber after being evaporated in the generator.

The working cycle in this machine requires heat energy supplied from the outside, and this creates prerequisites

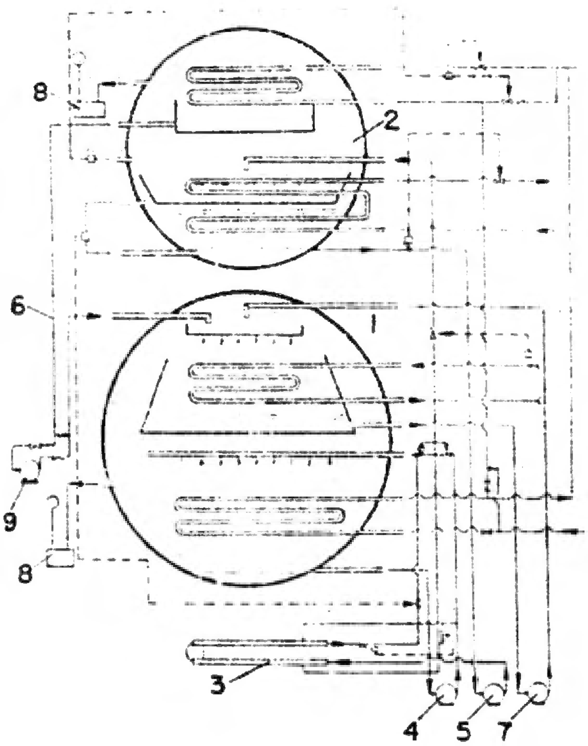

Figure 8. Principles of the lithium bromide machine scheme: (1) block absorber-evaporator, (2) block generator-condenser, (3) heat exchanger, (4) (5) (7) (8) and (9) pumps, (6) discharge line.

for the use of geothermal spring waters. The possibility of the unit's functioning as a cooling engine in summer and as a thermo-transformer in winter provides a constant water flow during the year, which is the most favorable condition for the geothermal borehole.

Depending on the temperature of the geothermal spring water, the lithium bromide machines can operate as step-up or step-down thermo-transformers, where the same working processes take place as inside the cooling machine, only at different temperatures.

The operation of a step-down transformer requires a boiler house connected to the generator, which is supplied with high-temperature heat (80 to 120°C). Geothermal spring water is fed to the evaporator tubing from the borehole at a temperature of 30°C and more. Here the water is cooled and is discharged into the sewerage.

The given scheme allows the complete use of the heat which is contained in geothermal spring water; and because of that, fuel is economized (up to 40%), and the system of heat supply gets a higher heat rate than from a common boiler house. The transmutation factor equals the ratio of the received amount of heat for the heating system to the amount of high-temperature heat led to the generator, and in some cases achieves the value of 1.7.

While working as a step-up transformer, the unit sends the geothermal spring water to the generator and in the tubing of the evaporator at a temperature of 50 to 70°C. In that case, a higher heat potential is being generated in the absorber than the heat of the geothermal spring water. The transmutation factor, which represents in this case the ratio of the received high-temperature heat in the absorber to the consumed low-temperature heat, is 0.45.

While working as a cooling machine, the chilling effect is achieved in the evaporator due to the boiling of water in a deep vacuum (5 to 8 mm Hg). The boiling water at a temperature of 2 to 8°C flows on the outer surface of tubing and cools the water inside the pipes; later the water goes into the air-conditioning system.

Normal unit performance is achieved at a temperature of the heating water of 80 to 120°C. With a drop in the heating water's temperature, the chilling efficiency of the unit decreases. Thus, if at a temperature of the heating water of about 120°C, the chilling efficiency reaches 2.5×10^6 kcal/hr, at a temperature of the heating water of 80°C, the chilling efficiency drops to 1.2×10^6 kcal/hr.

The machine heat factor, representing the ratio of the quantity of received cold to the quantity of consumed heat, averages 0.7.

Comparison

The economic estimates show a sufficiently high efficacy of the units. Technical economic comparisons of the two systems were made for urban thermic and cooling service; both systems were located in a climatic region with an estimated ambient outside air temperature for the heating purpose of $t_{air} = -13$°C. The first system includes a boiler house and a compressing cooling machine; the second, a geothermal spring source, peak boiler house, and a lithium bromide unit that ensure the loading of an urban cooling system and heat supply in winter. The temperature of the thermal water is 60°C; the maximum heat output, 10^7 kcal/hr; cold output, 2.2×10^6 kcal/hr. Results of the second system were heat consumption 5.8 times less, and expenses 2.3 times less than in the first one.

The tests of lithium bromide units showed the full performance ability and an efficacy in conditions when the flow of electrical energy was severely limited, and thermoenergy was available in a sufficient quantity.

CONCLUSIONS

Thus the analysis of the schemes examined above for geothermal heat supply leads toward the following conclusions. In Case 1 the use of the scheme for indirect application of highly mineralized geothermal spring waters becomes extremely advisable, when such substances as bromide, iodine, or rare elements are in the thermal water that has passed the heat exchanger and given away its heat to the secondary water parallel. In fact one requires here a set-up of materials for the supplying of pipelines and tubing of the heat exchangers. As a rule, these materials are expensive and scarce. Thus there is a tendency toward the compactness limit of such heat exchangers. In modern engineering there is a series of constructive solutions that raise the heat output inside the heat exchangers. This, for instance, is the manufacturing of tubing with fin surface, their gradual rotation, and so on. In fact, by applying such a scheme, the remote transportation of a geothermal heat agent is possible.

In Case 2 we dealt with complicated plants that consist of a whole chain of different energy transmutation units. According to their physical consistency the most efficient are the heat pumps, that is, their work leads to an increase of concentration of heating energy on account of energy directed from outside.

In fact the modern heat pumping plants of the compressing type are somehow cumbersome, expensive, and not reliable in action. Besides, as a rule, the working fluid is selected without considering the geothermal heating agent's specific character, and that reduces the already low efficiency factor.

An analysis of summarized expenses according to all schemes mentioned above was carried out. It has been established that the plants increasing the geothermal spring water's heat potential (peak boiler house, heat pumps, and so on) were attributed to heat sources. Finally it was established that all the additional devices reducing the number of boreholes decrease the expenses for the output of geothermal heat. However, the expenses spent in the heat source output as a whole increase quite considerably because of the investments in equipment and the special rise of operating costs due to amortization that composes the service cost and fuel and electrical energy costs. Also, the operation gets more sophisticated, and the reliability drops.

With temperatures of the geothermal heat supply within the range 85 to 100°C, the distribution networks (with the exception of single-string mains without discharge systems), as well as the heating systems and hot-water supply from the constructive point of view, are similar to the traditional ones. The evaluations show that in cases where the geothermal heat supply lies, according to those schemes, within the range of competition, the main benefit in comparison with traditional schemes is received actually if the cost of drilling geothermal boreholes is low. The mean economic efficacy of these schemes remains when drilling costs are not more than 100 to 130 thousand, more seldom, 150 000 rubles per borehole.

In conjunction with the above, it seems that further investigations in the field of geothermal heat supply must be directed in first line principally to find out new forms of "collecting" deep heat either indirectly or with the help of more efficacious, possibly nontraditional, transformers and concentrators of energy.

Now and again the tendency toward the lowering of losses in energy transmission will require the selection of an effective energy carrier, whose application will provide a minimum of constructive elements in conjunction with a high efficiency factor.

13

ANNEXE 13

ANNEXE 13

Prospects for Geothermal Energy for Space Heating in Low-Enthalpy Areas

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ABSTRACT

The economics of geothermal energy is evaluated, considering the geology and geothermal situation in Germany. Under the following conditions geothermal heat is competitive with conventional heat sources: (1) existence of a hot aquifer with a transmissivity exceeding 1000 md · m, (2) persistent peak recovery per production well of more than 12 Gcal/hr (24 000 Gcal/yr), (3) utilization of the heat in the immediate neighborhood of the wells, and (4) no major corrosion and scaling by the produced water. Artesian outflow from the hot aquifer diminishes operational costs and consequently alleviates the above requirements.

A pilot plant is being considered for installation in the upper Rhine Valley within a local geothermal anomaly of 4 hfu. Costs are expected to be \$12/Gcal at the borehole and \$16/Gcal after distribution to the consumer.

Introduction

By request of the Bundesministerium für Forschung und Technologie (Federal Ministry of Research and Technology) the Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Geological Survey) and the Niedersächsische Landesamt für Bodenforschung have carried out an investigation in 1974 to assess the geothermal potential of West Germany. The possible utilization of geothermal resources for space heating was stressed in this study, since no geothermal fields capable of supplying power plants for the generation of electricity were known or expected to exist. The economics of the construction of geothermal heat plants was evaluated, given the geological and geothermal situation.

We believe that the conclusions drawn concerning the economics of geothermal heat plants can be generalized to some extent for all countries with comparable geothermal, geographical, and climatic conditions.

PRESUPPOSITIONS FOR EXPLOITATION

Prior to any discussion of economic factors, we outline the geothermal situation in Germany, which serves as the basis of our considerations. With currently available technology, the utilization of geothermal energy requires the recovery of hot fluids from depth. Therefore, the following aspects are of special interest: (1) thermal conditions in the subsurface, (2) hydrogeological conditions at depth, and (3) geochemical composition of hot subsurface waters.

Geothermal Presuppositions

In Figures 1 and 2 subsurface temperatures at depths of 1000 m and 2000 m in Germany are shown. These illustrations are based on approximately 100 temperature logs measured in boreholes, and on approximately 1000 temperature logs constructed from temperature readings by maximum thermometer. The measurements were carried out mainly in oil fields currently in operation. Since the recorded temperature readings are not always reliable, numerous correctional procedures have been employed to improve the quality of the data. The theoretical basis of these procedures is described by Haenel (1975).

In northern Germany no well-documented and significant thermal anomalies have been discovered. In the central portion of the map, no isolines are drawn. No detailed subsurface temperature survey has been carried out in that area due to the lack of a sufficient number of deep drill holes.

The highest subsurface temperatures in Germany have been determined in the upper Rhine Valley, notably around Landau/Pfalz (Haenel, 1974a). Temperatures up to 100°C at 1-km depth and 150°C at 2-km depth have been measured; these correspond to a heat flow of 4 hfu. Probably extending over an area of about 60 × 150 km, elevated subsurface temperatures up to 70°C at 1-km depth have been determined in southern Germany. The anomaly, however, is only well documented by geothermal measurements around Urach, south of Stuttgart (Haenel, 1974b).

A comparison of the two maps shows that only the thermal manifestation at Landau continues to greater depth. It is possibly the sole thermal anomaly in Germany which can be attributed to some deep-seated geological process (Delisle, 1975a). Given this geothermal situation in Germany, hot aquifers in excess of 100°C can only be found at depths of more than 1 km.

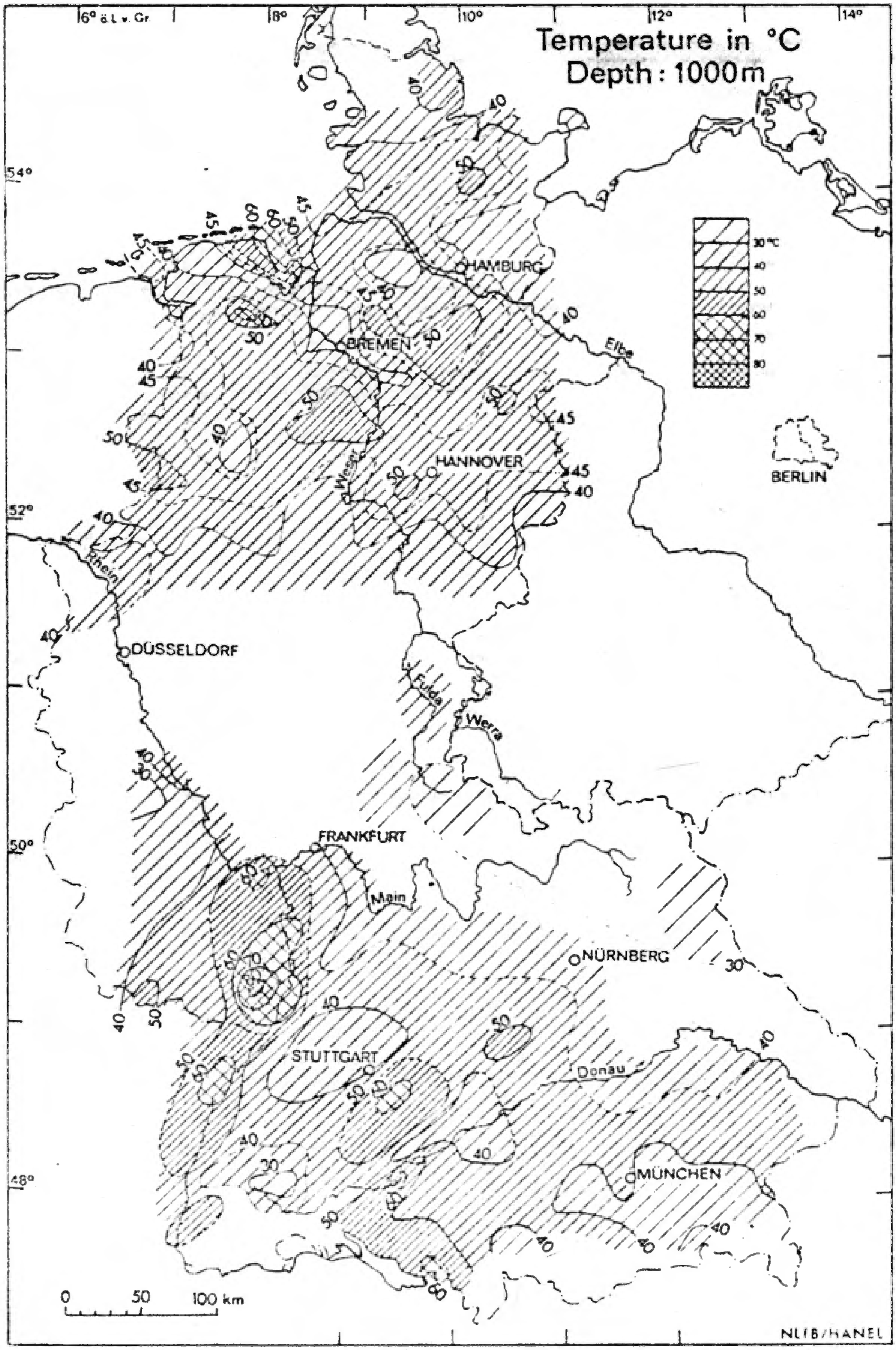

Figure 1. Temperature isolines (°C) at 1000-m depth.

Hydrogeological Presuppositions

In Figure 3 deep basin structures in Germany are indicated: sediments in the North German Basin reach a depth of about 6 km; in the graben system of the upper Rhine Valley, about 5 km. The Molasse Basin in southern Germany has a maximum depth of approximately 6 km.

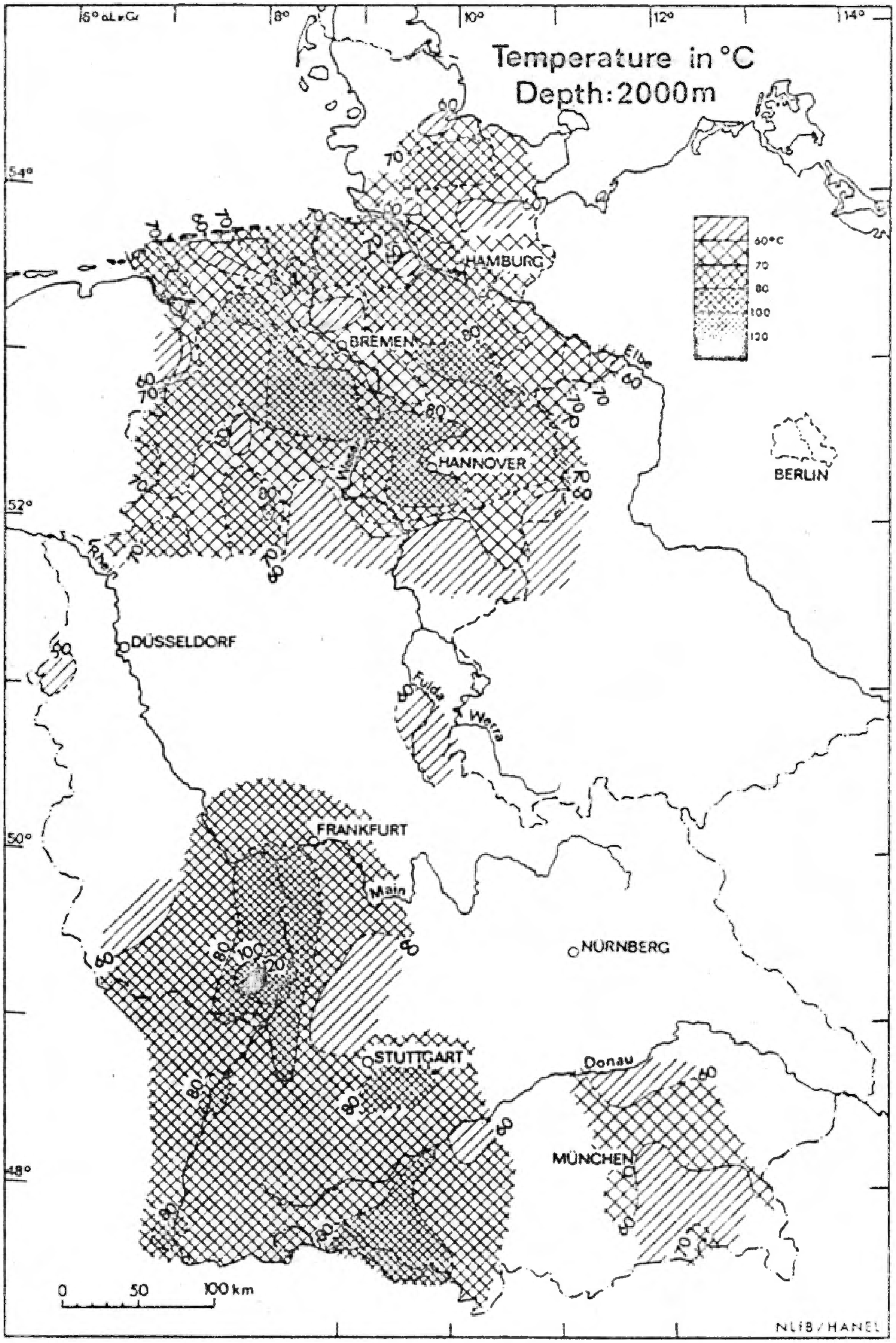

Figure 2. Temperature isolines (°C) at 2000-m depth.

The transmissivity in the North German Basin is to our present knowledge too low to allow substantial production rates of hot water above 120°C.

At the western flank of the Rhine graben at Landau, the subsurface is expected to be highly fractured due to the numerous fault systems in the area. The Tertiary sedi-

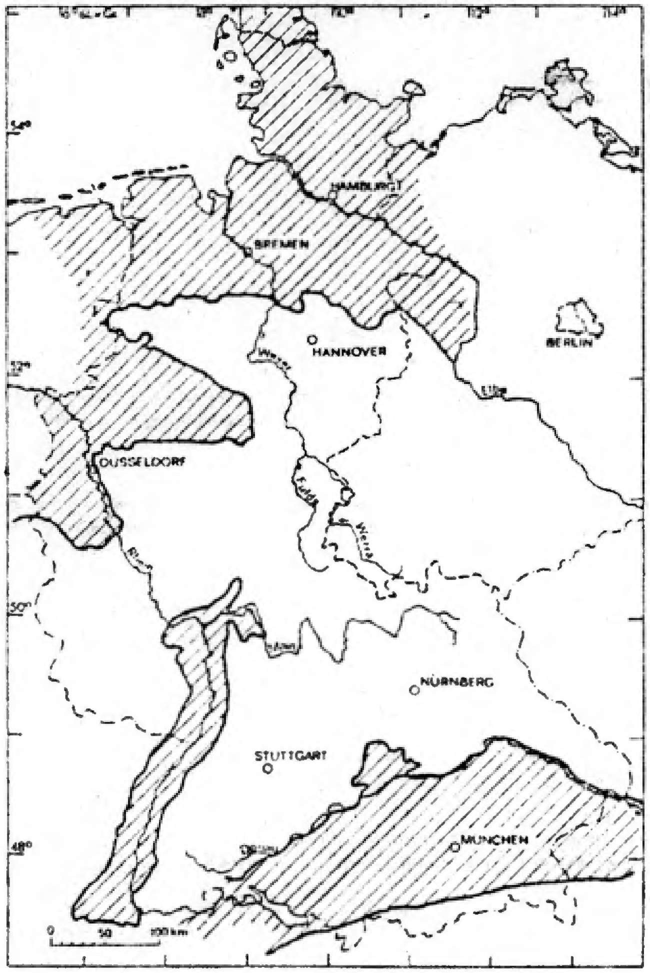

Figure 3. Basins in Germany: North German Basin, upper Rhine Valley, Molasse Basin.

ments, about 2.6 km thick, which are mainly clayey in composition and, in part, oil bearing, are not permeable enough to yield substantial amounts of hot water. The Triassic Buntsandstein formation at about 3-km depth has a thickness of at least 400 m. The primary permeability of this formation, which contains saline water, is estimated to range between 1 and 30 md (Döbl, personal commun.; Ortlam, 1974; Schopper, 1974).

The Molasse Basin in southern Germany includes a north-south-dipping formation of Jurassic age called Malm, which is expected to be highly fractured locally. For instance, one borehole reported to yield 470 gal (1800 l) per minute of 52°C warm water from this formation by artesian outflow has been in operation for more than 20 years (Cramer, 1953).

Geochemical Presuppositions

Little is known about the chemical composition of fluids in hot aquifers in Germany. The presence of numerous salt domes intersecting the North German Basin probably causes most fluids there to be highly concentrated with salts.

In the southern portion of the Rhine graben, thick salt beds have been discovered. To what extent the chemical composition of fluids at depth have been affected by these beds is unknown. In the northern part of the Rhine graben, salt concentrations up to 165 g/l (approximately 100 g Cl/l) have been observed (Fig. 4A).

In the Molasse Basin the salinity of deep aquifers is less severe; Figure 4B illustrates the corresponding relation of salinity to depth. The Jurassic Malm formation frequently contains water with uncommonly low chemical concentrations. The reason is not clear, but it is suspected that surface waters enter this formation at places where it outcrops at the surface.

LIMITING FACTORS

The type of geothermal heat plant we considered consists of the following components: (1) one production borehole and one injection well, (2) one submersible pump for production of hot fluids from depth and one pump for reinjection of the effluent, and (3) one heat exchanger at the producing well connected to the pipeline for transmission of water, heated by geothermal fluids, to the consumer.

Investment costs for a plant with a peak capacity output of about 10 to 15 Gcal/hr are estimated to range between $2 to 3 million, assuming a recovery of geothermal fluids from depths of 2 to 3 km (Delisle, 1975b). The operational costs, including discharge of investment and interest, will amount to approximately $0.3 to 0.5 million per year for projects not subsidized by government. The current price level for space heat in Germany averages $16. To finance the operation of the plant and to repay the invested money, given an interest rate of 9%, an output of 24 000 Gcal/yr is necessary to earn the required funds. Under the climatic conditions prevailing in Germany, only heat plants with a peak capacity of 12 Gcal/hr or more achieve this yearly output. If the construction of the plant is subsidized publicly by granting a loan with a favorable interest rate of 7%, then the required output of the plant amounts to 20 000 Gcal/yr, corresponding to a peak capacity of 10 Gcal/hr.

A peak production of 12 Gcal/hr requires a peak pumping rate of 35 l/sec (28 l/sec), if the geothermal fluids are cooled by 100°C (120°C) in the heat exchanger. To achieve these pumping rates, the transmissivity of the hot aquifer must amount to more than 1900 md·m, assuming the production pump to be placed at a depth of approximately 500 m and the water in the reservoir to be found initially at quasi-hydrostatic or above-hydrostatic pressure.

To reach the required annual output mentioned above, only aquifers above 120°C can economically be exploited, otherwise the flow rates necessary to achieve the desired energy yield would be excessively high.

The heating period in Germany lasts from late October until the end of April (approximately 4300 hr). Given an annual output of 24 000 Gcal, the average load of the heat plant amounts to 5.6 Gcal/hr. To satisfy peak demand, the following alternatives exist: (1) increasing the pumping rate of hot water from depth, (2) heat generation from other energy sources, and (3) use of geothermally heated water stored in a tank filled during times of low heat demand. The economics of alternatives (2) and (3) are not analyzed in this paper. However, a geothermal plant with an output of 5.6 Gcal/hr requires production rates of about 13 l/sec (ΔT = 120°C). The transmissivity of the aquifer ought to exceed in this 1000 md·m.

The analysis of the required transmissivity of the aquifer is based on a mathematical analysis of the theoretical pressure drawdown from an infinite reservoir of constant thickness and the corresponding maximum yield from a line source well, following the procedures outlined by Matthews

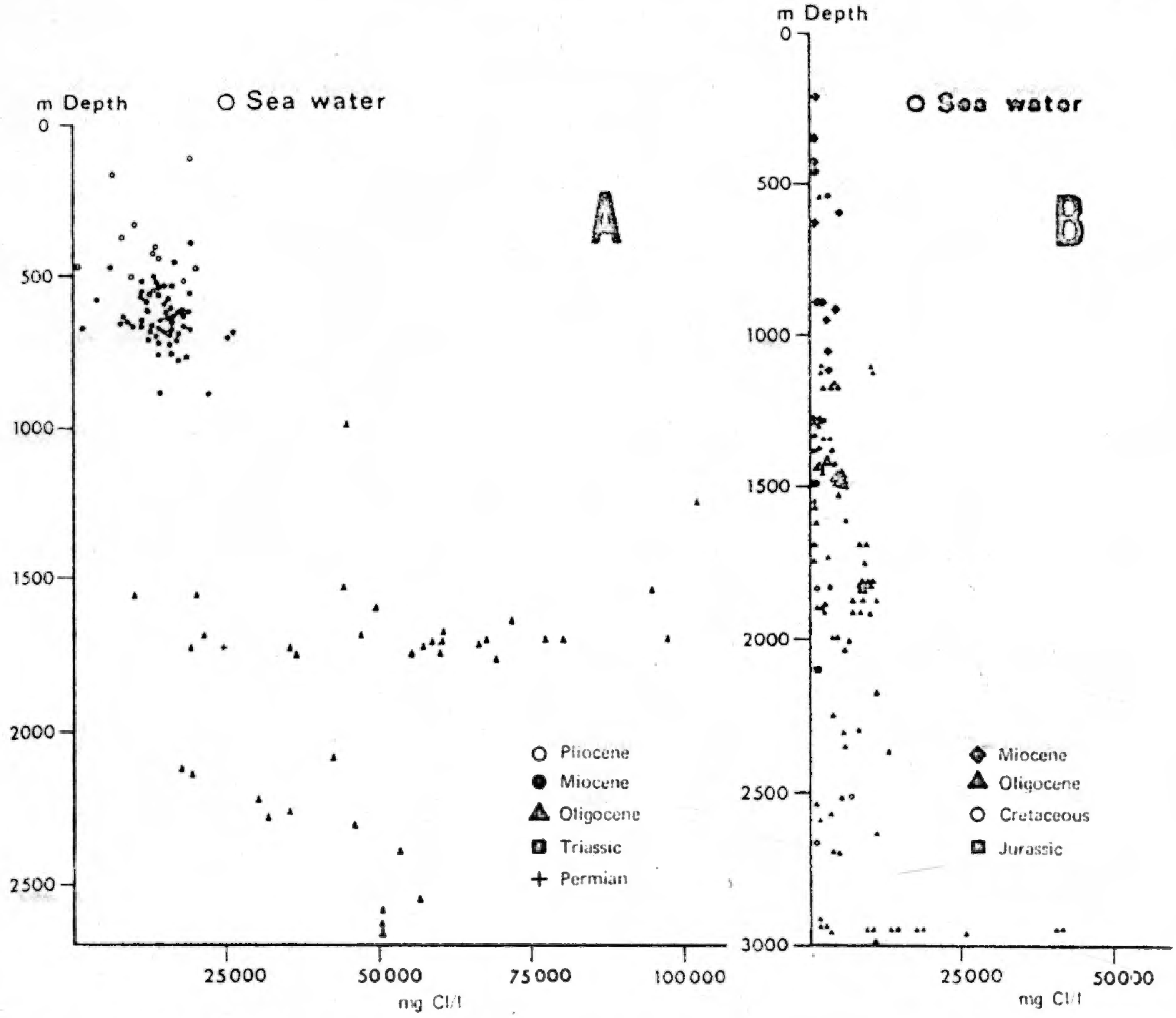

Figure 4. Cl content as a function of depth (from Hahn, 1974, personal commun.). (A) northern Rhine graben, (B) Molasse Basin.

and Russel in 1967. The above arguments are not valid in cases where a hot aquifer along a deep-reaching fracture system or through a well discharges large volumes of hot water at the surface. In these cases the expenditure for pumps and their operational costs can be neglected. Further savings are possible if the ascending waters due to their minor chemical contamination can be used for heating directly.

The limiting conditions for economical utilization of geothermal energy in low-enthalpy areas can be summarized by the following geological presuppositions:

Aquifer temperature >120°C
Depth of hot aquifer < 3 km
Transmissivity of aquifer > 1000 md · m

The above-mentioned limitations are valid if the market value of space heat averages $16. The project would be more economical if hot fluids ascend freely along fracture systems or through wells to the surface (artesian outflow).

ECONOMICS OF A GEOTHERMAL HEAT PLANT

Detailed calculations on the economics of a proposed geothermal heat plant at Landau have been carried out. For the calculation of the production costs (in U.S. dollars per gigacalorie) of geothermal heat the following equation is used:

$$S = \frac{1}{N}\left[\left(i \sum_{n=1}^{n} \frac{S_n(1+i)^{\alpha_n}}{(1+i)^{\alpha_n} - 1}\right) + S_{n+1}\right]$$

where N is the total amount of gigacalories per year; i is the annual interest rate, S_n is the cost for the components of the plant, S_{n+1} is the annual operating costs, and α_n is the amortization periods in years.

The following assumptions have been made: One production borehole produces 28 l/sec of 170°C hot water. The geothermal fluids are cooled in the heat exchanger by 100°C. This heat is transferred to a fluid, whose temperature is raised by 40°C in the exchanger and then transmitted via a 0.5-km-long pipeline to the consumer area. A load density of 40 Gcal/hr · km² is realistic for the heating district at the proposed site.

The cost analysis is carried out for a geothermal heat plant with a peak capacity of 10 Gcal/hr. We assumed that the project will be supported by the government. Therefore, the cost analysis can be based on a low interest rate of 7% on the invested money, which in turn lowers the annual operating costs to approximately $0.25 million. Initial "hook-up" charges demanded from the customers amount to a total of $0.48 million. Therefore, only a portion of the required money to construct the plant must be made available through a loan. The monetary return flow from the sale of heat to the consumers is expected to cover all the operational costs of the plant. The indicated cost figures (price level of 1974) for equipment and construction have been obtained from numerous sources, notably from manufacturers themselves. The estimates of the costs of transmission of hot water from the heat exchanger to the consumer area are taken from a study of Hübner (1974). This study is based on the cost figures of a German company, which operates approximately 70 heat plants. All price quotations have been converted to US dollars on the basis of $1 = 2.5 DM.

Costs of drilling. The drilling of a 3000-m deep production borehole and a somewhat shallower injection hole (2500 m) was estimated to cost $1.5 million = S_1. The lifetime of the borehole (n_1) is expected to be about 15 yr.

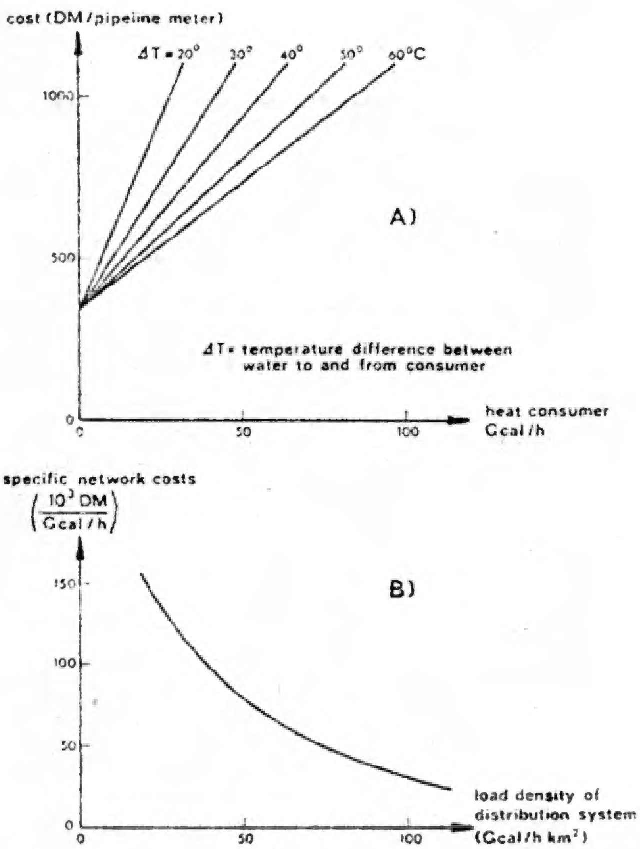

Figure 5. (A) Specific cost of pipeline per meter as a function of temperature difference between supply and return water (Hübner, 1974). (B) Specific cost of distribution network in heating district (Hübner, 1974).

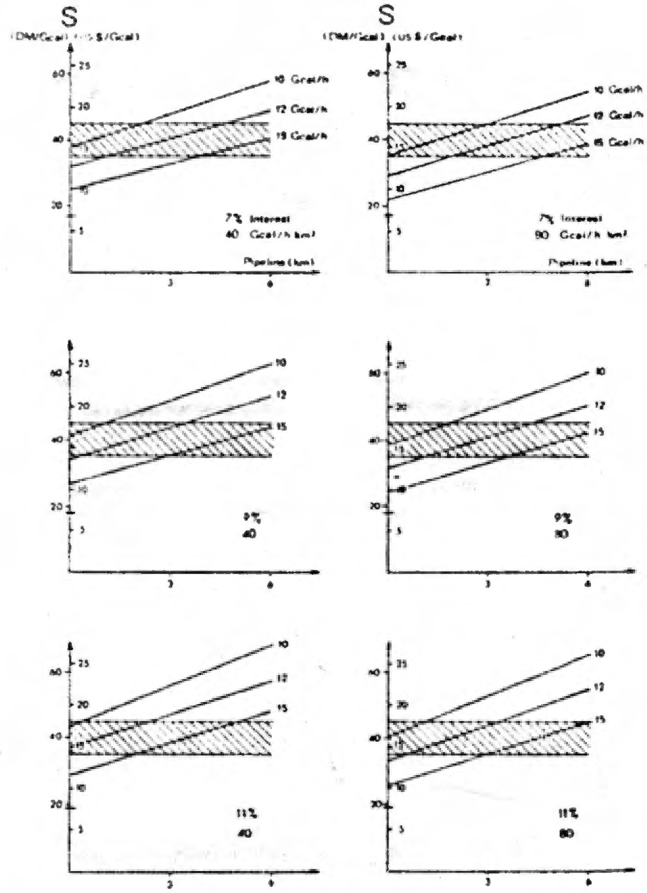

Figure 6. Costs, S, of geothermal energy for space heating; shaded area indicates current price range for space heat in Germany.

Pump costs. Since artesian outflow at Landau cannot be expected, a submersible pump needs to be installed. The transmissivity of the hot aquifer at depth is not sufficiently known to determine the required depth of placement for the pump. The same argument holds for the determination of the required power of the injection pumps. Further, the development of pumps capable of handling water above 135°C has not been successfully completed to our knowledge. The total costs (S_2) for pumps are arbitrarily assumed to amount to $\$1.8 \times 10^5$; $n_2 = 10$.

Heat exchanger. The heat of the geothermal fluids is transferred to water which circulates between the exchanger and the consumer via pipeline. The cost (S_3) of a heat exchanger with a capacity of 10 Gcal/hr, capable of sustaining highly saline water having been in contact with salt deposits is, according to one offer from a major manufacturing firm, $44 000; $n_3 = 10$.

Costs of distribution of hot water. Two systems are necessary to transport hot water from the heat exchanger to the consumer: (1) a pipeline system (2 pipes) for supply of hot water and return of cooled water, and (2) a distribution system in the heating district. The costs for the pipeline depend on its length and on the required pipe diameter, which in turn is dependent on the temperature difference between supplied hot water and the cooled return water at peak capacity of the system. From Figure 5A the costs per meter of pipeline can be read: the cost of a 0.5-km pipeline (S_4) is \$90 000; n_4 = 30.

The cost for the distribution system depends on the specific network costs, given the load density of the consumer area and the peak capacity of the system. For 10-Gcal/hr peak capacity, the network costs (S_5) here amount to 97 500 DM·hr/Gcal × 10 Gcal/hr = \$390 000 (see Fig. 5B); n_5 = 30.

Operating costs. Expenditures for administration, personnel, maintenance, and operation of the pumping system (S_6) were expected to amount to a total of \$139 000. The operation of the pumps was estimated to cost \$90 000/yr.

The cost of geothermally derived space heat at Landau can be calculated to be \$12 at the heat exchanger and \$16 at the consumer (market price). If we assume that the project will not be supported by government, then the cost analysis would have to be based on an interest rate of 9%. The required peak capacity of the plant would then have to be 12 Gcal/hr.

In Figure 6 the relation between market price per gigacalorie, load density of the distribution system, interest rate on invested money, and distance between borehole and heating district is illustrated, based on the above outlined assumptions.

CONCLUDING REMARKS

The major limitations for the construction of an economical heat plant are the required expenditures for drilling and transmission of hot water at the surface. These expenditures probably do not differ to a great extent world-wide. The arguments presented on the limitations on the operation of an economical heat plant can, in our opinion, to some extent be generalized for all low-enthalpy areas, where geographical, geological, and climatic conditions similar to those in Germany exist.

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14

ANNEXE 14

GEOTHERMAL ENERGY FROM SEDIMENTARY BASINS

A. M. Jessop

INTRODUCTION

Hot water from sedimentary rocks of the Paris Basin is now being used to heat large apartment buildings. The water being used is recovered at a temperature of only about 60°C (140°F), but it provides heating more economically than conventional energy sources. Since there are large areas of Canada underlain by deep sedimentary rocks, and since these sedimentary formations have been extensively explored for oil and gas, it is appropriate to enquire whether useful hot water is available to heat Canadian homes.

Geothermal energy is often thought of as being the result of volcanic action, and as being necessarily confined to areas of young tectonism and volcanism. These areas are confined to the relatively narrow tracts of land that are associated with the edges of moving plates in modern theories of earth structure. The spectacular and well-known occurrences of geothermal energy are found in the volcanic zones, but there is heat that may be used for space heating wherever sedimentary sequences reach a depth of at least 1500 m (5000 ft.) and coincide with geothermal gradients that are at least equal to the world average of about 25 mK/m (14°F/kft.). The useful energy is held in the form of hot water that fills the porous rocks in the lower parts of the basins.

The most significant example of current usage is in the suburbs of Paris, France. The particular significance of the Paris Basin is that there is nothing geologically unusual about it. The Basin is not large, and it does not have a high geothermal gradient. Water at about 60°C (140°F) is being taken from a reservoir at a depth of about 1500 m (5000 ft.) to supply apartments at Villeneuve-la-Garenne and at Creil. Full details of the reservoirs may be found in 'Potentiel Géothermique du Bassin Parisien' (Housse and Maget 1976), hereafter referred to as the *BRGM report*.

Earlier developments in other parts of the world are described in the proceedings of the first U.N. Symposium on the Development and Utilization of Geothermal Resources. Heat from the Hungarian Basin is being used for space heating in Szeged, where 1200 apartments were being supplied in 1970 (Boldizsar 1970). The Hungarian Basin is known to have a high geothermal gradient. Large resources of heat in the Gulf of Mexico Basin are described by Jones (1970). This basin contains large zones of geopressured formations, which have unusually high thermal gradients and water content. Makerenko et al (1970) claim that water in the temperature range 40°C - 100°C (104°F - 212°F) is to be found beneath 20% of the territory of the USSR. These resources are being exploited in many areas (Tikhonov and Dvorov, Makerenko et al, 1970), and probably include large volumes of water in sedimentary basins.

In Canada the first look at hot water in sedimentary basins as an energy source has been taken by the Geothermal Service by means of a contract to Sproule Associates Ltd. of Calgary. The investigators examined the existing information and produced a report that gave a summary of the possible water reservoirs in selected areas. This report will hereafter be referred to as the *Sproule report*.

EXPLOITATION IN FRANCE

After a feasibility experiment at Melun l'Almont in 1970, four geothermal projects have begun in France.

At Creil the completed development will contain 4000 apartments, 2000 of which were originally built with conventional heating facilities. About 75% of the energy requirements will be met, using water at about 60°C (140°F).

At Villeneuve-la-Garenne 1700 apartments have been converted to the use of geothermal heat.

At Mée-sur-Siene a major programme has been begun for the heating of 6000 apartments, 50,000 m^2 (540,000 $ft.^2$) of office space and community facilities.

At Mont-de-Marsan an entire community of both old and new buildings will be heated by geothermal water. This site is in the Aquitaine Basin of southwestern France and, because of the warm climate, 90% of the heating requirements will be provided by the hot water.

The Paris Basin is smaller than the western plains of Canada, being about 500 km (300 miles) across and having the deepest reservoirs at a depth of about 2800 m (9200 ft.), where temperatures as high as 110°C (230°F) are found. The main water-bearing reservoirs occur in the Purbeck limestone and the Lusitanian limestone of the upper Jurassic, the Dogger series of the middle Jurassic, the Lias series of the lower Jurassic, and Rhaetian sandstone, Keuper sandstone, Muschelkalk limestone and Bunter sandstone of the Triassic. Generally the basin rests on a basement of pre-Permian rocks and is bounded by massifs of Hercynian age, but some Devonian limestone is to be found in the north of France.

The basic information for the evaluation of the aquifer formations was provided by the records of oil exploration companies. Data from about one thousand wells were used in a computer-based study of the lithology and hydrogeology of the Basin. It was not practical to carry out a detailed study of all aquifers, and selection criteria were adopted based on temperatures greater than 50°C (112°F), adequate thickness and wide lateral continuity. The data assembled included the basic geological sections obtained during drilling and various geophysical measurements, including self potential, resistivity, gamma-ray, neutron and sonic logs. Some porosity and permeability data were obtained from tests on drill cores, and data from formation and production testing were also used. Complete analysis of aquifer potential was hampered by the fact that the original data collection was directed towards a different purpose.

The available temperature data were used to produce a map of temperature gradient. It was found that the gradient varied with depth according to conductivity variations, and that anomalies due to poor data had to be neglected. The resulting map is shown in the BRGM report (P36). Observed gradients are in the range 33 to 40 mK/m (18 to 22°F/kft.), and are similar to gradients in the western Canadian plains.

Total dissolved solids are quoted as being up to 26,000 ppm in the Dogger series and up to 10,000 ppm in the Lusitanian formation. These figures are considerably lower than most figures in the Sproule report. The presence of hydrogen sulphide in the Dogger series was also noted.

A set of coloured diagrams, separate from the bound text, forms part of the BRGM report. These include cross-sections and maps showing extent, depth, thickness, temperature, hydrochemistry and transmissivity for each reservoir unit of the Lusitanian, Dogger, Lias and Trias. Synthesis maps of transmissivity and temperature are also included. Notes on the extent and properties of each reservoir are included in the text.

The BRGM report does not mention any data that were actively obtained for geothermal purposes. All the analyses are based on data resulting from oil and gas exploration. Such data are bound to exhibit some shortcomings when used for a purpose that was not originally intended, but the successful exploitation of the hot water has demonstrated that the data were adequate.

CANADIAN STUDIES

It seems probable that sufficient information concerning the sedimentary basins of western Canada already exists from which to develop plans for the exploitation of hot water. There are many thousands of wells, the data from which are stored in the files of exploration companies and provincial governments. Some observation wells, maintained for repeated testing, might also be used to obtain detailed formation temperatures, provided they are not in areas of gas or oil production.

The geothermal potential of a sedimentary unit depends on its temperature, porosity, permeability, thickness and lateral extent. Within sedimentary areas, and particularly around oil and gas fields and exploration targets, detailed information is maintained by the oil companies concerned and by Provincial agencies. In formations devoid of hydrocarbons knowledge is less complete. Studies of the composition, origin and movement of formation water have also been made in both Federal and Provincial Government establishments, e.g. van Everdingen (1968) and Hitchon and Friedman (1969). The useful working knowledge of the reservoir formations resides with the experienced geologists of the oil companies and consulting companies. It is difficult to extract the information that one requires from the mass of available records without the benefit of experience.

The measurement of temperature in drilled wells is usually less thorough than the measurement of other properties and conditions. Most temperature readings have been obtained by including a maximum-reading glass thermometer in the logging tool. Accounts of the development and difficulties of this method may be found in early reports of the British Association for the Advancement of Science (Everett, 1868), and the technique has long since been abandoned for accurate scientific measurement. For results to an accuracy of 1°C (2°F) maximum-reading thermometers are adequate provided care is taken in recording the results, but unfortunately the required care is not usually applied. The value of the data is further reduced by the fact that measurements are made at a time when the well is most disturbed by the process of drilling.

A convenient file of temperature data, known as the *Geothermal Survey of North America*, was available for use in the search. This data file was organized by the University of Oklahoma and was sponsored by the American Association of Petroleum Geologists. Temperature data were extracted from company and State records and were placed on a computer-based file. Canadian data were added to the file by a Canadian coordinator, beginning in 1971. Using this data base, temperature gradients have been calculated and contoured maps of gradient have been produced wherever data are sufficient. The gradient maps for western Canada show many small anomalies that depend on only one well, and these anomalies are probably spurious. The gradients also show a tendency to increase with decreasing thickness of sedimentary column. This also is probably spurious and is probably due, at least in part, to the practice of taking the mean annual air temperature to represent the surface of the ground, whereas the true mean ground temperature is higher than the mean annual air temperature by as much as 5°C. In shallow sedimentary sections the variation in average thermal conductivity may play some part in creating anomalies, but large lateral variations are not probable in thick sections except where thick shale sequences in young delta areas predominate. Lateral water movement within permeable formations could cause irregular gradients, but one is forced to the conclusion that many of the anomalies are the result of inadequacies of the temperature data, the neglect of the thermal conductivity and the unsatisfactory method of assessing surface temperature.

Anglin and Beck (1965) reached the same conclusions on the quality of the data in a study that was completed before the Geothermal Survey of North America was begun. Data from about 70 wells were accepted as reliable and lines of equal gradient and geotherms at sea-level were produced, as shown in Fig. 1. The area covered was southern Alberta, and the results showed temperature gradients increasing to the east and north, in the direction of decreasing thickness of sedimentary formations.

THE SPROULE REPORT

The work done by Sproule Associates Ltd. was intended as a first look at the possibilities of using hot water from sedimentary basins in Canada, and it was based entirely on existing data. The original intention was to choose several areas of anomalously high temperature gradient for detailed examination. It was found that the areas of apparent high gradient usually coincided with areas of shallow drilling and consequently they had low bottom-hole temperatures. As a result of

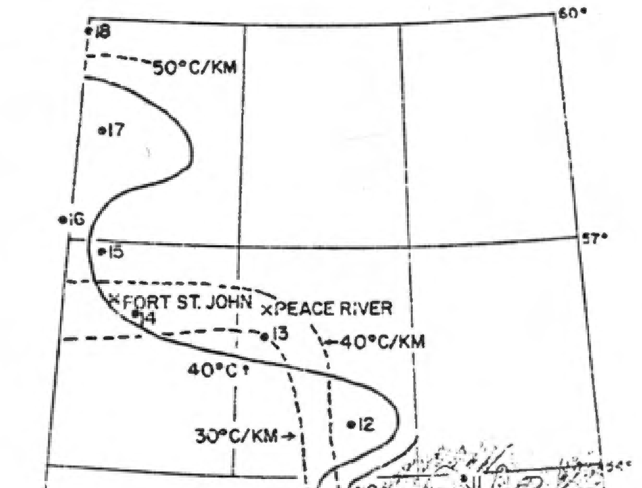

Fig. 1 Contours of isogeotherms and isogradients at sea level. Diagram by Anglin and Beck (1965).

this, the areas of detailed study were selected on the basis of high bottom-hole temperature rather than on the basis of high temperature gradient. The study consisted of the selection of a number of wells, usually five or six, from each area and a review of the data on porosity, salinity and temperature of the deep reservoir formations. Wells were chosen to produce profiles of 50 to 250 km (30 to 150 miles) in length, and information was displayed on large composite diagrams.

The areas studied are indicated in Fig. 2, with the maximum bottom-hole temperature indicated beside each profile. All temperatures quoted are based on the existing data and are subject to its general limitations, and they have been rounded downwards to the nearest 5°C (9°F). Since measured temperatures are usually below equilibrium rock temperatures because of cooling by circulation of drilling mud, these figures are probably minimum estimates of the temperature of the deepest reservoir formations. Other permeable formations are mentioned in the descriptions of the profiles, and temperature is roughly proportional to the depth. Fig. 2 also shows the boundaries of the region of sedimentary rocks, drawn to include the severely folded and faulted zone of the Rocky Mountains and Mackenzie Mountains. The sedimentary area is divided into areas where the majority of bottom-hole temperature readings are above 80°C (175°F) and below 80°C, regardless of depth. This dividing line runs through Alberta from north to south, the higher temperature being to the west of the line. There are insufficient data in the Northwest Territories to define the northward continuation. There is a further small area of southern Saskatchewan where temperatures over 80°C are found. This area is on the north flank of the Williston Basin, so that high temperature is related to great depth, but the area is in line with the high heat flow belt to the south associated with the Rio Grande Rift (e.g. Blackwell, 1971).

The highest temperatures recorded in the report are in the Pointed Mountain area, at the southern end of the Yukon-N.W.T. boundary. Bottom-hole temperatures are as high as 179°C (354°F) at a depth of 4419 m (14,498 ft.) and reservoir temperatures are about 170°C (338°F) at depths of 3400-4300 m (11,000-14,000 ft.). Unfortunately, the population density of the area is very low, the nearest settlement being Fort Liard. High temperatures are found in a continuous belt to the east of the Rocky Mountains, as far south as 50°N. There is a tendency towards lower temperature with lower latitude, but even in the Calgary area at about 51°N the temperatures are still about 120°C (248°F) at a depth of 3975 m (13040 ft.).

The Sproule report includes comments on the salinity of reservoir waters. In many of the areas covered by the profiles the total content of dissolved solids is high, and salinities in excess of 200,000 ppm are common. This may be compared with 35,000 ppm for average sea-water.

Table 1 summarizes the data from the fourteen sections and three single wells included in the report. The ranges of total depths and bottom-hole temperatures given apply only to the wells used in the survey. In most areas there are many more wells that are not included in the profile, and any formations mentioned usually extend for large distances (hundreds of kilometers) around the selected profiles. Although the profiles were selected on the basis of high bottom-hole temperature, the choice was still somewhat arbitrary and regional representation was intended. The particular profiles selected should not be taken as an indication of unfavourable interposed areas.

COMPARISONS

The Sproule report has already started along the path followed by French workers. The readily available temperature data have been examined, and the general areas most promising from the point of view of temperature have been indicated. Problems with the quality of the data have been commented on by both French and Canadian users. Brief comments on depth, thickness and permeability of the reservoirs and chemical composition of the water have been included, but no detailed account of these factors has been prepared.

French workers have made a detailed study of the whole central part of the Paris Basin, neglecting only the areas where sedimentary rocks are too thin to accommodate high temperatures. This amounts to an area roughly 300 km across in all direction. This distance is two to three times greater than the length of the profiles in the Sproule report.

From the point of view of markets, the Paris Basin is a thickly populated area, containing one of the world's major cities and many other cities and towns. In contrast, the Canadian plains are thinly populated, containing Edmonton (442,000), Calgary (433,000) and Regina (147,000) within the areas of reasonable probability of geothermal development. Other major municipalities are listed in Table 2. At Villeneuve-la-Garenne a complex of 4000 apartments is to be served by the

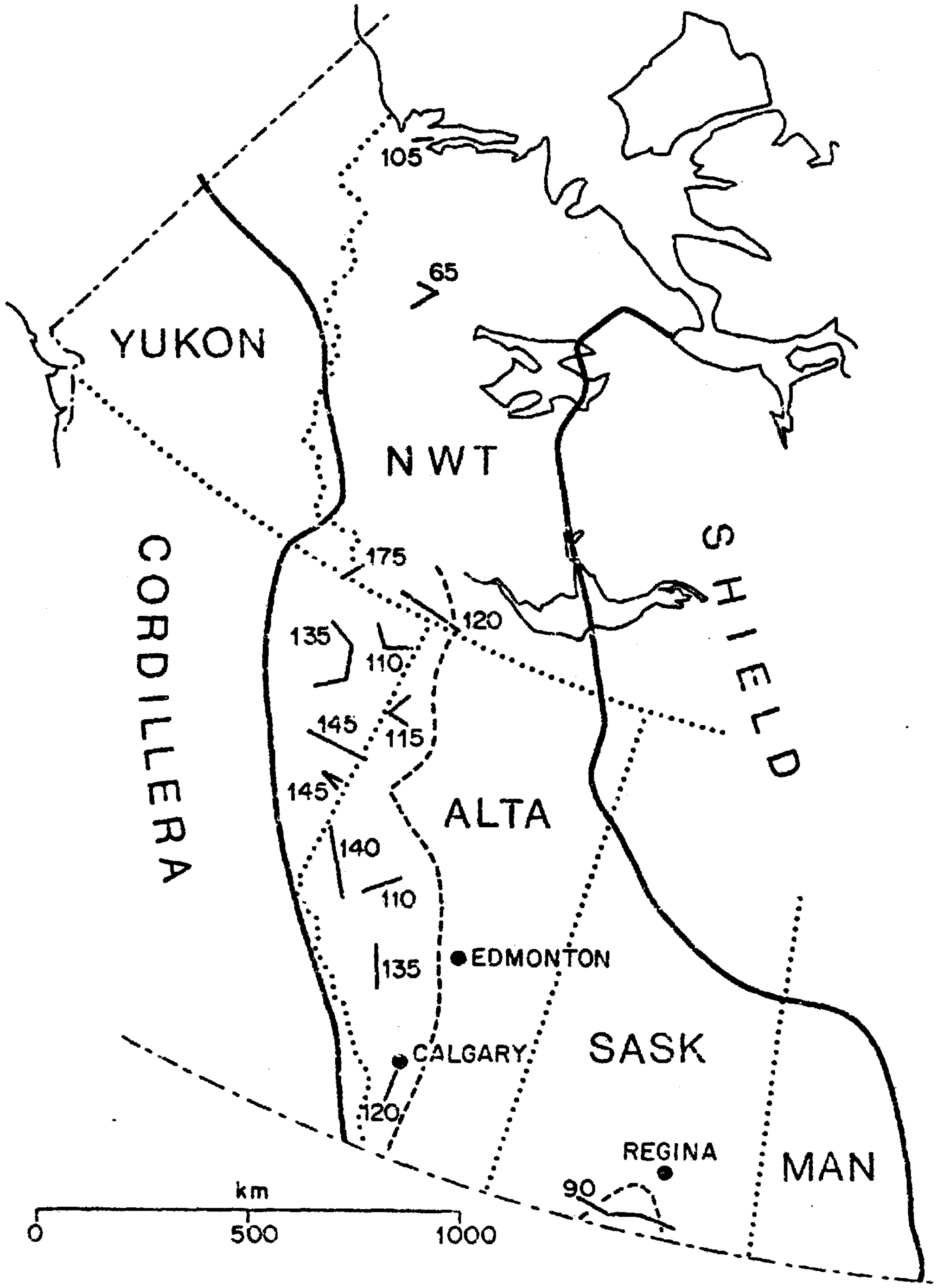

Fig. 2 Temperature in the lowest sedimentary formations based on data condensed from the Sproule report. The dashed line divides areas having bottom-hole temperatures above and below 80°C (176°F).

TABLE 1. Summary of Data in Sproule Report

Section	Wells	Total depth m & (ft)	B.H. Temp. °C & (°F)	Porosity	Dissolved Solids ppm	Towns or Cities
A	5	2644 - 3178 (8675 - 10426)	59 - 89 (139 - 198)	Several Fmtns.	15,000	Weyburn
B	6	2670 - 3975 (8760 - 13040)	79 - 122 (175 - 251)	Turner V	60,000	Calgary High River
C	7	4263 - 4843 (13986 - 15890)	113 - 138 (235 - 280)	Nisku Leduc	200,000	Harlech
D	6	4239 - 5480 (14070 - 17980)	121 - 142 (250 - 288)	Leduc Beaverhill	150,000	Grande Prairie
E	6	3108 - 4115 (10200 - 13500)	79 - 112 (174 - 234)	Cathedral Gilwood Stephen	200,000	
F	6	3545 - 4022 (11630 - 13196)	107 - 148 (224 - 299)			Fort St. John Dawson Creek
G	5	3184 - 3876 (10447 - 12715)	106 - 148 (222 - 298)			Fort St. John
H	9	2083 - 2932 (6835 - 9619)	92 - 116 (198 - 240)	Chinchaga Keg River Muskeg	18,000	
I	6	2450 - 3463 (8039 - 11361)	104 - 138 (220 - 280)	Cambrian Slave Point Elk Point		Fort Nelson
J	7	2035 - 2661 (6675 - 8730)	103 - 113 (218 - 235)	Keg River Slave Point Elk Point		
K	4	4369 - 4528 (14335 - 14856)	168 - 179 (335 - 354)	Nahanni	200,000	
L	7	1900 - 2484 (6234 - 8150)	69 - 122 (156 - 252)	Slave Point Keg River	150,000	
M	3	1724 - 1951 (5606 - 6400)	33 - 69 (92 - 156)	Ronning		Fort Good Hope
N	3	3205 - 3734 (10515 - 12250)	78 - 109 (172 - 228)	Devonian		
Tununuk	K-10	3757 (12326)	102 (215)			
Mayogiak	J-17	3681 (12077)	102 (216)			
Ellice	0-14	2898 (9507)	69 (157)			

TABLE 2. Municipalities in excess of 10,000 inhabitants within area of probable geothermal potential	
Alberta	
Edmonton	442
Calgary	433
Lethbridge	44
Red Deer	28
Medicine Hat	27
St. Albert	18
Grande Prairie	15
British Columbia	
Dawson Creek	12
Saskatchewan	
Regina	147
Moose Jaw	32
Swift Current	16

Figures are in units of 1000 persons and are taken from the 1971 Census.

geothermal development. An average occupancy of only two persons gives a total population of 8000, which is greater than most communities on the Canadian plains. On the other hand, because of the difference in climate, the energy that serves 4000 apartments in France will supply fewer units in Alberta, perhaps only 1000 or 1500. This situation will be helped by the fact that the temperature of the water is higher in Canada than in France, although this is counteracted to some extent by greater depth of the reservoirs.

ESTIMATES OF ENERGY

In order to obtain an estimate of the total energy contained in the formation waters of the western sedimentary basin it is necessary to make some simple assumptions. Hitchon and Friedman (1969) estimate the total pore volume as 63,600 cubic miles ($265 \times 10^{12} m^3$). Assuming a density of 1.0 Mg/m^3, this means that the rocks contain 265×10^{15} kg of water. Figure 3 shows the depths and temperature from Table 1, plotted to show geothermal gradient. Two linear geothermal gradients are drawn so that 50% of the points lie between them and 25% lie on each side. The gradients of these lines are 39.6 mK/m (21.7°F/kft) and 27.6 mK/m (15.1°F/kft). For ease of computation an average gradient of 33.3 mK/m (18.3°F/kft) is assumed. Water at less than 50°C (122°F) is of little value and is neglected. Using the assumed average geothermal gradient, 50°C corresponds to a depth of 1500 m (4920 ft). Only one point in Figure 3 is at a depth greater than 5000 m (16400 ft), and depths below this level are neglected. The temperature at 5000 m is 165°C (329°F), and two points exceed this limit. By adopting maxima of 5000 m and 165°C errors are introduced, but they are small and tend to produce an underestimate of the total energy. The upper and lower limits are shown in Fig. 3, and between these limits the points appear to be evenly distributed. Since these points represent the bottoms of wells, many of which are terminated near the base of the sedimentary sequence, it is assumed that they represent the true base of the sediments, and it is further assumed that this depth is uniformly distributed between outcrop at the surface and maximum depth at 5000 m. It is also assumed that pore volume is uniformly distributed. Since the uppermost 51% of the sediments are at a temperature of less than 50°C, only 49% of the volume is considered. The specific heat of the water is assumed to be 4.19×10^3 J/kg K.

It may now be calculated that the average temperature of the formation water below 1500 m is 89°C (192°F) and that the total heat content is 4.8×10^{22} J (4.6×10^{19} BTU) or 1.5×10^{15} Watt-years. This estimate is the total heat above 0°C in the formation water that is above 50°C. No account is taken of the heat in the solid rock.

The area of sedimentary outcrop is about 2×10^6 km^2 (7.7×10^5 square miles), but only 70% of the area contains sediments exceeding 1500m in depth. The stored energy per unit area is about 3.5×10^{16} J/km^2 or about 1000 MW years/km^2 (8×10^{13} BTU/square mile) for the western Canadian sedimentary basin.

The French literature (DGRST, 1976) describes a system having a rate of flow of 100 m^3/hour of hot water at temperature of 50°C. It is assumed that the water returned to the formation is at 10°C after passing through the heat pumps. This provides a heat extraction rate of 4.7 MW. Peak flow rates are somewhat higher, and supplementary conventional energy is used at times of peak load, so this figure can be taken as an average. The spacing between the producing and the return well is about 1 km, which means that the area being drawn upon is about 3 km^2 in extent. The expected lifetime of the wells is 30 years. The expectation of energy supply is thus about 47 MW years/km^2 in the areas that are now being exploited.

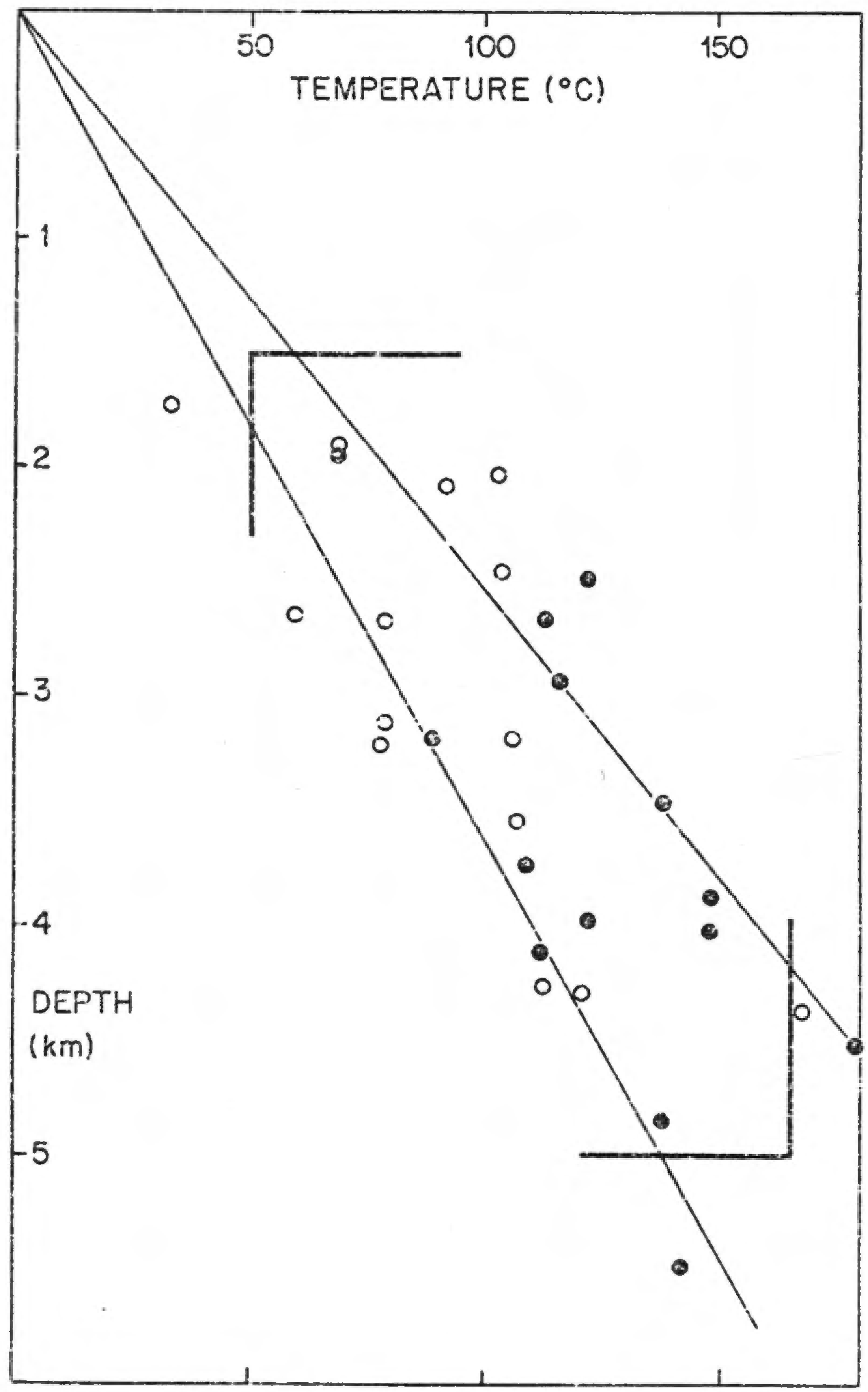

Fig. 3 Data from the Sproule report plotted as temperature against depth. Solid circles show the highest temperature in each section and open circles show the lowest. Bars show the assumed limits to useful water in the estimation of energy potential.

The difference between these two results is a result of the fact that the estimate of Canadian resources refers to total water-borne heat in all formations, whereas the estimate of French usage refers to the rate of production from one reservoir level only. If it is now assumed that one well can only draw on the water from 10% of the porosity in any one column the estimate of probable supply in Canada is 100 MW years/km^2, which is in good agreement with French experience. Because of the greater depth and temperature of aquifers in Canada, it is reasonable that the estimate of energy potential should be somewhat higher than that derived from French experience. In view of all the uncertainties in the assumptions related to Canadian conditions, 50 MW years/km^2 is a conservative figure for probable heat production, and favourable areas and deep reservoirs may yield considerably more.

No provision has been made for the energy required to produce the hot water. The static pressure in reservoirs is usually sufficient to support a water level that reaches a large fraction of the distance to the surface, and some formations produce artesian flow. However, some pumping is almost certainly required for water production. The potential energy required to lift the water is equivalent to 2.3 mK/m (1.3°F/kft), which is about 7% of the average geothermal gradient. Disposal of water in a reinjection well may also require pumping, but the maximum pumping for production is paired with the minimum pumping for reinjection, and a figure of about 10% represents the probable maximum energy cost.

OTHER SEDIMENTARY BASINS

The sedimentary basin of the western plains is not the only part of Canada where temperature and thickness of sediments may be sufficient for the existence of useful hot water.

The Cumberland Basin contains Carboniferous sediments of thickness up to 9 km, and much of northern Nova Scotia and eastern Prince Edward Island is underlain by at least 5 km of sediments. Published data (Jessop and Judge, 1971) show that the area has a low heat flow in accordance with the great age of the basin. Temperature gradients probably do not significantly exceed 20 mK/m (11°F/kft) and temperatures in excess of 100°C (212°F) at 5 km (16400 ft.) depth are probably not widespread. The Cumberland Basin thus offers prospects for geothermal heat considerably less attractive than those of the Paris Basin.

The Quebec Basin reaches depths of only about 2 km and heat flow is known to be low. Older folded sediments of the south shore of the St. Lawrence River between Quebec and Gaspé may be deeper, but unpublished data indicate temperature gradients of not more than 20 mK/m (11°F/kft). Prospects must be regarded as poor.

The deeper parts of the Michigan Basin may contain useful hot water, but the Canadian part of the basin contains large thicknesses of rocks of high thermal conductivity. The heat flow is moderately low and the high conductivity ensures low temperature gradients of not more than 20 mK/m (11°F/kft). Since the depth of sediments in Canada is not more than 3 km, prospects for hot water are poor.

In the Sverdrup Basin sediments extend to a depth of more than 6 km before metamorphosed sediments are reached. Unpublished data indicate high heat flow and temperature gradients that are generally greater than 30 mK/m (16°F/kft). Prospects for hot water are good, but sufficient markets are not available.

In the Mackenzie Delta temperature gradients are about 30 mK/m (16°F/kft), and high water pressures have been reported. Over-pressured formations would probably produce artesian hot water, but markets are again lacking.

CONCLUSIONS

From the general overview provided by the Sproule report, it appears that geological conditions for the production of hot water are at least as favourable in Canada as they are in France. Depending on the engineering requirements of producing water from deep aquifers, it may be possible to extract considerably more energy in Canada than is possible from an equivalent area in France. The low population density, the high requirement for space heating in the harsh Canadian winter, and the availability of other energy sources influence the economic situation, but this has not been thoroughly analyzed. Economic studies cannot be usefully pursued until more specific information is available concerning the possible rates of supply of energy and the lifetime of equipment and production.

The next step in Canada will be the detailed examination of the data of temperature, permeability and volumes of potential producing aquifers in selected areas of possible application. When the availability of supply is known with confidence the economic and engineering studies can begin.

Even if this source of energy does not turn out to be economically attractive now it is important to be aware of possible alternate sources of heat energy. Hot water from sedimentary basins may become a valuable means of maintaining the comfort of Canadians and of conserving supplies of high grade fossil fuels for those applications that need them.

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ANNEXE 15

Five Measurements of Heat Flow in Southern Canada[1]

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Five heat flow results from widely separated locations are reported. The results conform to existing heat flow patterns where established, but only very general interpretative comments are possible.

Nous présentons les résultats de cinq mesures de flux thermique. Ces résultats révèlent des flux comparables à ceux qui ont déjà été établis mais leur interprétation ne peut donner lieu qu'à des commentaires généraux.

Terrestrial heat flow has been measured at five widely separated sites in southern Canada. Each site contains a single borehole only, four of which are of approximately 600 m depth, and the other is of 400 m depth. At least three years were allowed for return to equilibrium temperatures in the boreholes. Methods of measurement have been described previously (Jessop 1968), and only variations from routine methods will be mentioned. It might justifiably be argued that all borehole sites have their own individual peculiarities, and that routine measurement of heat flow does not exist. For those interested in the peculiarities of each measurement and the detailed method of measurement and analysis, this information will appear elsewhere.

The locations of the sites are shown in Fig. 1, and the results are given in the top part of Table 1. More detailed data are shown in Table 2.

[1]Contribution of the Earth Physics Branch No. 347.

Oldham

The Oldham borehole was made available for heat flow measurement by the Nova Scotia Department of Mines. The rocks penetrated were quartzites and slates of the pre-Carboniferous Meguma shelf of Nova Scotia. The rocks gave very good conductivity results in the divided bar, the variations between individual discs from any single sample being very low. There was a marked difference between the conductivities of the slates and of the quartzites, and any sampling bias was corrected by means of a series model based on the core log of Townsend and Grimm 1964.

Temperature, conductivities, and heat flow are shown in Fig. 2. The heat flow is shown in

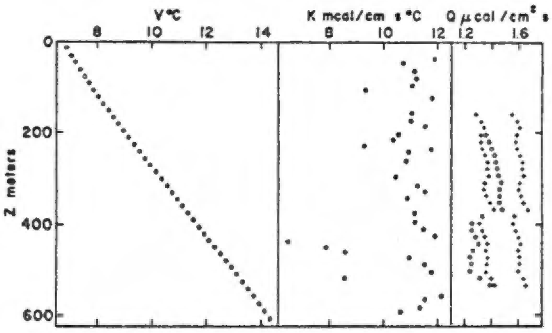

Fig. 2. Temperature, conductivity, and heat flow data from Oldham. Circles denote measured data and uncorrected heat flow, crosses denote heat flow corrected for sample bias and glaciation.

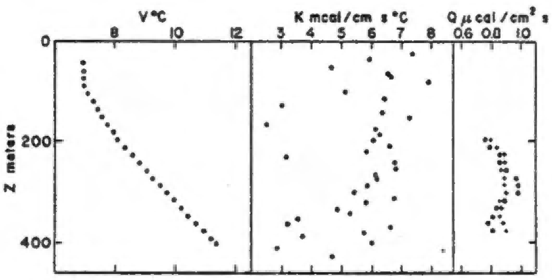

Fig. 3. Temperature, conductivity, and heat flow data from Kelly Cross. Circles denote measured data and uncorrected heat flow, crosses denote heat flow corrected for sample bias.

Temperature, conductivity, and heat flow are shown in Fig. 3. There is considerable scatter in the conductivity, owing to the mixture of rock type, and this is reflected in the heat flow results calculated by normal sectional analysis. A heat flow profile with less scatter has been obtained by separating the rock into sandy and shaley components in each section. The two fractions were credited with the average conductivity for the appropriate rock types, and the overall conductivity of the sections were calculated by means of a series model. In the depth range 244–401 m, both methods give an average heat flow of 0.88 μcal/cm^2 s and the second method gives a standard deviation of 2 %.

Above 200 m in depth heat flow is disturbed. This is believed to be due to ground-water movement and possibly to water temperature changes due to recent climatic changes. P. Carr (1969) cites evidence for ground-water movement to depths of about 150 m on Prince Edward Island. In particular, the region above 100 m depth has a uniform temperature, probably caused by rapid water movement around the hole. Owing to these disturbances, it is not clear what surface or temperature should be used in calculating a glacial correction, but a reasonable compromise yields a correction of 0.19 μcal/cm^2 s $\pm$ 20 %, giving a total heat flow of 1.07 μcal/cm^2 s $\pm$ 4 %.

Wright and Garland (1968) obtained a conductivity measurement of 9.75 mcal/cm s °C, by means of a down-hole heater method, at a depth of 115 m. The closest specimen measured on the divided bar gave a result of 6.43 mcal/cm s °C, and no specimen from the core showed a conductivity higher than 8.0 mcal/cm s °C. Wright and Garland's measurement was made in the zone of suspected water disturbance, and the result is consistent with a small water movement.

Ottawa

The Ottawa borehole was drilled at the Dominion Observatory site, and penetrated 14 m of overburden, 220 m of Ordovician sediments, about 100 m of Precambrian schists and weathered gneisses, and gneisses of the Precambrian Shield to a total depth of 602 m. Small temperature fluctuations in time in the upper 200 m indicated water movement in the sediments. Rocks between the depth of 240 m and 300 m were very fragile and porous, and reliable conductivity measurements were not easily obtained. Because of these difficulties, only results from below 300 m depth have been used in the calculation of heat flow. Results are shown in Fig. 4. The heat flow is 0.80 μcal/cm^2 s $\pm$ 4 %. The glacial correction

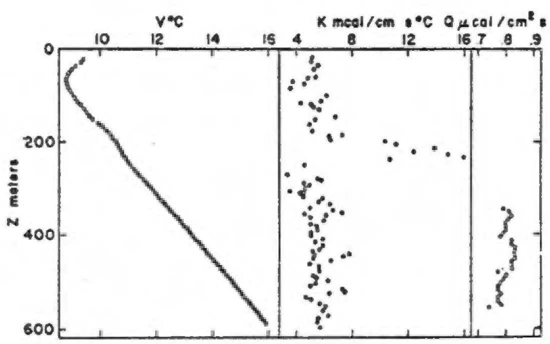

Fig. 4. Temperature, conductivity, and heat flow data from Ottawa.

is 0.21 μcal/cm² s ± 20 %, giving a total heat flow of 1.01 μcal/cm² s ± 5 %.

Winnipeg

The Winnipeg borehole was drilled on the campus of the University of Manitoba by the Dominion Observatory. The rocks penetrated were 18 m of overburden, 115 m of Red River limestone, 57 m of Winnipeg sand, and 420 m of Precambrian gneisses. It was clear from the temperature profile and from the nature of the rocks penetrated that only the part of the hole in Precambrian rock would yield reliable temperature and measurable conductivity, and all heat flow calculations have been restricted to this part, which lies below a depth of 190 m.

Results are shown in Fig. 5. The average heat flow is 0.70 μcal/cm² s ± 5 %. The heat flow is not randomly scattered, but shows a smooth variation from 0.74 μcal/cm² s at 260 m to 0.64 μcal/cm² s at 540 m. The reason for this variation is not known with certainty, but is believed to be connected with water movement in the loose sand of the Winnipeg formation. Variations of water temperature in the sand, due to climatic change at the surface or due to changes in flow direction, could have caused a non-equilibrium heat flow condition. No adjustments can be made to the result, since any assumptions of water movement changes are only speculations. A heat flow value of 0.70 μcal/cm² s has been adopted and instead of using the standard deviation of 5 %, an error limit has been arbitrarily set at 10 %. A glacial correction for an uncomplicated hole in this location, which was submerged beneath Lake Agassiz for a time, is 0.21 μcal/cm² s ± 20 %, giving a total heat flow of 0.91 μcal/cm² s ± 10 %.

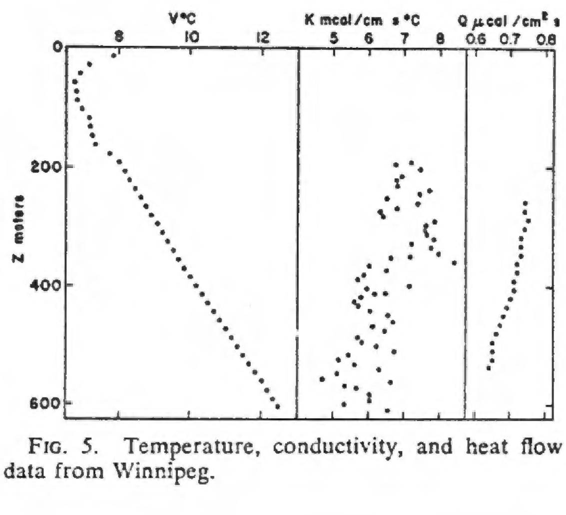

FIG. 5. Temperature, conductivity, and heat flow data from Winnipeg.

Penticton

The Penticton borehole is on the site of the Dominion Radio Astrophysical Observatory. The site is in a valley, with topographic relief of about 800 m within 4 km, and measured temperatures have been corrected for the effects of proximity to elevated land by the method of Jeffreys (1937), giving a reduction in gradient of 7.5 %. The rocks penetrated were tuffs, graywackes, and shales of the White Lake formation to 597 m, and lava of the Marron formation in the lower 14 m.

Owing to the large number of thin rock units in the core, a large number of conductivity measurements were necessary. Every third sample was measured as a set of four discs, and the remainder were measured as single discs, all discs being soaked in water.

Results are shown in Fig. 6, and temperature and heat flow are shown both uncorrected and corrected for topography. There is a great deal of scatter in the heat flow results, particularly around 270 m, where the nature of the peak suggests a small groundwater effect. Below 300 m the heat flow seems to follow the conductivity sampling despite the large number of specimens measured. The average heat flow when corrected for topographic effects is 1.60 μcal/cm² s ± 8 %. A correction for Pleistocene glaciation adds a further 0.26 μcal/cm² s ± 20 % to give a heat flow of 1.86 μcal/cm² s ± 8 %.

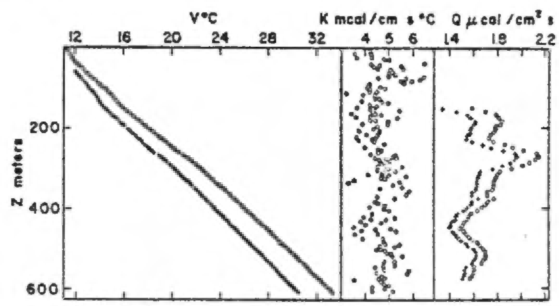

FIG. 6. Temperature, conductivity, and heat flow data from Penticton. Circles denote measured data and uncorrected heat flow, crosses denote temperature and heat flow corrected for topographic distortion.

Discussion of Results

It has been suggested that low values of heat flow may be caused by the measurement of conductivity of low-porosity rocks in an unsaturated state (Walsh and Decker 1966). In the current work, all rocks with significant porosity were measured in a saturated state, but the others were not saturated. Porosity of a random selection from the gneisses of Ottawa and Winnipeg was measured and the greatest porosity found was 0.25 %. The effect on the average conductivity is not likely to exceed 3 % at Winnipeg and 1½ % at Ottawa, and no correction has been made for these small effects.

Since the five measurement sites are so widely separated, it is impossible to draw detailed conclusions from the results, but two of the sites are close to results published previously (Jessop 1968). In the previous work, the glacial corrections were based on a slightly different model, and for the purpose of comparison these corrections have been recalculated to conform with the model used in the present calculations. The recalculated results are shown in the lower part of Table 1. Unfortunately, no data are available concerning heat production by radioactive decay.

The Oldham site is only 33 km north of Halifax, but the heat flow is higher at Oldham by 14 %, which is within the range of significance. The geological environments are similar, but the Oldham site is further inland, so that a thickening, and consequently higher heat production of the crust is a possible explanation. The Kelly Cross site is a further 150 km north of Oldham and is in a sedimentary basin of younger rocks. The heat flow at Kelly Cross is only two-thirds of the flow at Oldham, a difference that cannot be explained on the basis of crustal thickness, since the crust is probably slightly thicker under Prince Edward Island than it is under the Atlantic Coast of Nova Scotia. (Dainty *et al.* 1966.)

The Ottawa site is 50 km northeast of Franktown, where the heat flow is 21 % higher, but owing to uncertainties in the Franktown measurement, the significant difference is much less. The holes are in similar environments, both being in Precambrian rock with a thin cover of Paleozoic sediments, and the lower than average heat flows are normal for the Grenville Province of the Shield. The Winnipeg site is in a similar situation near the exposed edge of the Superior Province of the shield. The heat flow is slightly lower than at Ottawa and Franktown.

The Penticton site is in the interior plateau of British Columbia. There are no other completed Canadian measurements with which to compare it, but there are measurements in the northern U.S.A., where there is a similar value 150 km to the south–southeast, a low value 240 km to the southwest, and several higher values to the southeast (Roy *et al.* 1968, Blackwell 1969). These other measurements have not been corrected for glacial disturbance, and so comparisons are with the uncorrected Penticton figure. Penticton lies within the western side of the northward continuation of Blackwell's (1969) "Cordilleran thermal anomaly zone", and the result is consistent with that concept.

Acknowledgments

We acknowledge the kind cooperation of the Nova Scotia Department of Mines and the Geological Survey of Canada in making boreholes available for our use, and of the University of Manitoba for allowing the drilling of the Winnipeg borehole on the University campus.

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16

ANNEXE 16

Man-Made Geothermal Reservoirs

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ABSTRACT

Many drilled holes encounter rock at usefully high temperatures but produce little or no natural steam or hot water. The energy content of these "dry" geothermal reservoirs is enormous; and if means can be found to extract and use it economically, it can contribute significantly to satisfying the world's energy needs.

One way to accomplish this is to inject water into the hot rock through one hole, permit it to circulate through natural or man-made flow passages, and recover it as steam or hot water through another hole. The major problems are those of avoiding excessive water loss if natural permeability is high or, if it is low, of creating openings for fluid circulation and enough surface to permit extraction of heat at a useful rate for a usefully long time.

The possibilities, problems, and engineering requirements of such man-made geothermal systems are now being investigated in the hot granites underlying the Jemez Plateau of northern New Mexico. These contain many natural fractures which, however, are well sealed at most horizons, so that *in situ* permeabilities are generally low. Hydraulic fracturing—a promising method of creating flow channels and new surface—has been accomplished at pumping pressures of less than 175 bars at 760 m (rock temperature 100°C), at 2040 m (rock temperature 146°C), and at 2920 m (rock temperature 197°C). The fractures produced have been essentially vertical and the rate of water loss from them has been low.

Additional experiments are now in progress at 2920 m and drilling has begun on the first of two holes expected to reach depths of about 3810 m and rock temperatures of about 250°C. These will be connected at depth through a large hydraulic fracture to produce a circulation loop for geothermal energy extraction.

INTRODUCTION

It has been demonstrated in many places in the world that geothermal temperatures as low as 80°C are economically useful for space heating and many other purposes, and in a much smaller number of places that 180°C is a sufficient temperature for economical generation of electricity. If the mean temperature at the earth's surface is 10°C and a "normal" geothermal gradient of 25°C/km exists, a "useful" temperature of 80°C should normally be encountered at a depth of about 2.8 km, and the relatively high geothermal temperature of 180°C at about 6.8 km. These are depths that are now reached more or less routinely in the petroleum and natural gas industries using conventional drilling equipment and procedures. Evidently, geothermal heat at usefully high temperatures is now accessible to man from most points on the earth's surface, and the energy supply which it represents is enormous. The problems of extracting and using it are simply those of engineering and economics.

Where a natural hydrothermal system can be found which contains steam or hot water at a usefully high temperature, the engineering problem of extracting energy from the earth is relatively simple. Wells are drilled into the reservoir and heat is brought to the surface in the natural or pumped flow of steam or hot water. Unfortunately the combination of high rock temperature, adequate permeability, low reservoir pressure, and a sufficient water supply, all of which are required to maintain a "vapor-dominated" geothermal system, is rare in nature; and productive natural steam fields are correspondingly uncommon. "Liquid-dominated" systems, in which the fluid pressure in the reservoir is sufficient to prevent boiling, are much more common, although the frequency of their occurrence diminishes with increasing temperature. In general, the higher the temperature of a geothermal water, the more mineral it will have dissolved during its residence in the geothermal reservoir. Particularly if the reservoir rock contains highly soluble minerals (as, for example, do the evaporites of California's Imperial Valley), the hotter geothermal waters are usually so saline that they are extremely corrosive to drilling tools, production piping, and surface plumbing. They are also generally troublesome with regard to plugging and scaling by minerals deposited as their temperatures and pressures are reduced, whether in the reservoir, in the production string, or at the surface. Commercial utilization of heat from liquid-dominated reservoirs has been handicapped in many places by the geochemical problems associated with both the production and the use of the highly mineralized waters which they normally contain.

Many "dry" holes—not productive of useful amounts of any reservoir fluid—have been drilled in exploring for petroleum, natural gas, and geothermal energy, and for other purposes. Often these have penetrated rock at commercially useful temperatures. Obviously, and as would be expected, geothermal heat is present and accessible even when geothermal fluids are almost or entirely absent. If means can be found to extract and use such heat economically, it is sufficiently abundant and broadly distributed so that it can contribute significantly to the world's energy supply. Further, since it already exists as heat, it should in general be possible to produce and use it in environmentally acceptable ways.

EXTRACTION FROM DRY RESERVOIRS

A variety of methods can be suggested for penetrating "dry" geothermal reservoirs and recovering heat from them. Certainly the simplest and probably the most economical of these is to imitate nature by introducing water into the hot rock where nature has failed to provide it, permitting it to circulate until it has been heated to a usefully high temperature, and then recovering it as either steam or hot water. Where the permeability of the hot rock is high, the problems of circulating and heating the water are minimal but those of containing and recovering it are difficult. Efficient heat-extraction systems are probably possible using water-flooding and reservoir-management techniques similar to those developed for secondary recovery of petroleum. Unless the geologic structure is very unusual, however, this requires drilling an array of holes in which injection wells are surrounded by recovery wells and vice versa, and developing effective hydraulic control at the perimeter of the field to minimize fluid loss to the permeable formations around it. Very large man-made systems of this type should be possible, producing very large amounts of energy by sweeping the natural heat efficiently from large masses of permeable rock. Small water-flooding systems, however, are likely to be inefficient with regard to recovery both of the water injected into the reservoir and of the heat which it extracts from the rock. They are likely to be used only where water is plentiful and the accessible geothermal reservoir is so large that efficiency in the recovery of heat is unimportant.

Where permeability of the dry hot rock is low, the problems of containing and recovering the injected water are replaced by those of creating flow passages through which it can circulate freely and sufficient heat-transfer surface so that usefully large rates of heat extraction can be maintained for economically long periods of time.

LASL GEOTHERMAL ENERGY PROJECT

Under sponsorship of the Division of Geothermal Research of the U.S. Energy Research and Development Administration (ERDA), the Los Alamos Scientific Laboratory (LASL) of the University of California is investigating the possibilities and problems of extracting energy from "dry" hot rock in the earth's crust. To minimize both the fluid-containment and recovery problems and also those associated with dissolution and reprecipitation of minerals, LASL is investigating first the development of man-made geothermal systems in the hot, relatively impermeable granitic rocks which, at moderate depth, underlie the southern Rocky Mountains in northern New Mexico. It is hoped that the technology developed there will be useful wherever low-permeability rock at usefully high temperatures can be reached economically from the earth's surface. And it is intended that, when systems that are economically useful in this environment have been developed and demonstrated, modifications of them will be investigated that may be useful in other geologic situations elsewhere—at higher and lower temperatures, greater and shallower depths, in other types of rock, where permeabilities are greater, and in more complex geologic settings.

To create a fluid circulation system for successful energy extraction from hot rock having initially low permeability, it is necessary to produce continuous flow passages between the injection and recovery holes with reasonably low impedance to fluid flow and large surface area for heat transfer from the rock to the fluid. There are several obvious ways in which this might be accomplished, including chemical leaching, fragmentation by explosives, and hydraulic fracturing, and probably all of these should eventually be tried. It has been decided, however, that the first major LASL experiments should be with hydraulic fracturing, on the basis of its apparent environmental acceptability, probable economy, and familiarity as a common method of well stimulation in petroleum and natural gas fields. Because there was little experience in the hydraulic fracturing of crystalline rocks and apparently none at all in hot granitic rocks, many advisers to the LASL project expressed grave doubts that this was a feasible approach to creating the proposed energy extraction system. Accordingly, much of the project emphasis has so far been on investigations of the production and behavior of hydraulic fractures in hot granitic rocks.

To avoid the problems associated with two-phase fluid flow and with mineral precipitation where boiling occurs, and to maximize the rate of energy transport up the recovery well, it is desirable to operate the proposed circulation system with a condensed phase throughout—that is, with liquid water instead of steam or a mixture of the two. This requires pressurization throughout the system sufficient to prevent boiling. Computer modeling of fluid flow and heat transfer within the hydraulic fracture (McFarland, 1975) has demonstrated the desirability of holding the fracture open with fluid pressure alone—without the use of particulate proppants—if this can be done without excessive fluid loss or uncontrolled extension of the fracture. Again many advisers to the LASL project have been convinced that this will prove impractical because of high rates of fluid loss into natural joints and fractures in the rock or because of inherent instability of a large inflated crack. Accordingly, much project attention has also been given to initial permeability of the hot granite at depth, to its stress and pore-pressure environment, and to its behavior with regard to inflation, deflation, extension, and return of the contained fluid when it is permitted to collapse.

To this point, no attempt has been made to produce the pressurized-water circulation loop with which continuous energy extraction will eventually be accomplished. Project activity has been directed entirely toward acquiring the background information required to understand and design such a system and toward developing the technology required to create it.

Site Selection

The Valles Caldera in north-central New Mexico formed several million years ago on the western edge of the Rio Grande rift. Caldera collapse was followed by deposition of sediments, resurgence, extrusion of a series of rhyolite domes along the ring fault bounding the caldera, and most recently—about 50 000 to 100 000 years ago—by a pumice and a vitrophyre flow at the southwestern edge of the caldera

(Purtymun, 1974). Because of this geologically recent volcanism, the generally high terrestrial heat flow along the western edge of the rift valley is enhanced locally, and relatively high geothermal temperatures are encountered at moderate depths.

As might be expected from its history of collapse, caving, sedimentation, resurgence, periodic volcanism, and repeated faulting, the geologic structure within the caldera is exceedingly complex and, at least locally, is highly permeable to ground-water circulation. The commercial possibilities of a liquid-dominated geothermal reservoir discovered in the southwestern part of the caldera are now being investigated by a major energy company.

Outside the caldera the geology is much less disturbed than within it, the depth to the basement granite is moderate, and heat flow is still relatively high. In 1971 seven shallow temperature-measurement holes were drilled by LASL in the National Forest east, south, and west of the caldera rim (Fig. 1). Geothermal gradients in the surface volcanics were found to increase along the counterclockwise path from east to west around the outer caldera rim. Accordingly, in 1972, four deeper heat-flow holes were drilled west of the caldera to depths of 150 to 230 m. These penetrated the Cenozoic volcanics and entered the Permian sediments. Measured heat flows about 3 km west of the ring-fault structure were 5 to 6 hfu (μcal/cm^2-sec), increasing slightly from south to north, and decreasing rapidly with increasing radial distance to 2.2 hfu at a point 7 km west of the ring fault (Albright, 1974). Two deep exploratory holes have since been drilled in the area: GT-1, completed in 1972 at a depth of 785 m, and GT-2, completed in 1974 at a depth of 2928 m.

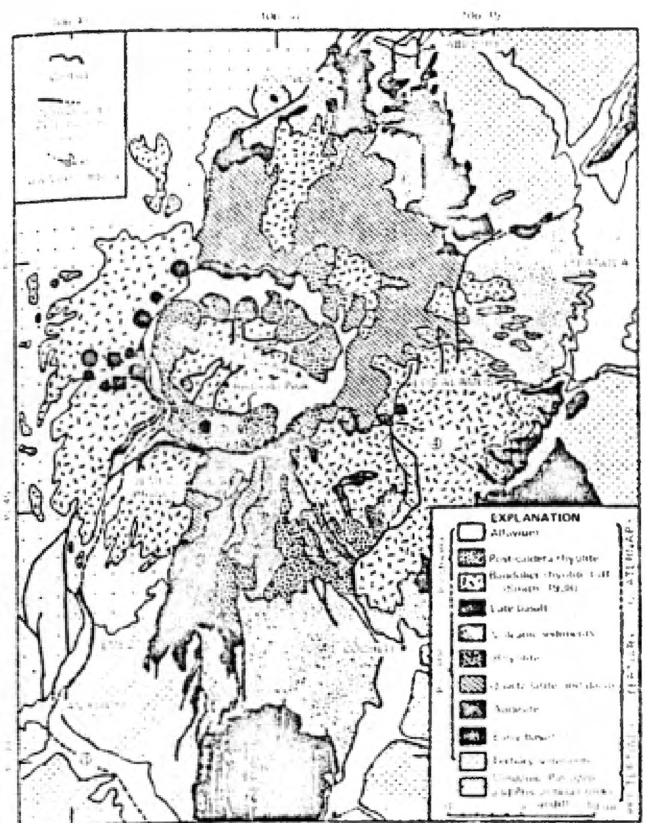

Figure 1. Generalized geologic map of the Jemez Mountains region showing locations of shallow temperature-measurement holes (small circles), intermediate-depth heat-flow holes (large circles), and deep exploratory holes (squares) (Smith, 1974).

In 1973, a detailed study was completed of the existing faults and the earthquake history of the area of experimental interest west of the caldera (Slemmons, 1975). No large or active faults were found within several kilometers of the locations of GT-1 and GT-2, and there was no record of any earthquake centered in the area. It was concluded that the risk was very small that significant seismic activity could be triggered by hydraulic-fracturing and fluid-injection experiments there, or by the subsequent development of an experimental energy extraction system.

Because of its accessibility and inherent geologic interest, the region of the Valles Caldera has been studied intensively for many years by the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Resources, the University of New Mexico, New Mexico Institute of Mining and Technology, and many other organizations and individuals. As a result, a great deal of geological, geophysical, and hydrologic information is available concerning the area, most recently from hydrologic studies by the U.S. Geological Survey (Trainer, 1974), from deep electrical resistivity studies by the University of New Mexico and LASL (Jiracek and Kintzinger, 1975), and from seismic and microseismic investigations and monitoring by LASL (Kintzinger, 1974; Newton, 1974). The general geology, hydrology, and fault structure of the region west of the caldera is now reasonably well understood. Unexplained magnetic and resistivity highs and lows have been mapped. Depth to the Precambrian surface has been estimated, and it has been established that at some distance below this surface the resistivity of the Precambrian granitic rocks becomes high. In fact, however, no convincing criterion other than actually drilling deep exploratory holes has yet been established for predicting whether or not dry hot rock will be encountered in a particular area at a drillable depth. Locations of the two deep exploratory holes so far drilled for this project were selected on the bases of (1) the general geology and volcanic history of the region; (2) the absence of nearby faults or earthquake activity; (3) geothermal gradients measured in shallow holes; (4) heat flows measured in somewhat deeper ones; (5) availability of the land for experimental use; (6) environmental considerations; (7) accessibility with regard to transportation, communications, and electrical power; and (8), in the case of the second exploratory hole, the very encouraging results of experiments conducted in the first one.

Stratigraphy and Core Studies

Exploratory hole GT-1 was drilled in Barley Canyon about 3 km west of the ring fault representing the western geologic boundary of the Valles Caldera. It penetrated 49 m of surface tuffs, 277 m of Permian sediments, 315 m of Pennsylvanian limestones and shales, and reached the Precambrian surface at 641 m depth. It was then extended 143 m into the crystalline Precambrian basement rock, encountering chiefly gneissic granodiorites, granites, and amphibolites (Purtymun, 1974). It was lined with 12.7-cm-diam casing to a depth of 732 m, leaving 53 m of uncased granitic rock exposed at the bottom of the hole for experiments.

Exploratory hole GT-2 was drilled on Fenton Hill, a flat-topped mesa, about 2.5 km south of GT-1 and also about 3 km west of the ring fault bounding the caldera.

It penetrated 137 m of volcanics, 238 m of Permian "red beds," 355 m of Pennsylvanian rocks, and reached the Precambrian surface at 733 m depth. It has since been extended in stages to a final depth of 2928 m, through gneissic granodiorites, granites, amphibolites, monzonites, quartz monzonites, gneisses and schists (Purtymun, 1974). The final 1000 m or so of the hole were drilled through a relatively uniform, substantially equiaxed, gray quartz monzonite containing well-developed biotite flakes. The hole was cased at 0.27 m diam to a depth of 773 m, about 43 m into the granitic basement rock, and was left uncased below that depth. However, a 0.178-m-diam steel liner was temporarily installed in the depth interval 1917 to 1981 m to facilitate experiments at and just below those depths. It has since been removed and a similar liner cemented in place in the interval 2731 to 2917 m for the same general purpose.

Cores were taken at intervals throughout the Precambrian sections of both exploratory holes and are being used for petrographic studies, geochemical investigations, property measurements, geochronology and geothermometry. In general the cores have shown several families of natural fractures which, however, at most horizons, have been tightly filled with calcite, quartz, muscovite, epidote, and occasional clays (Laughlin, 1974). In one interval in GT-2, around 1100 m depth, a region of unsealed, water-filled fractures was encountered. Elsewhere the natural fractures have been well sealed, and there appears to be a tendency for them to become less frequent and more tightly closed as the Precambrian column is descended.

Permeabilities

Permeabilities of the exposed crystalline basement rock in the uncased bottom section of GT-1 were measured at several levels of pressure from 13 to 177 bars above surface hydrostatic. With increasing pressure they ranged from 5×10^{-8} to 6×10^{-3} darcy, increasing by a factor of 10 for each pressure increase of about 40 bars (West, 1974). However, this pressure dependence of permeability has not been observed in GT-2.

In GT-2, permeabilities measured in the Precambrian section by drill-stem testing have ranged from 4×10^{-7} to 10^{-5} darcy (West, 1974). Permeabilities of freshly exposed fracture surfaces in the uncased region around 2820 m depth appear to be near the lower limit of this range. No satisfactory measurements have so far been made in the region of unsealed fractures around 1100 m, where a somewhat higher permeability is expected. It is of interest, however, that since the hole was completed, the mean permeability of the uncased Precambrian section between the bottom of the casing and the top of the liner—which includes this region of unsealed fractures—has diminished steadily to a present value of less than 10^{-7} darcy. This is apparently a result of plugging of the initial porosity either by mineral alteration or by fine particles of drill cuttings or alteration products suspended in the water filling the hole.

Except perhaps in the zone around 1100 m, the permeabilities measured in the granitic rocks in both exploratory holes have consistently been in the range generally considered to represent "dry" or "impermeable" rock. At least at depths below about 1200 m, the crystalline rocks underlying the experimental area appear competent to contain pressurized water with acceptably low leakoff rates. As is described below, this is true even of fresh fracture surfaces which expose relatively large granitic sections extending outward from the borehole.

Temperature Gradients and Heat Flow

The bottom-hole temperature in GT-1 is 100.4°C at a depth of 785 m. With considerable uncertainty because of the relatively short section of uncased granite exposed, the geothermal gradient in the crystalline basement rock is estimated to be about 50°C/km.

Special apparatus and techniques were developed for measurement of bottom-hole temperature in GT-2 during interruptions in drilling, over periods of time long enough to permit confident extrapolation to an equilibrium rock temperature (Albright, 1975). Temperatures so determined are plotted as a function of depth in Figure 2. Temperatures in the water-filled hole appear, since drilling has been terminated, to be slowly approaching the values indicated by this curve.

From temperature measurements in intermediate-depth holes and thermal-conductivity measurements on cores from those holes, it was estimated that terrestrial heat flow at the Fenton Hill site was 5 to 6 hfu. This was verified in the sedimentary section penetrated by GT-2 and—with an assumed value for the thermal conductivity of granite—was used to predict that a rock temperature of 200°C would be reached at a depth of about 1.5 km. In fact, however, heat flow in the Precambrian section of GT-2 is only about 3 to 4 hfu, and it was necessary to drill to a depth of about 3 km in order to reach a temperature approaching 200°C. It appears that there is a horizontal flow of warm water near the Precambrian surface, perhaps through the cavernous Pennsylvanian limestone encountered just above it, and that this has augmented heat flow through the overlying sediments and volcanics. In any case, the geothermal gradient in the upper part of the Precambrian section is only about 50°C/km. This increases to about 60°C/km at greater depth, presumably because of changes in rock type and a reduction in the thermal conductivity of granite that results from an increase in its temperature.

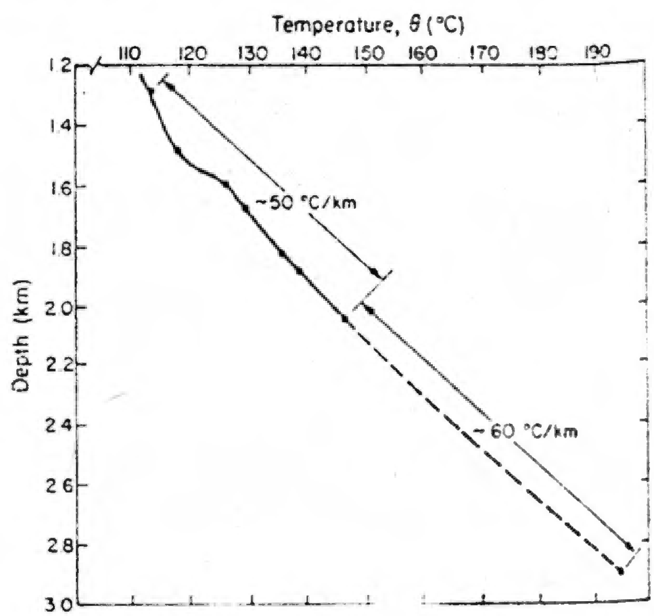

Figure 2. Geothermal temperatures and temperature gradients in GT-2 (Albright, 1975).

Logging

Standard geophysical logs have been run repeatedly in both GT-1 and GT-2. Of these, the caliper logs have been particularly useful in selecting relatively smooth sections of hole in which open-hole packers could be set successfully for hydrologic studies; the spectral-gamma log in mapping changes in lithology; and the sonic-velocity logs in locating zones containing unsealed fractures. Except perhaps in the more mafic rocks, density logs have been found to correlate well with densities measured in the laboratory on core samples, and elastic properties deduced from sonic-velocity logs have agreed well with laboratory measurements made on core samples.

Much of the commercial logging equipment has given trouble as downhole temperatures approached 150°C, and most of it has been unreliable at temperatures approaching 200°C.

Fracturing and Earth Stress

Hydraulic fractures were produced in the uncased bottom section of GT-1 at pumping pressures (measured at the surface) of about 100 to about 150 bars. Only a few sharp "breakdowns" were observed, suggesting that the initial fracturing event at the borehole wall was usually the reopening of a natural fracture sealed with a relatively weak mineral such as calcite. Fracturing pressure increased with the apparent competency of the rock as indicated by cores and downhole logs, and also with the pumping rate used to fracture. As would be expected, the pressure required to extend a crack was found to decrease steadily as the crack radius increased. Even after extensive fracturing, permeability of the uncased Precambrian section exposed in GT-1 remained very low.

When GT-2 had been drilled to a depth of 1937 m, drilling was interrupted for a series of successful hydrologic measurements and largely unsuccessful hydraulic-fracturing attempts. The hole was sufficiently oversize and its wall sufficiently rough so that commercial open-hole rubber packers did not seal successfully against the fluid pressures required for fracturing. Therefore the hole was deepened, eventually to 2042 m, to expose "fresh" rock, and a steel liner 64 m long was cemented in place about 60 m above the bottom of the hole. Commercial casing packers were set successfully within this liner, and a long series of experiments was completed in the uncased hole below it. The liner was then perforated about 40 m above its lower end, and additional experiments were conducted through the perforations.

When the uncased section of hole below the liner was first pressurized, it began to accept fluid at a pumping (surface) pressure of about 150 bars. With continued injection of water at a constant rate of 454 liters/min, the pumping pressure increased to a maximum of 172 bars and, with no indication of a formation breakdown, leveled off at that value. This behavior suggests that a pre-existing natural fracture began to open at a downhole pressure of approximately 340 bars. Subsequent pressurizations at a variety of flow rates and repeated observations of the decay of shut-in pressure have confirmed that the least principal earth stress at this depth is in the range 330 to 340 bars.

Spinner surveys, used to measure fluid velocity as a function of position in the hole during subsequent repumping operations, indicated the existence of two closely spaced parallel fractures in the borehole wall, one in the depth interval 1989 to 1993 m and the other in the interval 1998 to 2002 m. As shown by later impression-packer results, both fractures were vertical within 1 degree and were oriented N 35° E ±5°. They were offset horizontally by about 67 cm because in this section the borehole is inclined 4.5 degrees from the vertical; and, from their behavior during pressurization and depressurization experiments, it is speculated that they join in a single fracture not far from the borehole wall.

Twenty pumping experiments were performed on this fracture system with progressively increasing quantities of injected water, and the volumes of fluid returned were measured as the crack was permitted to deflate. The largest volume of water injected was 136 000 liters. When the system was vented, return of fluid from the unpropped fracture was relatively slow and the fraction of the injected fluid returned depended on the shut-in time before venting, but was as high as 84%. After the fracture was propped with 4300 kg of sand, fluid return was much more rapid and returns as high as 92% were observed.

Permeability measurements in the fracture were somewhat uncertain because of uncertainties concerning its actual area. If k is permeability and A is the total area of both surfaces of the fracture, a value of $\sqrt{k}A$ = 19 cm^3 was deduced from the rate of pressure rise when fluid was injected at a constant rate of 132 liters/min. Using an area calculated from the assumption that the sand proppant formed a monolayer, the calculated permeability is 6 microdarcys (μd). However, the fluid-return behavior of the system during fracture deflation indicated that the fracture was to some degree self-propping. This suggests relatively rough fracture surfaces, an actual area larger than that assumed above, and a true permeability significantly less than 6 μd.

The cemented-in liner above this uncased region was perforated with 80 1-cm-diam holes in the region from 1941 to 1945 m. A commercial bridge packer was set to straddle the perforated zone, with a clock-driven pressure gauge suspended below the lower packer to record pressure continuously in the uncased region below the liner. When the perforated zone between the packers was pressurized at a flow rate of 477 liters/min, a hydraulic fracture was initiated at a pumping (surface) pressure of 275 bars. With some shut-ins and flow reductions, the fracture was extended by injecting a total of 11 000 liters of water in a period of 42 min. A leak rate of 4 liters/min was observed past the upper packer into the annulus around the pressurizing line. Subsequent examination of the pressure record from the bottom of the hole indicated that there was no significant leakage past the lower packer.

When this fracture was initiated through the perforated liner, a small pressure rise—corresponding to injection of about 1 liter of additional fluid—occurred in the uncased section of hole below the lower liner. Since the fracture produced in the uncased section was vertical and had a calculated radius of 200 m, it should have extended to some level above that of the perforations through which the second fracture was produced. If the second fracture was also vertical it should, because of the inclination of the borehole, have been separated from the first fracture by a horizontal distance of 3.8 m. The observed communication between the two fractures could be explained if they were separated by a slab of rock having a permeability of about 50 μd and a uniform thickness of 3.8 m. Evidently the fractures did not intersect and were not directly connected through any open natural fractures.

The cemented-in liner in this part of the hole was removed, the hole deepened to 2928 m, and a similar liner cemented in place in the interval 2731 to 2917 m. Approximately 30 individual pumping experiments have now been completed in the 11-m-deep section of uncased hole below this liner. A single hydraulic fracture was produced there at a pumping (surface) pressure of about 120 bars. It has since been extended in stages to an apparent volume of 5700 liters and a calculated radius of 57 m. Total permeation loss during growth of this fracture is estimated to have been 3800 liters. The permeability of the freshly fractured rock is estimated to be about 0.3 μd, which is consistent with a value of 0.15 μd given by Brace (1968) for Westerly granite at similar stress levels. No measurement of the initial pore pressure was made at this depth. However, an increase of 62 bars in poor pressure adjacent to the fracture increased the fracture-extension pressure (measured at the surface) from 103 bars to 109 bars. Fluid recoveries substantially greater than 80% have been recorded from deflation of unpropped fractures with volumes of 2000 to 6000 liters.

These experiments have yielded measured values of the least principal earth stress of 355 to 375 bars at a depth of about 2920 m, obtained from the analysis of both pressure vs total flow curves and shut-in pressure vs time curves. These values are lower than those which would be predicted from the measurements noted above, which were made at about 2040 m depth in the same hole, and may indicate some relaxation of tectonic stress at greater depth.

CONCLUSIONS

A great deal of additional analysis will be required before the results already obtained in exploratory holes GT-1 and GT-2 are completely understood, and many more experiments will be conducted in these holes before they are abandoned. However, the engineering information already collected from them is extremely encouraging with regard to the probability that the world's first dry hot rock geothermal energy extraction system can be built and operated successfully at the LASL Fenton Hill Site in northern New Mexico. It has already been demonstrated that dry hot rock at commercially useful temperature exists there at accessible depths; that this rock can be drilled and hydraulically fractured without unusual or unexpected difficulty; that its permeability is low enough to contain pressurized water with acceptably low leak-off rates; and that the stress condition of the rock, particularly after its pore pressure has been increased locally by permeation from the fracture system, is such that a hydraulic fracture can probably be held open by fluid pressure alone without becoming unstable.

Although experiments of several types are continuing in GT-2, these results are sufficiently convincing with regard to the engineering feasibility of creating and operating a pressurized-water energy extraction loop so that construction of the demonstration system shown in Figure 3 has already been initiated. Drilling of the first hole, identified as EE-1, has started at a location about 75 m from GT-2. It is expected to reach a depth of about 3800 m and a rock temperature of about 250°C. When it has been completed, it is planned to drill a second hole ("EE-2") about 60 m from EE-1, connect the two holes at depth through the hot granite by means of a hydraulic fracture having a radius of about 500 m, and complete the circulation loop through a 100 MW air-cooled heat exchanger at the surface. It is hoped that this system can be completed and fluid circulation initiated in it during 1976.

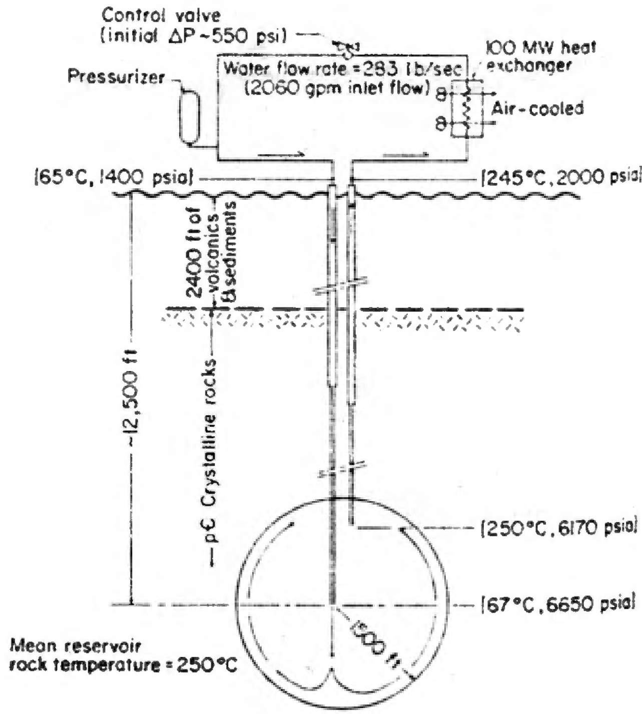

Figure 3. Proposed LASL demonstration system for geothermal energy extraction from dry hot rock.

This work is being done under the auspices of the United States Energy Research and Development Administration.

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17

ANNEXE 17

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Tectonic and Hydrologic Control of the Nature and Distribution of Geothermal Resources

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ABSTRACT

Under foreseeable economics and technology, extraction of geothermal resources is limited to the upper few kilometres of the earth's crust. At these depths, the global distribution of geothermal resources is primarily controlled by plate-tectonic features. Geothermal resources related to igneous intrusions in the upper crust occur along spreading ridges, subduction zones, inter-arc basins, and melting anomalies. Geothermal resources unrelated to igneous intrusions in the upper crust occur most commonly in porous sedimentary rocks near convergent or divergent plate boundaries where regional heat flow is high. Geothermal reservoirs at pressures well in excess of hydrostatic occur commonly in young tectonic basins characterized by high rates of sedimentation and subsidence; these reservoirs are commonly termed "geopressured." Except for the scattered melting anomalies, the central parts of crustal plates have low heat flow, little volcanism or tectonism, and accordingly no geothermal potential except at depths beyond present drilling limits.

The hydrologic properties of crustal rocks are very important in determining location, size, and type of geothermal resource. Hot dry rock can result from solidification of a young intrusive body or from conductive heating of impermeable rock around such a body. Convective hydrothermal systems result either from convection of meteoric water around young intrusive bodies or from deep circulation of meteoric water along fracture zones. Geopressured reservoirs are formed in deep sedimentary basins when escape of connate water and water produced by the thermal dehydration of clays is impeded by sediments of low permeability.

INTRODUCTION

This paper presents a broad overview of the geologic controls of the nature and distribution of geothermal resources. Consideration of the basic principals of crustal heat transfer, plate tectonics, and igneous processes allows us to split geothermal resources into two broad classes: (1) geothermal resources related to young igneous intrusions in the upper crust, and (2) geothermal resources not related to young igneous intrusions in the upper crust. The first class can be broken down into three types of resources: (a) magma, (b) hot dry rock, and (c) convective hydrothermal systems. The second class can be subdivided into four resource types: (a) resources in a low-porosity conductive environment, (b) resources in a low-porosity conductive environment modified by circulation of meteoric water, (c) resources in a high-porosity environment at hydrostatic pressure, and (d) resources in a high-porosity environment at pressures greatly in excess of hydrostatic (that is, "geopressured").

PRINCIPLES OF HEAT TRANSFER IN CRUST

Geothermal energy consists of heat produced naturally within the earth by a combination of several mechanisms: (1) decay of long-lived radioactive elements, particularly uranium, thorium, and potassium; (2) segregation of the earth into the present core, mantle, and crust; (3) dissipation of rotational energy as the rate of rotation of the earth decreases with time; and (4) conversion of kinetic energy to heat as the earth was accreted from primordial matter some 4.5 billion years ago (Smith, 1973, p. 135–139). Of these four mechanisms, radioactive decay is likely to have been the most important.

The heat of the earth is transmitted to the earth's surface at a rate of about 10^{21} joules per year (Smith, 1973, p. 105) primarily by three mechanisms: (1) conduction, (2) movement of magma, and (3) movement of water. In order to understand the nature, distribution, and extent of geothermal resources, we must consider both the principles that govern these modes of heat transfer in the earth's crust and the ways in which these modes interact.

Extensive study of conductive heat transfer in the earth's crust has demonstrated that the regional heat flow at the earth's surface (q) has two components: (1) heat flow due to conduction from the lower crust and mantle (q^*), and (2) heat flow due to the decay of radioactive elements in the upper crust (Roy, Blackwell, and Birch, 1968). In some granitic terranes, these components are related by the equation $q = q^* + DA$, where A is the radioactive heat production of local intrusive rock and D is a constant with units of length. For a given geologic province, a plot of q vs. A is nearly linear; the intercept at $A = 0$ is q^*, and the slope D. Geologic provinces display characteristic values of q^* but variable values of q depending on the amount of U, Th, and K in the upper crust (Fig. 1). If A decreases exponentially with depth in the crust (Lachenbruch, 1968), q^* is a good approximation to heat flow from the mantle (Sass, 1970). The worldwide average heat flow is approximately 1.47 μcal cm^{-2} sec^{-1} [= 1.47 heat-flow units (hfu) = 61.4 mW m^{-2}; Sass, 1971]. The value of q^* ranges from

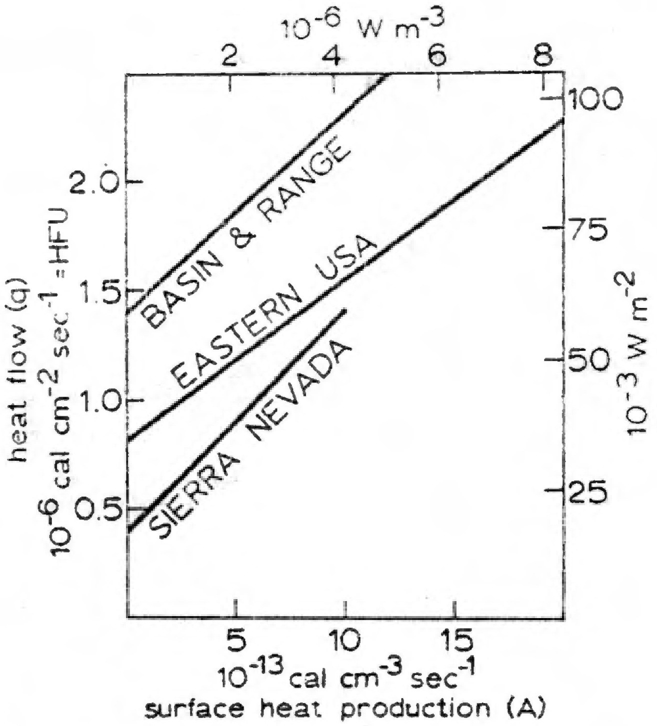

Figure 1. Relation between heat flow and surface heat production for three provinces of the United States (from Roy, Blackwell, and Birch, 1968, Fig. 6).

about 0.4 hfu for geologic provinces like the Sierra Nevada to approximately 1.4 hfu for geologic provinces like the Basin and Range (Fig. 1).

Assuming a purely conductive regime, the temperature distribution with depth may be inferred from a knowledge of surface heat flow and surface heat production (Lachenbruch, 1970). Representative temperature distributions for several heat-flow provinces (Fig. 2) show clearly that high values of q^* imply magmatic temperatures at the base of the crust. Consequently, penetrative movement of magma in the crust is likely in these provinces, and high surface heat flows cannot be interpreted by a purely conductive model. According to Roy, Blackwell, and Birch (1968), partial melting at the base of the crust would occur in those oceanic areas (crust 5 to 10 km thick) where regional heat flow is 5 to 10 hfu, and in those continental areas (crust 30–40 km thick) where regional heat flow is about 2.5 hfu.

Igneous bodies emplaced in the upper crust in impermeable rocks could produce high near-surface conductive gradients and heat flows (Blackwell and Baag, 1973). Alternatively, intrusive bodies in permeable rocks could drive overlying convective hydrothermal systems (White, 1968; Taylor, 1971), also producing high near-surface gradients and heat flows (Blackwell and Morgan, 1975). Heat flow measured at the surface, therefore, gives us information about deeper crustal processes only when the influence of meteoric circulation of water can be ruled out. Even in regions where there are no young intrusions to drive overlying convection systems, meteoric water can penetrate to depths of 5 to 10 km, acquire heat by conduction from rocks, and rise to the surface in warm plumes of relatively restricted cross section. Near-surface gradients and heat flows near these plumes can be very high, but extrapolation of gradients to depth is not warranted (Fig. 3).

Even under purely conductive crustal conditions, near-

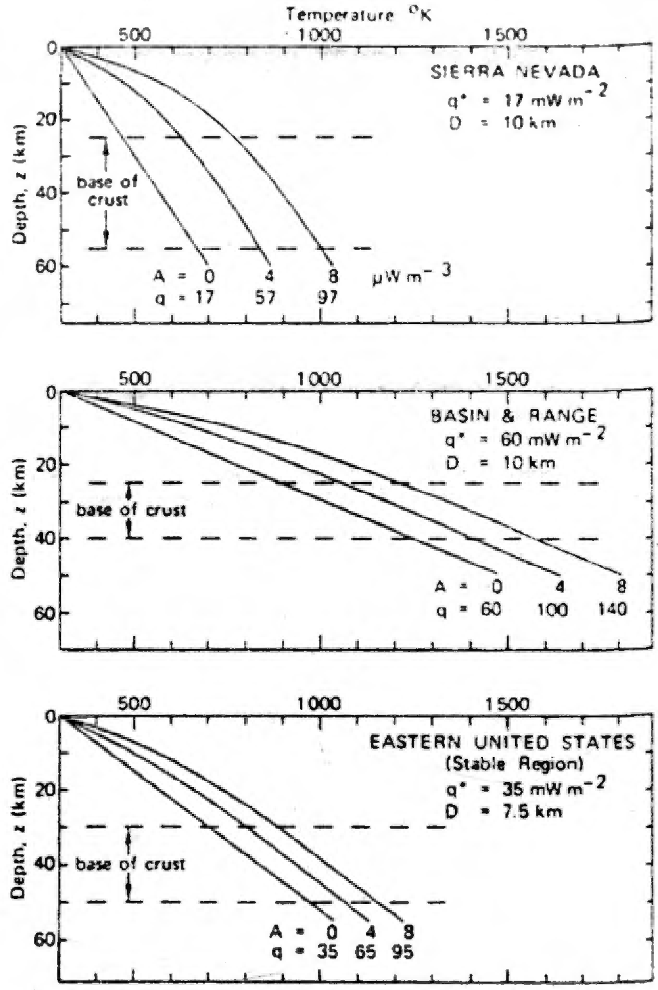

Figure 2. Temperature distributions in three heat-flow provinces of the United States at various heat flow (q) and surface heat productions (A) for an exponential decrease of heat production with depth in the crust (from Sass, 1971, Fig. 5.3 after Lachenbruch, 1970, Fig. 5).

surface heat flow can be misleading in that it does not reflect young transients at depth. For example, using any of the models of Lachenbruch et al., (1975) the thermal effect of a granitic pluton intruded 10 000 years ago at a depth of 4 km would not be detectable at the surface today if conduction were the only mode of heat transfer.

Heat flow information can also be misleading in a region of rapid sedimentation and diagenesis, such as the Gulf Coast. Here the conductive transfer of heat is grossly distorted by rapid sedimentation and subsidence, by expulsion of water upon compaction and diagenesis, and in some regions by the presence of salt domes (Jones, 1970).

These general concepts of heat transfer through the crust allow us to divide geothermal resources into two broad classes depending on whether or not the region is characterized by recent emplacement of magma into the upper crust. These two classes can then be further divided into geothermal resource types that depend on the nature of the local hydrologic regime.

PLATE TECTONICS

Consideration of the modern principles of plate tectonics allows us to delimit geographically the broad areas in which

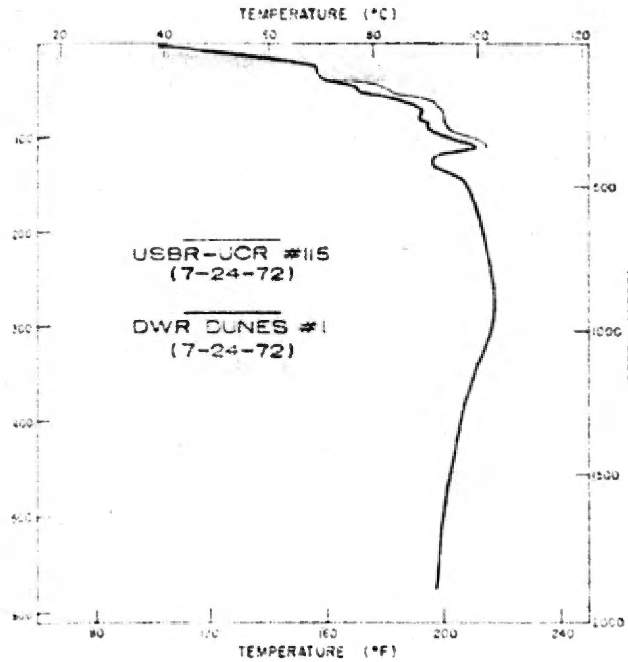

Figure 3. Temperatures measured on July 24, 1972, in USBR-UCR No. 15 (solid line) and DWR Dunes No. 1 (dashed line) from Combs (1973, Fig. 5). Drilling of USBR-UCR No. 15 was completed on Feb. 2, 1971; drilling of DWR Dunes No. 1 was completed on June 29, 1972, Fig. 27.

the two primary categories of geothermal resources are found. The central precept of plate tectonics is that the outer 100 km or so of the earth consists of large, rigid plates that move relative to each other at rates of several centimetres per year (See reviews by Wylie, 1971; Bird and Isacks, 1972; Cox, 1973; Le Pichon, Francheteau, and Bonnin, 1973). Where plates move apart, molten material rises and forms new crust at spreading ridges. Where plates move together, one plate is thrust beneath the other along subduction zones. Parallel movement of plates is taken up along transform faults. Tectonic activity is concentrated primarily along all these plate boundaries, whereas magma generation takes place along spreading ridges, along subduction zones, and at intraplate melting anomalies (such as Hawaii). Consequently, one would expect to find geothermal resources related to magma intrusion primarily near spreading ridges, subduction zones, and hot spots. Geothermal resources related to a conductive crustal regime would be expected throughout.

Figure 4 shows the general framework of the earth's plates and the major, known, high-temperature, convective hydrothermal systems. It should be kept in mind that this map displays the present plate configuration. This pattern has not been static with time, however, and the present thermal structure of the crust reflects the history of plate movements throughout at least the past few million years. Interpretation of the thermal structure and the geothermal resources of western North America clearly requires consideration of position and nature of plate margins and related tectonic and igneous activity in the late Cenozoic (Atwater, 1970; Scholz, Barazangi, and Sbar, 1971; Christiansen and Lipman, 1972).

YOUNG IGNEOUS INTRUSIONS

Geothermal resources related to young igneous intrusions in the upper crust require transient storage of heat high in the crust (<10 km) either as magma, hot dry rock, or a convective hydrothermal reservoir. All three modes of heat storage are due to emplacement of a body of magma in the upper crust, with subsequent cooling by a variety of conductive and/or convective schemes. The resource is either the intrusion itself (magma, or solidified hot rock), the adjacent country rock heated by the intrusion, or a hydrothermal convection system driven by either of the above. In all three situations, the model requires that the upward movement of at least part of the magma be arrested within the earth's crust. If magma comes directly and quickly to the surface from the mantle or lower crust, the heat is dissipated rapidly to the atmosphere and no significant geothermal resource is produced.

It is commonly accepted that ocean crust is formed at mid-ocean spreading ridges and that ophiolite sequences represent fragments of ancient oceanic lithosphere (Coleman and Irwin, 1974). Field observations of these ophiolites show layered cumulates and some differentiated rocks, indicating that magma is stored as intrusions in the crust, at least along slow-spreading ridges (Coleman and Peterman, 1975). Although oceanic spreading ridges are therefore attractive targets for geothermal exploration (Lister, 1973, 1975; Williams, 1975), they have received little attention except at Iceland, where the mid-Atlantic ridge is above sea level.

Where a spreading ridge impinges a continent, the magmatic situation becomes far more complex because the crust is thicker and more silicic. At such situations, silicic magma can be formed by partial fusion of mantle periodotite, by differentiation of basalt, or by partial fusion of crustal material (Robinson, Elders, and Muffler, 1975). Accordingly, silicic extrusions and intrusions are more common where spreading ridges impinge on continents than at mid-oceanic sites.

Zones of subduction provide an ideal setting for generation of silicic magma (Gilluly, 1971). At these zones a variety of materials ranging from exceedingly siliceous sediments to mafic and ultramafic rocks are thrust down into the mantle where they are partly melted to produce a variety of intermediate and silicic rocks. The composition of the rocks thus produced varies according to whether the subduction zone is an oceanic-oceanic plate contact (for example, the Marianas), an oceanic-continental plate contact (the west coast of South America), or a continental-continental plate contact (the Himalayas).

Melting anomalies within plates also provide situations in which magma can be stored in the shallow crust. The origin of these melting anomalies is subject to controversy. According to Morgan (1972), they lie above narrow (<150 km diameter) plumes that originate deep in the earth's mantle; others relate melting anomalies to propagating fractures (McDougall, 1971) or to shear melting (Shaw and Jackson, 1973). One of the best known melting anomalies is beneath Hawaii (Dalrymple, Silver, and Jackson, 1973), where voluminous basaltic magma has been erupted from depths of at least 60 km (that is, well into the mantle). An example of an intracontinental melting anomaly may be Yellowstone (Christiansen and Blank, 1969) where not only basalt but also voluminous rhyolite was erupted throughout the Pleistocene, the rhyolite probably produced by partial fusion

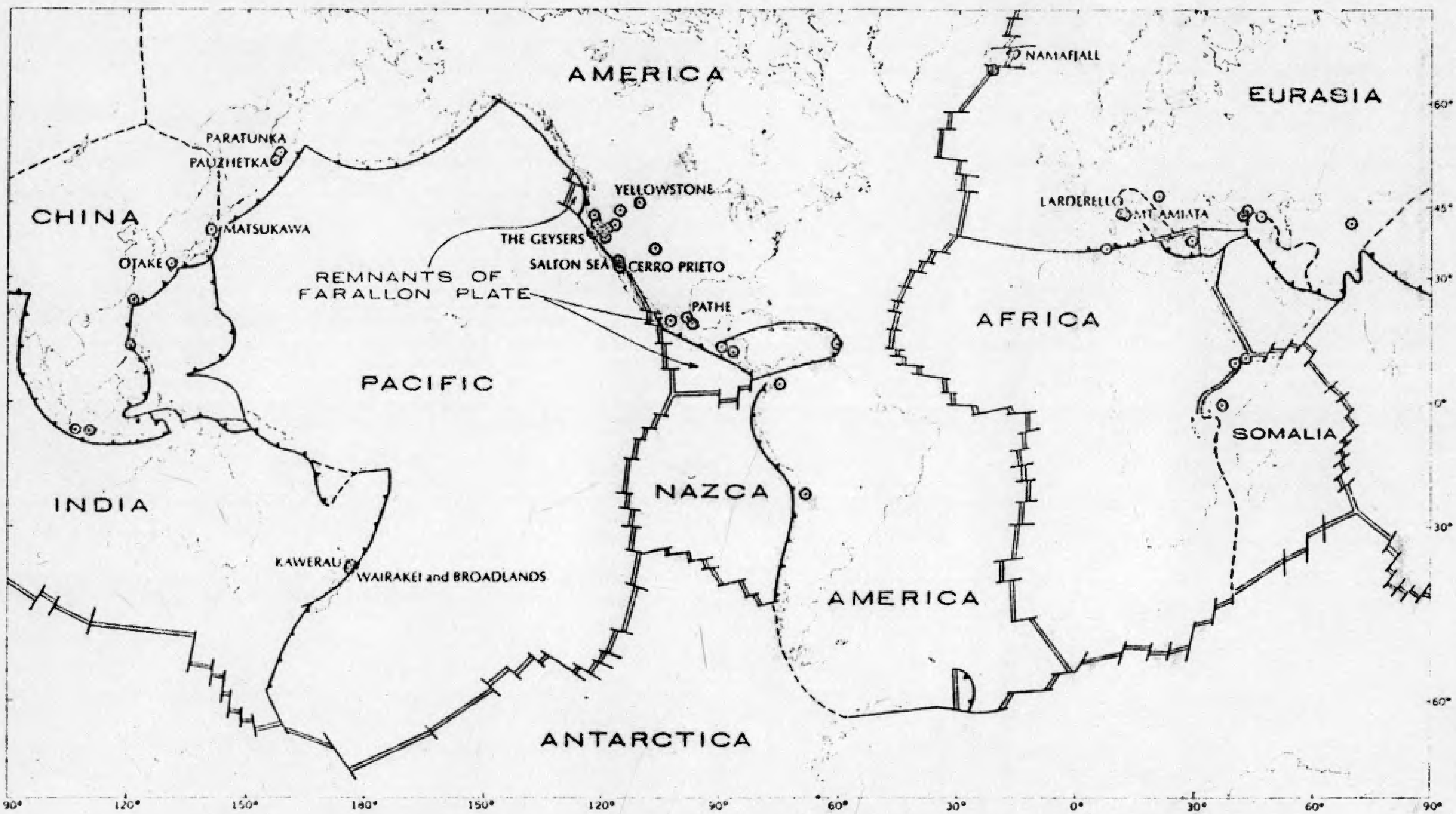

Figure 4. Map showing major lithospheric plates (after Le Pichon, Francheteau, and Bonnin, 1973, Fig. 27) and geothermal areas developed or being explored. Spreading ridges are shown by double lines, subduction zones by barbed lines, and transform faults by single solid lines. Plate boundaries of uncertain nature shown by dashed lines.

in the lower crust (R. L. Christiansen and H. R. Blank, Jr., written commun.).

Petrologic and experimental studies have shown that basalts are generated by partial melting of material in the mantle (Wylie, 1971, p. 168–208). Field studies of intrusive rocks of all ages show that most large (10^2–10^5 km^3) igneous intrusions in the upper 10 km of the continental crust are silicic (Smith and Shaw, 1973). Basaltic magma tends to rise directly to the surface in thin sheets or pipes without forming large shallow intrusive bodies. Accordingly, as a first approximation, geothermal resources on the continents are more likely to be associated with silicic volcanism than basaltic volcanism (Smith and Shaw, 1973). This generalization does not seem to hold for oceanic spreading ridges, where the crust is thin and extensive ophiolite complexes with large intrusive components can form.

Accepting that large volumes of molten rock can be intruded into the shallow crust, we can then look at the types of geothermal resources than can occur in this magmatic environment, continuing to restrict our discussion to the upper 10 km. The most obvious potential resource is the magma itself. A cubic kilometre of granite magma at 800°C contains 3×10^{18} joules (above surface temperatures), which is equivalent to the heat content of 480 million barrels of crude oil. Obviously molten rock is an attractive potential energy source, even in small volumes such as at Kilauea Iki lava lake (Kennedy and Griggs, 1960), but the technological problems of utilization are extreme (Colp and Branvold, 1974).

A magma intruded into the crust will cool and solidify with time, losing heat by conduction and convection. If the permeability of the intrusion and the rock into which it is intruded are low, one might develop a hot dry-rock resource in both the intrusive rock itself and in the surrounding country rock. Even though solid, this could be still an immense potential energy resource. One km^3 of granite at 600°C contains 1.6×10^{18} joules of heat (above 0°C); at 300°C, 0.8×10^{18} joules. However, the technological problems of extraction and utilization of the heat in this impermeable rock are formidable. Proposals for hydraulically fracturing hot dry rock and circulating pressurized water in a closed loop have been put forward (for example, Smith, et al., 1973), and an extensive program of experimentation is underway at the Los Alamos Scientific Laboratory (Smith, 1974; Tester, 1974; Smith, et al., 1975). Significant problems concern the creation of sufficient heat-transfer area between rock and water (Gringarten, Witherspoon, and Ohnishi, 1975), possible extension of cracks owing to thermal contraction (Smith, et al., 1973), and chemical reaction of hot rock and water.

If, however, an igneous intrusion is emplaced in rocks of significant intergranular or fracture permeability, the cooling history will be greatly affected by movement of water. In this model, the intrusive body will act like a stove burner under a tea kettle, setting up a strenuous convection system of meteoric water (White, 1968). This water can penetrate not only through the country rock but also through the cooling intrusion as demonstrated by studies of ^{18}O in young intrusive and volcanic rocks (Taylor, 1971; Friedman, et al., 1974). The heat thus convected upward from the intrusion can either go to the surface directly or be stored at an intermediate depth in a hydrothermal reservoir, the only type of geothermal resource exploited to date. Depending on the local hydrologic situation this reservoir can be either hot water- or vapor-dominated (White, Muffler, and Truesdell, 1971).

Any particular crustal thermal anomaly can give rise to all three types of geothermal resources (magma; hot dry rock; convective hydrothermal), either simultaneously or sequentially. The overall potential of these three types of geothermal resources in any given area can be evaluated crudely by considering the size-age relations of the crustal igneous anomaly (Smith and Shaw, 1973). Clearly, the geothermal potential of any igneous system increases with the size of the anomaly and decreases with age. These relations have been quantified by R. L. Smith and H. R. Shaw (written communs., 1972–1975; White and Williams, 1975) by plotting age and volume data against a family of curves showing solidification times of hypothetical magma chambers as functions of various geologically reasonable boundary conditions.

It is clear that the major potential resource in this regime of upper crustal magmatism lies in the magma itself and in the hot dry rock. Calculations by my associates in the U.S. Geological Survey (White and Williams, 1975) indicate that the potential geothermal resources of magmatic and associated hot dry rock systems in the United States are many times the potential geothermal resources of associated convective hydrothermal systems. However, it must be emphasized that this analysis considers only heat in the ground. Many convective hydrothermal systems are utilizable under present or foreseeable (by 1990) economic conditions and technology, whereas the technology for tapping the heat in hot dry rock and magma is only just beginning to be developed (Smith, 1974; Colp and Branvold, 1974).

REGIMES NOT RELATED TO YOUNG INTRUSIONS

It has long been recognized that the large regions of normal thermal gradients in the crust contain an immense amount of heat. White (1965), for example, calculated that the total heat stored above surface temperatures in the earth to a depth of 10 km is about 1.3×10^{27} joules. At a geothermal gradient of 20°C per km (typical of crystalline rocks of the eastern United States) temperatures at 10 km would exceed 200°C. At 35°C per km (approximately that for crystalline rocks in the Great Basin) temperatures at 10 km would approach 400°C.

Most of this potential resource, however, is at depths too great to allow economic exploration and development with existing drilling technology. The deepest well drilled to date for geothermal energy is approximately 3 km, whereas the deepest well drilled in petroleum exploration is slightly less than 10 km. But at depths greater than 3 km drilling costs go up exponentially with depth (Anderson, 1973). A well to 3 km should cost less than \$500 000, whereas a well to 10 km probably would cost over \$6 000 000. Accordingly, the vast regions of normal geothermal gradients are unlikely to be explored and utilized at depths greater than 3 km unless there is a major technological breakthrough that drastically lowers deep drilling costs. The leverage of such a breakthrough would be immense, however, and research in advanced drilling technology presents an exciting opportunity.

Geothermal resources unrelated to upper crustal magmatism can be subdivided into four types:

1. Resources in a low-porosity, conductive environment.

2. Resources related to deep circulation of meteoric water along faults and fractures.
3. Resources in a high-porosity environment at hydrostatic pressure.
4. Resources in a high-porosity environment at pressures greatly in excess of hydrostatic (that is, "geopressured").

These types are actually end members, with most natural situations displaying intermediate characteristics.

Resources in a Low-Porosity Conductive Environment

A purely conductive thermal regime requires that there be no movement of water and thus implies either no vertical hydraulic gradient or no permeability. The latter condition may be approximated in crystalline basement rocks and in terranes characterized by metamorphic complexes or homogeneous intrusions. Extraction of significant quantities of heat from these conductive environments is impossible without artificial fracturing of extensive volumes of rock, either by hydrofracturing or by explosive devices. The mechanical problems are similar to those referred to previously with regard to extraction of heat from hot dry rock but are exacerbated by the much greater depths required to get high temperatures. Extraction of geothermal energy from a purely conductive non-magmatic environment would therefore seem to be a step beyond the successful demonstration of energy extraction from hot dry rock in an environment of crustal magmatism.

Deep Circulation of Meteoric Water

Many regions characterized by low to moderate regional geothermal gradients do contain sporadic warm springs, usually along faults. One example is in the eastern United States, where springs with temperatures up to 40°C occur in a belt along the Appalachian Mountains. This area shows no evidence of late Cenozoic volcanism, and geothermometry based on existing chemical analyses gives no indication the temperatures at depth are significantly higher than surface temperatures (A. H. Truesdell, oral commun., 1975). These warm springs appear to be related to deep circulation of meteoric water along faults and accordingly can be viewed as a convective aberration of the basically conductive crustal regime.

The eastern United States is a region of low to normal heat flow (Fig. 1). One would expect that in regions of higher heat flow, thermal springs would be in general more abundant. With even greater regional heat flow, such a regime would grade into a regime characterized by intrusion of basalt into the upper crust and eventually to emplacement of silicic material in the upper crust.

The transition from a regime characterized by deep circulation of meteoric water to one characterized by movement of magma into the upper crust is perhaps illustrated by the Basin and Range Province of the western United States. Regional heat flow is approximately twice normal (Fig. 1), and the area is characterized by many hot springs (Waring, 1965), a number of which have a chemistry suggesting high subsurface temperatures (Mariner, et al., 1974). The Basin and Range Province is an area of extensive normal faulting and tectonic extension (Thompson and Burke, 1973), and most hot springs are located along faults. The province displays sporadic late Cenozoic basaltic volcanism and is underlain by relatively shallow mantle of anomalously low seismic velocity (Archambeau, Flinn, and Lambert, 1969). During the late Cenozoic, silicic volcanism spread east and west from the center of the Great Basin, and Quaternary silicic volcanic rocks occur only along the east and west margins of the Great Basin (Armstrong, et al., 1969). Scholz, Barazangi, and Sbar (1971) suggest that these geologic and geophysical characteristics can be explained by upward and outward flow of partially melted material originating from the Farallon plate subducted beneath the North American plate in the late Cenozoic.

The hot springs and geothermal systems of the Basin and Range Province are unlikely to be related to intrusions in the upper crust, except at the east and west margins where Quaternary silicic volcanic rocks occur. The sporadic basalts probably came directly to the surface from the mantle or lower crust, producing few if any shallow intrusions. Accordingly, the hot springs of the Great Basin can best be interpreted as due to deep circulation of water along faults in a region of elevated heat flow (Hose and Taylor, 1974). Major unknowns are the volume and permeability of any reservoirs that may exist at depth.

High-Porosity Environment, Hydrostatic Pressure

Many regions throughout the world are characterized by deep basins filled with sedimentary rocks of high porosity and permeability. Where these basins occur in regions of elevated geothermal gradient and heat flow, temperatures approaching 200°C can be achieved at depths where extraction is feasible. Even in regions of normal heat flow, permeable sedimentary rocks at great depth (3 to 10 km) have been found in the course of oil exploration and represent a significant potential source.

Geothermal resources at hydrostatic pressure in young sedimentary basins are typified by the Hungarian Basin (Boldizsár, 1970), where up to 3 km of porous, Cenozoic sediments occur in a region characterized by temperature gradients of 50 to 70°C/km. Boldizsár (1970) concludes that over 4000 km^3 of water at 60 to 200°C is stored in porous rocks at depths greater than 1 km. Successful extraction and utilization of this geothermal resource for space and agricultural heating have been demonstrated in Hungary, as well as in similar geologic environments of the USSR (Tikhonov and Dvorov, 1970) and France.

Geothermal resources of this type require two coincident factors: (1) a sedimentary basin containing rocks of high porosity and permeability; and (2) elevated regional heat flow. The second condition is likely to be met only near plate margins, which are also tectonically active zones where the formation of deep, sedimentary basins is likely.

Geopressured Resources

Extensive drilling for oil in many sedimentary basins has delimited zones characterized by pressures greatly in excess of hydrostatic. These geopressured zones are also at elevated temperature, and the interstitial fluids contain significant quantities of dissolved methane. Accordingly, three kinds of energy could be extracted from geopressured reservoirs: kinetic, geothermal, and combustion.

Most data on geopressured resources come from oil wells drilled in the Gulf Coast of the United States. These data were summarized and interpreted by Jones (1970), and the following discussion is based primarily on Jones's paper.

Since the early Cenozoic, the Gulf Coast has been the site of extensive deposition of clastic sediments eroded from the central United States, particularly the Rocky Mountains. These sediments consist of interfingering deltaic and marine sand and clay. Sedimentation rates ranged up to 1.2 m per 1000 years (Jones, 1970, Table 1), and the maximum thickness of the Cenozoic sedimentary pile approaches 15 km. In general subsidence has kept pace with deposition, with the locus of deposition shifting gulfward with time. The depositional pattern is modified by major faults parallel to the basin margin; these faults were active throughout the formation of the sedimentary pile and have broken up the sand layers into discrete reservoirs.

In the upper few kilometres of the Gulf Coast pressures are hydrostatic and temperature gradients are normal (20–40°C / km). But at depths of 1.5 km or greater, both pressures and temperatures rise strikingly, with pressures approaching lithostatic (Fig. 5) and temperatures exceeding 200°C.

These geopressured zones occur in sand beneath low-permeability shale, and are bounded laterally by faults to produce discrete reservoirs several tens or hundreds of square kilometres in area. The overlying impermeable clay beds act as thermal insulators because of their high content of static water, a substance that has low thermal conductivity (Lewis and Rose, 1970).

The water in these reservoirs is not meteoric but is both connate water and water released upon dehydration of montmorillonite during diagenesis at temperatures of 80 to 120°C. These waters are expelled into adjacent sand reservoirs.

Salt domes, derived from the Louann Salt (Jurassic) that underlies the basin, are abundant throughout the Gulf Coast sedimentary section (Halbouty, 1967). Some of these domes have penetrated many kilometres bringing salt at relatively high temperature (200–300°C) to shallow depths in a manner analogous to the intrusion of an igneous body. Furthermore, salt has a thermal conductivity two to three times that of the sediments (Clark, 1966), and the salt diapirs thus provide a mechanism whereby heat is transported upward in an irregular manner.

It is not known whether the regional heat flow in the Gulf Coast is normal or high. Traditional measurements of gradient and thermal conductivity, even at great depths, cannot be used to calculate a regional heat flow, owing to the aberrations induced by movement of water, sediment compaction, diagenesis, and salt dome intrusion. The relatively shallow Moho and the basalt of unknown age recently identified beneath some offshore salt domes (P. H. Jones, oral commun., 1975) may suggest that the regional heat flow is indeed elevated.

Geopressured reservoirs in the Gulf Coast are likely to be very abundant and quite large in aggregate. The oil well data are more than adequate to define a belt of geopressured reservoirs extending over 1000 km along the coast of Texas and Louisiana, both onshore and offshore (Jones, 1970, Fig. 20). Unknown are the rate at which these reservoirs might be produced, the longevity of production, the economics of use, and the environmental impact, particularly subsidence. The determination of these factors will depend largely on hydrologic analysis; the major unknown is how the geopressured reservoirs will react to prolonged fluid extraction. It seems clear that the geopressured resources of the Gulf Coast are ripe for a demonstration study involving reservoir delineation, production testing, electricity generation, economic analysis, and environmental monitoring.

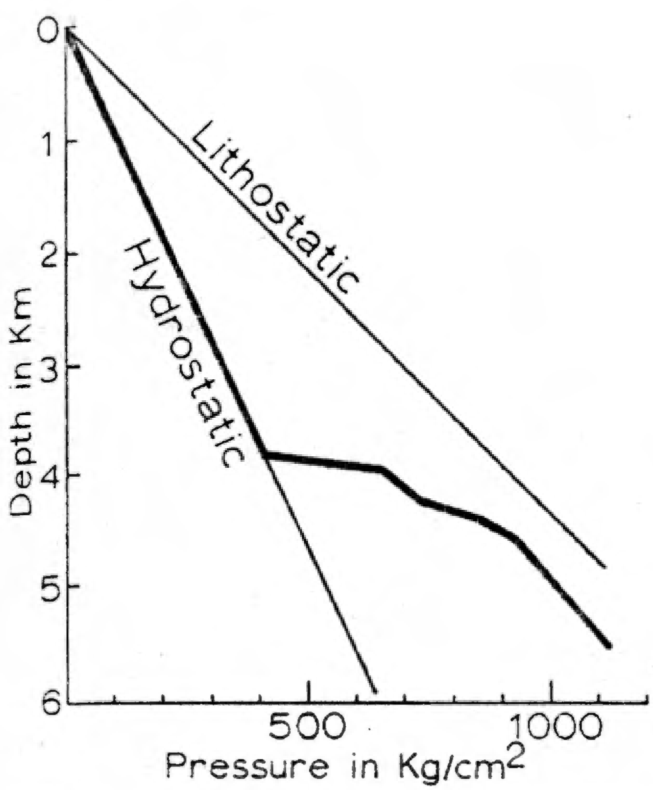

Figure 5. Graph showing pressure vs. depth in a geopressure area offshore from Louisiana (from Myers, 1968).

SUMMARY

There is a geologic rationale for dividing geothermal resources into two broad categories, depending on whether the resource is or is not related to young igneous intrusions emplaced in the upper crust. Resources related to such intrusions can be subdivided into magma, hot dry rock, and convective hydrothermal reservoirs; any given upper crustal thermal anomaly can produce all three subtypes. Geothermal resources unrelated to young intrusions in the upper crust can be sub-divided into resources in a low porosity, conductive environment, resources related to deep circulation of meteoric water along faults and fractures, resources in a high-porosity environment at hydrostatic pressure, and geopressured resources.

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18

ANNEXE 18

snc

17.1.7
RN-M-208 157

MINISTÈRE DES RICHESSES NATURELLES DU QUÉBEC – DEPARTMENT OF NATURAL RESOURCES, QUEBEC
DONNÉES SUR LES PUITS — WELL DATA

No du dos.: / File No.:

Puits: / Well: Canac-B.P.-Sisque Brossard No 1

Particip. et accords / P'T'C'P'T'S & AG'R'TS

Région: / Area: Lowlands

Classification: Wildcat

No du permis: / License No.: 239

Localité: Comté / Location: County: Laprairie — Canton ou Seign. / Twp. or Seign.

Elév. Terr. / Grd. Elev. 54.20' — F.T.D. 4754'

Elév. C. d'E. / Pl. F. 64 [x] KB [ ] RF Elev. — P.B.D.

Paroisse / Parish: Laprairie de la Madeleine

Lot: 31 — Conc. ou Rang / Conc. or Range

Commencé / Spudded: May 2nd, 1971

Diagrammes / Logs: E [ ] R [ ]

Densilog	4754'
Induction log	4754'
Dip log	4754'
Directional Survey	4750' - 2500'
Dip log	2500' - 709'

Coords. Latitude 45° 26' 39.854"
Longitude 73° 29' 27.626"

Outil. enlevé / Rig Release: July 1, 1971

En production / On Prod.

Levés: / Surveys:

Entr. de For. / Dr'g Ctr.: BrinKerhoff Brothers Ltd. — Type For. / Type Rig: ~~Cable~~ Rotary — F.D. / D.D.

Données de production / Production Data

Opérateur / Operator: Canac Exploration Inc.

Abandonné / Abandoned: June 30th, 1971

I.P.

Préliminaire – Preliminary W.R.McEachern (samples) — Final

Formation	Repère Marker	Int. de Prof. Depth Interval Samples	Service log	Elév.	Epaisseur Thickness	Formation	Membre ou repère Member or Marker	Interv. de prof. Depth Interval	Elév.	Epaiss. Thickness	Remarques Remarks
Overburden		0			20'						
Utica Shale		20		+ 44'	558'						
Trenton Limestone		578	578'	+514'	818'						
Black River Ls.		1385'	1396'	-1332'	107'						
Chazy Ls.		1503'	1503'	-1439'	327'						
Chazy Ss.		1833'	1830'	-1766'	160'						
Beckmantown		2005'	1990'	-1926'	1428'						
Beek. Dol. Sands		2757'									
Upper Potsdam		3426'	3418	-3354	989'						
Lower Potsdam		4424'	4407	-4343	421'+						

ANNEXE 18
Log du Puits 157

4275

ESSAIS - TESTS

No. / No.	Formation ou Réservoir / Formation or Reservoir	Intervalle / Interval	Durée / Duration	Résultats / Results

ABANDONMENT

Plug # 1 4654' - 4754' with 24 Sacks of cement
2 3350' - 3550' with 60 sacks of cement felt plug at 3360'
3 1750' - 2050' with 85 sacks of cement " " 1750'
4 670' - 770' with 40 sacks of cement " " 660'

Plate welded on top of casing located 10' below surface

Gaz - Gas	Profondeurs / Depths	Mcf / Mpc	Pression / Pressure	Remarques / Remarks

Pétrole / Oil	Profondeurs / Depths	Barils/jour / Barrels/day	Pression / Pressure	

Eau / Water	Profondeurs / Depths	Barils/jour / Barrels/day	N.S.E. / SWL	
4400'		2 gpm		
	3778 - 3958			
	4438 - 4708			
	4708 - 4754			

Tubage(s) / Casing(s)

119' K.B. 10¾" 140 c.f. cement
722' 7 5/8" 200 c.f. cement

Inter. de perf. / Perf. Interval	Tirs / Shots	Acide / Acid

CAROTTES - CORES

Formation ou membre / Formation or Member	No Inter. / No. prof.	Depth Interval	(Epais) / (Thick)

Analyse: / Analysis: Benzine and Tolmene
3778' - 3958', 4438' - 4708', 4708' - 4754'

Gaz / Gas [ ]

Petrole / Oil [ ]

Eau / Water [x] 3778' - 3958' - 4438' - 4708', 4708' - 4754'

Carotte / Core [ ]

Inform. de: / Infmtn. from:

Descr. éch.: / Sple. Descrip.:

Date:
Par: / By:
Revisé: / Revised:
Approuvé: / Approved:

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ANNEXE 19

snc

ANNEXE 19

Unités - Géothermie
D'après I.I. Glass

UNITS (from Ref. 48)

"The terms *energy policy* and *fuels policy* are often used interchangeably and this can lead to some confusion. Inanimate energy, as required by a highly industrialized society such as ours, has been traditionally provided by primary fuels (e.g. wood, coal, oil, natural gas, uranium). Consequently, one normally counts the amount of gross energy input in terms of quantities of fuels used (e.g. tons of coal, barrels of oil, etc). What is sometimes overlooked is that some of these minerals are used for non-energy purposes. For example, at current levels of consumption, approximately 10% of the coal mined or oil produced annually goes to non-energy use (e.g. metallurgical processes, lubricants, petrochemicals, etc); a comparable amount of natural gas is consumed as feedstock for the manufacture of fertilizers, drugs, etc. This follows the more or less conventional accounting method of treating gross energy input in terms of fuel equivalent, without disaggregating into non-energy and energy quantities. Another element of confusion is how to count electricity produced by hydropower inasmuch as this is useful energy derived from gravity and not primary fuels. The practice adopted here, dubious as it may be, is to treat hydroelectricity in terms of fuel equivalent - that is, to convert to heat units using the heat rate of steam plants (i.e. relative efficiency) rather than the physical ratio of electrical energy units to heat. This method of accounting will have to be scrutinized more carefully in future years when geothermal, solar, and other nonprimary fuel sources become more significant contributors to the energy sector.

The unit of accounting is based on British thermal units (Btu), where the unit of preference is $Q = 10^{18}$ Btu or 1.05×10^{21} joules. Rates of consumption are given in $mQ = 10^{-3}Q$. For approximate comparisons, one can readily convert from heat units to fuel units by noting: 1 mQ = 1 Tcf (10^{12} cubic feet) of natural gas, or 0.5 Mb/d (10^6 barrels per day) of oil times 365 days or 50 million tons of an appropriate mixture of eastern and western coal. Similarly, 1 mQ = 10^{11} kW-hr of electrical energy, assuming a heat rate of 10^4 Btu/kW-hr. This amount of electrical energy could be produced by approximately 20 GW (10^9 watts) of installed steam-generated electric capacity operating for 365 days at a capacity factor of about 65%, that is, 40 GWe is roughly equivalent to 1 Mb/d of oil. These approximate conversions are valid within a 10% margin of error, given current efficiencies of fuel utilization and plant reliabilities.

For purposes of comparison with the above figures, the gross energy consumption in the United States was 72 mQ in 1972 and that of the entire world was about 225 mQ. A midrange estimate of the total recoverable crude oil of the world is 12 Q, and of this 1.5 Q has already been consumed. The amount of recoverable gas in the world is a comparable figure. The reason for particular concern with oil and gas is that these liquid and gaseous fuels have been supplying roughly three fourths of the energy requirements in the United States and throughout the world. Coal is often mentioned as being far more plentiful than oil or gas. While in principle the statement is correct, if we consider only those deposits economically recoverable by present techniques, the worldwide figure is about 25 Q. This can be doubled, in effect, to 50 Q if we include the so-called para-marginal deposits. Cumulative production of coal in the United States alone has been about 1 Q to date. The United States is believed to have somewhat less than 10% of the world's oil and gas resources and perhaps one third of its coal resources."

TABLE D-2 (After Ref. †)

"PRACTICAL" FUEL-ENERGY CONVERSION CONSTANTS

Fuel	Usual unit	Heat content (rough average)	Amount necessary for operation of one large power station (1000 MW_e and 3000 MW_t)*
Coal	metric ton $=10^6$ g =1.102 short tons =0.9842 long tons $\equiv 3 \times 10^{10}$ J (joules)	=8600 kWh/ton $=8.6 \times 10^{-3}$ kWh/g	10,000 ton/day =1 train/day
Oil●	barrel (U.S.) =42 gal =158.98 liter $=1.43 \times 10^5$ g $\equiv 6 \times 10^4$ J $\equiv$ 1.2 metric ton TNT	=1700 kWh/bbl $=11.9 \times 10^{-3}$ kWh/g	40,000 bbl/day =1 supertanker/week
Natural gas (95% methane)	cubic foot =20.3 g $=2.83 \times 10^4$ cm^3	=1000 Btu/ft^3 =0.29 kWh/ft^3 $=14.7 \times 10^{-3}$ kWh/g ($\Delta H = 19.8 \times 10^{-3}$ kWh/g)	2.5×10^8 ft^3/day $=10^4$ m^3/day LNG =1 ship/5 days
U^{235} (fission)	gram	23,000 kWh/g =2620 W-yr/g	3 kg/day (negligible compared to container weight)
Deuterium (fusion)	gram	66,000 kWh/g	1 kg/day

* Subscript e is electrical, t is thermal
● 6.35 barrels in a short ton of oil
† Unfortunately the original reference was misplaced

TABLE D-1 (Ref. 3)

EQUIVALENT UNITS OF ENERGY

	Energy in joules
1 gram matter equiv. = 8.988×10^{13} J	10^{14}
	10^{12}
1 metric ton coal equiv.[a] = 2.952×10^{10} J	
	10^{10}
1 barrel oil equiv.[b] = 5.925×10^{9} J	
1 ton TNT equiv.[c] = 4.184×10^{9} J	
1 gallon gasoline equiv.[d] = 1.318×10^{8} J	
	10^{8}
1 watt-year = 3.1536×10^{7} J	
1 kWh = 3.6×10^{6} J	
1 horsepower-hour = 2.685×10^{6} J	
1 ft^3 natural gas equiv.[e] = 1.138×10^{6} J	10^{6}
	10^{4}
1 Wh = 3600 J	
1 Btu = 1054 J	
	10^{2}
1 cal = 4.184 J	
1 ft-lb = 1.356 J	1

1 quadrillion Btu is approximately 172 million barrels of oil; 970 billion ft^3 of natural gas; 41,700,000 tons of coal.

[a] 28×10^{6} Btu/metric ton [b] 5.62×10^{6} Btu/barrel [c] 10^{9} cal/ton
[d] 1.25×10^{4} Btu/gallon [e] 1080 Btu/ft^3

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ANNEXE 20

ANNEXE 20

Memo de Pierre Lefebvre de SOQUIP

MEMO AU DOSSIER

DATE: Décembre 1977

OBJET: Gradient géothermique dans les Basses-Terres

AUTEUR: Pierre Lefebvre, secrétariat technique du département d'Exploration

SOURCE D'INFORMATION: Logs des puits excédant 500' de profondeur

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Afin de déterminer le gradient géothermique local et régional dans les Basses-Terres, un relevé a été fait de toutes les données disponibles concernant les températures dans les puits.

Ces températures sont normalement enregistrées au fond des trous lors de l'enregistrement des diagraphies.

Afin de déterminer le gradient géothermique à partir des données des forages, il faudra également tenir compte de la température moyenne annuelle à la surface. Cette température a été déterminée à 60°F ou 15.5°C. Cette valeur semble assez logique puisque les étés au Québec sont relativement chauds, tandis que le recouvrement par la neige donnera une température moyenne hivernale d'au minimum 32°F ou 0°C.

Sur la carte annexée, les valeurs de températures et des profondeurs respectives ainsi que les gradients correspondants sont indiqués.

LE GRADIENT GEOTHERMIQUE MOYEN EST 0.61°F/100'
ou 1.17°C/100 mètres

donc pour atteindre la température du corps humain vivant, il faudra creuser un trou d'approximativement 6,500'.

Moyenne Mondiale 2.5°C

.../2

CONFIDENTIEL

Dans la région de Trois-Rivières, le puits CapRive # 2 Trois-Rivières, montre le gradient le plus élevé connu à savoir 1.03°F/100' ou 1.87°C/100 m (75°F ou 23.8°C à 1,452' ou 442.5 m). Le puits SOQUIP Laduboro Baieville # 1 avec un gradient de 0.93°F/100' ou 1.66°C/100 mètres (99°F ou 37.2°C à 4,280' ou 1,304.4 m), se situe dans cette région la plus "chaude".

Dans la région de Ste-Croix, le puits SOQUIP Shell Ste-Croix # 1, nous révèle le plus faible gradient 0.04°F/100' ou 0.09°C/100 m (63°F ou 17.2°C à 6,137' ou 1,870.4 m). Le puits Québec Natural Gaz # 16 St-Vincent de Paul ayant un gradient de 0.06°F/100' ou 0.13°C/100 mètres (61°F ou 16.1°C à 1,503' ou 458.0 m) se localise dans cette même région.

Pierre Lefebvre

PIERRE LEFEBVRE, technicien

PL/Mjm

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ANNEXE 21

ANNEXE 21

Envoyé par Paul P. Simard
Chef de l'Exploration
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1305 Chemin Ste Foy, Québec G1S 4N5

How to determine static BHT from well log data

Walter H. Fertl, Director of Interpretation and Field Development, and **Paul A. Wichmann**, Manager Log Analysis, Dresser Atlas Division, Dresser Industries, Inc., Houston

10-second summary

Technique for estimating static bottom hole temperature uses temperatures recorded while logging and extrapolation methods similar to those used in determining static bottom hole pressure. The following report includes discussion of how the technique is used in the field.

A SIMPLE and rapidly applied analytical technique has been developed for analyzing maximum bottom hole temperatures (BHT), which are recorded during well logging operations, to determine static formation temperature. The method requires use of a maximum recording thermometer on each logging run, plus information concerning circulating time and time that the logging instrument was last on the bottom of the borehole.

It is well known that downhole temperatures recorded during routine logging operations do not measure true, static formation temperature. Due to cooling effects while circulating (i.e., conditioning hole prior to logging operations), recorded temperatures can be 25° F to 70° F lower than true, static formation temperature.

Static formation temperature is an important working parameter for the geologist, drilling and completion engineers and in reservoir engineering studies. Furthermore, all downhole well logging and perforating instruments exhibit certain inherent temperature limitations.

TEMPERATURE DETERMINATION

An analytical extrapolation technique has been proposed to obtain true, static formation temperature at any particular depth from maximum downhole temperature (BHT) data measured and recorded while running conventional well logs. Besides maximum borehole temperature for each log run, it is necessary to record the time (after circulation stops) that the logging instrument was last on bottom. Also, duration of hole conditioning (i.e., circulation time) prior to logging must be known.

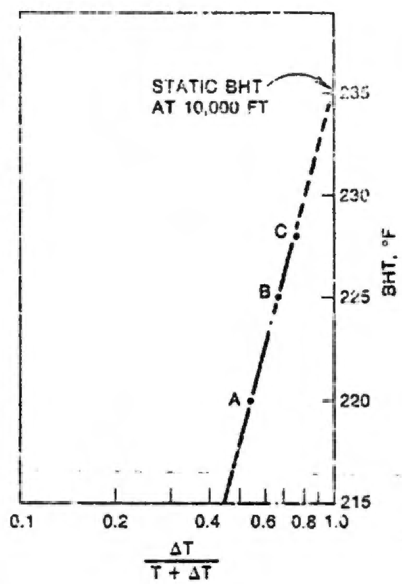

Fig. 1—Graph shows an example extrapolation to determine static BHT. Circulating time in hours is t and Δt equals time after circulation stopped, hours.

Since a rise in pressure was found to be similar to a rise in temperature, it has been suggested that increases in BHT after circulation is stopped may be analyzed in a manner similar to Horner's pressure build-up technique.

Both temperature and pressure build-up can be described by the diffusivity equation, subject to constraints of an initial condition and a set of boundary conditions. A recent study has shown that, mathematically, the inner boundary condition for the temperature case is not analogous to that for the pressure case. However, since under most practical field conditions in-situ temperature gradient changes very slowly, particularly for short circulating times, the proposed method will give a reliable estimate of true, static formation temperature. Extremely long circulation times (in excess of a day) would lead to static temperature estimates somewhat lower than actual.

The basic criterion for the technique is the straight-line relationship on semilogarithmic paper of maximum recorded temperature (BHT in °F) versus the ratio of:

$$\frac{\Delta t}{t + \Delta t}$$

Where

Δt = time after circulation stopped in hours

TABLE 1

Point	Dimensionless time	Temperature °F
A $\frac{\Delta t}{t + \Delta t} = \frac{7}{6 + 7}$	0.538	220
B $\frac{\Delta t}{t + \Delta t} = \frac{7 + 4.5}{6 + 7 + 4.5}$	0.671	225
C $\frac{\Delta t}{t + \Delta t} = \frac{7 + 4.5 + 8}{6 + 7 + 4.5 + 8}$	0.765	228

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t = circulating time, in hours.

Then, extrapolation of this straight line to a time ratio of

$$\frac{\Delta t}{t + \Delta t} = 1$$

will define true, static formation temperature.

Example Determination

Assume that after drilling to 10,000 feet, the operator circulated six hours before starting to pull drill pipe. From the time the bit was pulled off bottom until the induction log started out of the hole, another seven hours elapsed. The maximum recording thermometer showed 220° F at that time (Point A).

Similarly, the compensated neutron-density log combination was pulled off bottom after passage of another 4½ hours. The maximum recorded temperature from this run was 225° F (Point B).

The operator also decided to run an acoustic log, which was finally pulled off bottom eight hours after the compensated neutron-density log combination left the same point in the hole. The temperature recorded at the time was 228° F (Point C).

To determine extrapolated static formation temperature the following pairs of data are plotted as shown in Fig. 1 and Table 1. The static BHT is indicated to be 235° F at 10,000 feet.

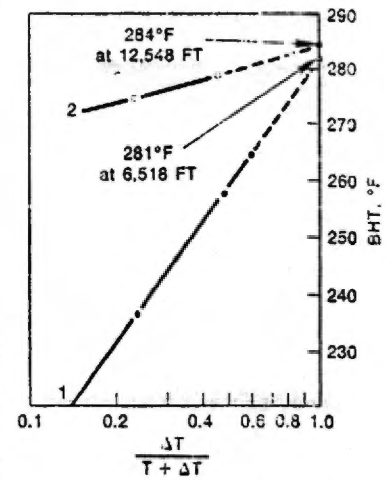

Fig. 2—Technique was used to find true formation temperature for a well in the South China Sea where the temperature gradient is very steep (Well 1) and for an onshore Texas well (Well 2).

Field Examples

The extrapolation technique for true, static formation temperature in two wells drilled in different geothermal regimes is shown in Fig. 2. Well 1 is a high-temperature well, located in the South China Sea. Four logs were run to 6,518 feet. First log, four hours after mud circulation stopped, recorded 218° F. Log 2, six hours later, measured 265° F. Straight-line extrapolation to infinite time indicates a BHT of 281° F. Well 2 is a deep onshore Texas well. Three logs were run to 12,548 feet. First-recorded temperature was 272° F, whereas actual stabilized BHT is 284° F. The drastic difference in the geothermal gradients observed in the two wells and its impact on completion and exploration concepts is obvious.

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ANNEXE 22

ANNEXE 22

TEMPERATURES DE SOUS-SURFACE

TEMPERATURE DE SOUS-SURFACE

(obtenues de diagraphies)

BASSES TERRES

(Température moyenne de la surface = 40^oF ou 4.4^oC)

No. du puits	Nom du puits	Profondeur pieds	Profondeur mètres	Température °F	Température °C	Gradient °F/100'	Gradient °C/100M Calculé SNC	Gradient °C/100M	Coordonnées	
13	Bald Mountain Louiseville # 2	1126'	343	55°F	13°C	1.33	0.8	2.48	46°13'55"	72°56'32"
* 29	Cap Rive # 2 Trois-Rivières	1399'	426	75°F	24°C	2.50	3.2	4.58	46°21'30"	72°34'49"
63	Laduboro # 3 La Baie Yamaska	3017'	919	84°F	29°C	1.45	2.06	2.66	46°10'18"	72°40'40"
65	Laduboro # 5 La Baie Yamaska	4441'	1353	98°F	37°C	1.30	2.07	2.40	46°10'14"	72°40'28"
125	Laduboro C.I.G. # 1 Nicolet	4166'	1270	94°F	34°C	1.29	1.8	2.32	46°11'25"	73°37'30"
*126	Laduboro Q.I.G. # 1 Yamaska	4400'	1341	118°F	48°C	1.77	2.8	3.24	46°09'15"	72°40'42"
134	Québec Natural Gas # 10 St-Vincent-de-Paul	1504'	458	56°F	13°C	1.06	0.6	1.85	45°39'42"	73°38'31"
135	Québec Natural Gas # 11 St-Vincent-de-Paul	1516'	462	58°F	14°C	1.18	0.8	2.05	45°38'34"	73°40'09"
136	Québec Natural Gas # 12 St-Vincent-de-Paul	1474'	449	57°F	14.5°C	1.15	1.0	2.23	45°38'52"	73°39'09"
147	Québec Natural Gas # 2 St-Gérard-Magella	828'	252	54°F	12°C	1.69	0.8	2.98	45°54'33"	73°26'58"
148	Québec Natural Gas # 3 St-Gérard-Magella	856'	261	55°F	13°C	1.7	1.14	[illegible]	45°54'09"	73°26'27"
149	Québec Natural Gas # 15 St-Vincent-de-Paul	1254'	382	58°F	14.5°C	1.4	1.18	2.61	45°39'40"	73°38'34"
150	Québec Natural Gas # 16 St-Vincent-de-Paul	1503'	458	61°F	16°C	1.4	1.3	2.51	45°39'39"	73°38'40"
151	Louvicourt Métal # 8 L'Assomption	2614'	796	72°F	22°C	1.2	1.5	2.19	45°52"46'	73°22'45"
152	Shell St-Simon # 1	8707' 11992'	2654 3655	115°F 156°F	46°C 69°C	0.86 0.96	1.3 1.6	1.56 1.76	45°43'13"	72°48'08"
156	Husky Gentilly # 1	8568'	2611	137°F	58°C	1.13	1.8	2.04	46°21'30"	72°16'46"
*157	Canac B.P. Sisque Brossard # 1	4754'	1449	134°F	56.5°C	1.97	3.2	3.59	45°26'40"	73°29'27"
159	SOQUIP Laduboro Baieville # 1	4280'	1304	99°F	37°C	1.39	2.0	2.49	46°07'43"	72°45'16"

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SNC

No. du puits	Nom du puits	Profondeur pieds	Profondeur mètres	Température °F	Température °C	Gradient °F/100'	Gradient °C/100M Calculé SNC	Gradient °C/100M	Coordonnées	
160	CPOG Sisque SOQUIP Ile d'Orléans # 1	5950'	1813	108°F	42°C	1.14	1.7	2.06	46°58'29"	70°55'25"
161	Shell Ste-Françoise Romaine # 1	8489'	2587	130°F	54.5°C	1.06	1.7	1.93	46°28'25"	71°54'57"
162	Sarep - Laduboro St-Ours # 1	6156'	1876	110°F	43°C	1.13	1.22	2.05	45°52'45"	73°05'30"
163	Shell Wickham # 1	12342'	3761	165°F	74°C	1.	1.70	1.84	45°48'04"	72°25'42"
164	Shell St-Flavien # 1		1209	99°F	37°C	1.5	2.23	2.68	46°39'38"	71°34'08"
165	C.S. SOQUIP Laduboro # 1 (et # 1A) Nicolet	6363'	1939	112°F	44.5°C	1.13	1.78	2.06	46°10'42"	72°37'41"
166	Shell St-Armand ouest # 1	12483'	3804	140°F	60°C	0.82	1.3	1.45	45°04'00"	73°04'00"
167	SOQUIP Shell Ste-Croix # 1	6122'	1865	67°F	19.5°C	0.44	0.5	0.8	46°37'17"	71°42'16"
168	SOQUIP Shell Villeroy # 1	7026'	2141	108°F	42°C	0.96	1.4	1.75	46°27'55"	71°54'06"
169	SOQUIP Shell St-Flavien # 1	8205'	2500	112°F	44.5°C	0.88	1.38	1.6	46°29'24"	71°36'19"
170	C.S. SOQUIP Yamachiche # 1	1447'	441	64°F	18°C	1.65	1.8	3,08	46°17'22"	72°54'06"
173	SOQUIP et al. Villeroy # 2	7266' 7293'	2956 2967	118°F 130°F	48°C 59°C	1.07 1.23	1.2 1.6	1.47 1.83	46°29'47"	71°51'24"
174	SOQUIP et al. Ile d'Orléans # 2								47°00'01"	70°53'18"
175	SOQUIP et al. les Saules # 1	3148'	959	82°F	28°C	2.6	1.8	2.45	46°49'05"	71°20'09"
177	SOQUIP et al. St-Flavien # 2	5947'	1812	98°F	36.5°C	0.97	1.5	1.76	46°30'38"	71°32'48"
178	SOQUIP et al. St-Flavien # 3	5884'	1793	104°F	40°C	1.08	1.6	1.97	46°30'21"	71°36'30"
180	SOQUIP et al. St-Flavien # 4	7321'	2231	109°F	42°C	0.94	1.43	1.68	46°29'42"	71°34'00"
181	SOQUIP et al. Ste-Hélène # 1	1975'	602	73°F	23°C	1.7	2.15	3.07	45°44'12"	72°46'27"
183	SOQUIP et al. St-Flavien # 6	6185'	1885	100°F	37°C	0.97	1.43	1.72	46°31'51"	71°34'47"
185	SOQUIP Dome et al. Bon Conseil # 1	14033'	4277	174°F	78.8°C	0.81		1.48		
186	SOQUIP Nicolet # 1	4541'	1384	92°F	33.3°C	0.70		1.29		
187	SOQUIP et al. Duchene # 1	10413'	3173	210°F	98.8°C	1.44		2.62		

No. du puits	Nom du puits	Profondeur		Température		Gradient			Coordonnées
		pieds	mètres	°F	°C	°F/100'	°C/100M Calculé SNC	°C/100M	
188	SOQUIP Nicolet # 2	4623'	1409	100°F	37.7°C	0.87		1.58	
189	SOQUIP et al. St-Thomas d'Aquin # 1	8259'	2544	133°F	56.1°C	0.88		1.60	
190	SOQUIP Ste-Françoise Romaine # 1	7132	2174	110°C	43.3°C	0.70		1.28	

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ANNEXE 23

ANNEXE 23

Enquête téléphonique sur les températures des eaux de puits à Montréal

- Gulf Oil Canada Limited
  Profondeur 300', température 90°F (probablement erroné)

- Laurentian Spring Water
  Profondeur 500', température 50°F
  N.B.: Ce puits est au voisinage du puits Cadbury-Fry qui est abandonné

- Rolls-Royce Canada (Dorval)
  Profondeur 300', température 41°F

- Seagram Jos E. & Sons Limited
  Profondeur inconnue, température 51°F

- Les autres compagnies ne savent pas ou ne veulent pas communiquer leurs résultats