Argonne National Laboratory

MASTER

Preliminary Feasibility Study

Injection of Radioactive Waste by Hydraulic Fracturing at West Valley, New York

Volume 3 - Appendices

MAY 1978

by

Acres American Incorporated

Buffalo, New York

in association with

Terra Tek Incorporated

Salt Lake City, Utah

The information in this document, prepared in support of a study concerning the Western New York Nuclear Service Center, does not present all the data from which conclusions were drawn. The report, TID-28905, Vols. 1 & 2, Western New York Nuclear Service Center Study, was prepared after reviewing and evaluating this and other studies.

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Preliminary Feasibility Study

**INJECTION OF
RADIOACTIVE WASTE BY
HYDRAULIC FRACTURING AT
WEST VALLEY, NEW YORK**

Contract No. 31-109-38-4238

Volume 3 — Appendices

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Acres American Incorporated
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APPENDIX A - LOG DATA
FROM WEST VALLEY

This appendix contains a summary of the logs of the boring performed at West Valley.

TABLE A-1

SUMMARY OF PERTINENT ROCK CHARACTERISTICS FROM CORE AND GEOPHYSICAL LOGS

<u>Feet below and surface</u>		<u>Description</u>
0	- 169	Soil, glacial drift, and till (driller and personal observation). Contains numerous large boulders and cobbles in a firm matrix of clay and silt.
169	- 175	Shale, weathered.
175	- 356	Shale, medium light gray, medium dark gray and greenish gray, noncalcareous, mostly nonmontmorillonitic, moderately fissile to blocky fracture; interbedded with numerous thin layers (most less than 0.01 ft but some up to 0.1 ft) of medium to coarse-grained siltstone, some of which are calcareous; small-scale angular and erosional disconformities common at the contacts of shale and siltstone layers; also at or near such contacts some crumpling of beds and sharpstone conglomerate indicating penecontemporaneous effects; such contact features constitute lines of weakness and exhibit preferential tendencies toward "bedding-plane" or near-horizontal fracture. Slightly to moderately montmorillonitic 206-21 ft.
356	- 490	Shale, as above but with much less interbedded siltstone; most of these rocks have a tendency toward blocky fracture but some - especially the shale - break readily on bedding planes. Slightly montmorillonitic at 370 ft and 430 ft.
490	- 527	Shale, light gray to medium dark gray, with widely scattered thin beds of siltstone; small-scale disconformities noted at many of the contacts and planes of weakness noted in tension are parallel to the bedding. Slightly montmorillonitic at 518 ft.
527	- 528	Sharpstone conglomerate.
528	- 618	Shale, silty, noncalcareous, nonmontmorillonitic, medium dark gray to dark gray; interbedded with thin layers of light gray to medium gray shaly siltstone, some of which is slightly calcareous; individual beds massive, but tend to fracture parallel to contacts.
618	- 730	Siltstone, shaly, light gray, noncalcareous or only moderately calcareous, nonmontmorillonitic, in thicker beds than above, variously indurated; interbedded with silty noncalcareous and nonmontmorillonitic darker gray shale; an exceptionally calcareous zone with a small septarian nodule noted from 634.5 to 635 ft.

730	-	749	Shale, silty, medium gray, with some slightly calcareous sharpstone at 730 ft; becomes brownish black and petroliferous between 742 and 749 ft.
749	-	771	Siltstone, shaly, mostly gray but containing scatter grayish-black layers; interbedded with silty, non-calcareous, nonmontmorillonitic medium gray shale; small-scale disconformities noted near contacts.
771	-	901	Shale, mostly silty, medium gray, greenish gray and grayish black, nonmontmorillonitic, petroliferous 802 to 803 ft, 864 to 865 ft, and 872 to 874 ft, in general well laminated; fractures parallel to bedding, very pyritic at 815 and 864 ft; at 815 ft pyrite is so common that the rock resembles a conglomerate at first glance; contains scattered very thin siltstone layers, the thickest of which are between 771 and 815 ft.
901	-	901.7	Sharpstone conglomerate.
901.7	-	907	Shale, gray black to brownish black, very petroliferous, noncalcareous, nonmontmorillonitic.
907	-	908	Sharpstone conglomerate.
908	-	910.9	Shale, silty, dark gray to black or brownish black, very petroliferous, noncalcareous, nonmontmorillon well laminated.
910.9	-	913.7	Siltstone, shaly, medium gray.
913.7	-	916.5	Sharpstone conglomerate and poorly bedded shale.
916.5	-	927.7	Siltstone, massive, light gray to medium gray.
927.7	-	934.5	Shale, medium gray to greenish gray, noncalcareous, nonmontmorillonitic, fairly thin bedded.
934.5	-	937.5	Sharpstone conglomerate.
937.5	-	1014	Siltstone, medium gray, mostly shaly but in places fairly coarse-grained, massive-bedded, moderately to very calcareous, nonmontmorillonitic; interbedded with thin layers of dark gray to grayish black, mostly noncalcareous, petroliferous shale; contain sharpstone conglomerate from 955.3 to 955.7 ft.
1014	-	1055	Shale, dark gray to grayish black, noncalcareous, petroliferous, very pyritic and marcasitic 1126.5 to 1127 ft; interbedded with lighter gray siltstone thickest layer 1030.5 to 1032 ft.
1055	-	1055.6	Sharpstone conglomerate.

1055.6	-	1138	Shale, silty, dark to grayish black, moderately petroliferous, noncalcareous, very pyritic and marcasitic 1126 to 1127 ft; interbedded with fine-grained shaly, medium gray, calcareous, nonmonomil-lonitic siltstone; percentage of siltstone decreases with depth to about 1118 ft, but several layers below 1118 ft are 2 to 4 ft thick and massive: small-scale disconformities, both angular and erosional are noted at the contacts of the thickest beds.
1138	-	1139	Sharpstone conglomerate.
1139	-	1144	Shale, greenish-gray, moderately petroliferous; contains numerous pyritic seams; interbedded with light to medium-gray siltstone; small-scale angular disconformities at or near contacts.
1144	-	1149	Sandstone, very fine-grained, silty, and coarse-grained calcareous siltstone, pyritic; interbedded with thin layers of shale.
1149	-	1212	Shale, brownish-gray to grayish-black, mostly very petroliferous, noncalcareous, very thin bedded but massive in appearance in the freshly cut core; interbedded with very thin layers of siltstone - especially between 1171 and 1181 ft; very pyritic and marcasitic 1159 to 1161 ft and 1198.4 to 1200 ft; planar fracture habit parallel to bedding when under tension but rather well indurated.
1212	-	1256.1	Shale, mostly silty, in general less petroliferous than the shale described above but with some thin petroliferous beds, mostly medium gray to olive gray; abundant pyrite and marcasite at 1218.4 and 1238 ft; banding appears related to relative amounts of hydrocarbons present but perhaps also to depositional situation; fairly well laminated; planar fracture habit under tension.
1256.1	-	1257.1	Large calcareous septarian nodule or concretion, having most intersecting internal cracks filled with secondary mineralization.
1257.1	-	1298.1	Shale, medium gray, dark greenish gray and brownish black, noncalcareous, well laminated, very petroliferous 1259 to 1264 ft and 1283 to 1298.2 ft; contains large concretions of pyrite and marcasite between 1270 and 1271 ft and much disseminated pyrite elsewhere; planar fracture habit-parallel to bedding planes, when under tension.
1298.1	-	1299.1	Large calcareous septarian nodule or concretion with filled intersecting internal cracks.

1299.1	-	1307	Shale, noncalcareous, nonmontmorillonitic, silty, well laminated, very petroliferous; interbedded with two siltstone layers about 0.5 ft thick and with scattered very thin light gray siltstone layers; planar fracture habit under tension.
1307	-	1308	Siltstone, medium gray; solid petroleum residues of 1308 ft.
1308	-	1322.8	Shale, noncalcareous, mostly silty, thin bedded, very petroliferous between 1308 and 1311 ft; interbedded with a few very thin scattered siltstone layers.
1322.8	-	1323.8	Large, silty calcareous septarian nodule or concretion having intersecting internal cracks filled by secondary mineralization.
1323.8	-	1340.2	Shale, silty, noncalcareous, medium gray to brownish black, very thin bedded, mostly nonpetroliferous; interbedded with a few very thin light gray siltstone layers.

RHINESTREET SHALE MEMBER:

1340.2	-	1371.7	Shale, black, well laminated, very petroliferous, noncalcareous, very pyritic and marcasitic; contains numerous pyritized septarian nodules; interbedded with thin layers of siltstone; small-scale angular unconformities near contacts of siltstone and shale.
1371.7	-	1447.8	Shale, grayish-brownish black, very petroliferous, mostly noncalcareous and nonmontmorillonitic; in part slightly silty but very few siltstone layers of appreciable thickness (most less than 0.01 ft, however two of 0.1 and 0.2 ft between 1390 and 1391 ft and one of 0.2 ft at 1432 ft); contains 1/2-inch pyritized concretions between 1421 and 1422 ft and finely disseminated pyrite and marcasite on bedding planes between 1428 and 1439 ft; especially calcareous at 1391 ft; good planar fracture habit under tension; well laminated; some banding apparently due to differences in hydrocarbon content; fairly well indurated.
1447.8	-	1449	Large calcareous silty septarian nodule or concretion with only partially filled intersecting internal fractures; small angular unconformities noted in beds above and below this layer.
1449	-	1497.5	Shale, silty, noncalcareous to slightly calcareous, mostly very petroliferous, nonmontmorillonitic; finely laminated; good planar fracture habit under tension but well indurated; interbedded with shaly siltstone layers - especially from 1464 to 1465 ft and from 1482 to 1483 ft; pyritic and marcasitic seams noted especially between 1480.9 and 1481.9 ft and between 1465 and 1468 ft.

APPENDIX B

DETERMINATION OF ELASTIC CONSTANTS FOR TRANSVERSELY ISOTROPIC ELASTIC MEDIA BY ULTRASONIC VELOCITY MEASUREMENT

APPENDIX D - CRITICAL REVIEW OF IN SITU STRESS MEASUREMENT TECHNIQUES

This appendix contains a critical review of in situ stress measurement techniques.

APPENDIX D - CRITICAL REVIEW OF IN SITU STRESS MEASUREMENT TECHNIQUES

Four major techniques have been used by various authors for the determination of one or several principal stress components. In order to appreciate the merits and drawbacks of these methods, a cursory outline of the philosophies of each particular method is given.

(a) Borehole Deformation Meters

Principles

If a circular hole is drilled into rock, the hole deforms according to the applied stresses. The deformation of the borehole can be used to measure changes in stresses in the rock provided the elastic constants of the rock mass are known. Measuring the variation in diameter across three different orientations on overcoring, the secondary principal stresses (i.e. acting perpendicularly to the boreholes axis) can be calculated.

Requirements and Limitations

- (1) If three non-parallel boreholes are not used, and diametral measurements only are made, simplifying assumptions about the stressfield must be made, such as the orientation of the principal stresses.
- (2) Elastic properties must be known.
- (3) Conventional analysis requires assumption of elasticity, homogeneity and isotropy.
- (4) Measurements are usually limited to shallow depths or performed by drilling from an underground access.

(b) Borehole Strain CellsMeasurements at the End of a Borehole

(eg. CSIR Doorstopper)

Strain gauges are attached to the ground and polished end of a borehole. Relief due to overcoring is measured. The major problems are:

- (i) Difficulty of attaching the gauges, particularly under wet conditions.
- (ii) Relating strain relief at the end of the borehole to the stresses in the rock (No theoretical closed-form solution exists for describing the stress concentrations at the bottom of a borehole).

Measurements at the Surface

Some researchers measure strain relief by overcoring strain gauges fastened to outcrop surfaces. There are extreme disadvantages to this method particularly due to temperature effects and the relatively greater ease with which surface strains may have been already relieved.

(c) Fault Plane Solutions and Shallow Structural Features

The seismic trace allows the determination of the focus and the orientation of the principal stresses with respect to a known structural discontinuity. Unfortunately this technique does not permit the determination of the magnitudes of the stress components.

A few authors (Sbar & Sykes, 1973, White & al, 1973) have correlated this trend and plunge of surface features, such as pop-ups, to the direction of the controlling principal stress.

(d) Hydraulic Fracture

Fluid is pumped into an isolated section of a borehole until stress conditions are such that a fracture is initiated and propagated from the borehole wall. Measurement of the fluid pressure at which fracture occurs, the pressure under which the crack extends and the pressure after pumping stops can allow the calculation of some or all of the in-situ stresses.

This technique allows deep stress measurement but does have certain drawbacks among which are:

- (i) Either the tensile strength or fracture toughness of the rock must be known or estimated.
- (ii) Fracturing at shallow depths is generally horizontal or turns to the horizontal. If this is the case, unless two shut-in pressures can be measured (one of which is immediately after breakdown), little can be determined except an estimate of the overburden pressure.
- (iii) Existing fractures may make it impossible to determine a breakdown pressure.
- (iv) Propagation behaviour as affected by rock mass anisotropy is not adequately appreciated.
- (v) Pore pressure and host permeability complicate analysis.

Limitations of Stress Measuring Techniques

Any attempt to categorically determine precise values of the horizontal stresses must be tempered with an appreciation of the limitations of stress measuring techniques. These are briefly highlighted below.

Shallow Measurements

Measurements at shallow depths can be performed relatively cheaply but are particularly susceptible to:

- (i) Diurnal, seasonal etc. temperature fluctuations and near surface thermal stressing.
- (ii) Prominent influence from local topographic features.

Deep Measurements

Measurements at great depths are performed by hydraulic fracturing or are made from existing underground cavities. Interpretation of measurements made in deep mines may in some cases encompass stress concentrations due to the presence of the mine opening. Hydraulic fracture measurements are sometimes difficult to interpret. In fact most calculations to date have been based on a fracture occurring and extending on the basis of a tensile strength criterion. A more appropriate approach is probably to consider the problem from a fracture mechanics point of view, at least for the propagation phase.

APPENDIX E

STRESS MEASUREMENT DATA

APPENDIX E - STRESS MEASUREMENT DATA

This appendix contains a compilation of available stress measurement data for the north-central United States and southeastern Canada.

Reference:

de Laguna, W., Hydraulic Fracturing Test at West Valley, New York,
ORNL-4827, 1972.

Sun, R.J., Morgan, C.E., Hydraulic Fracturing in Shale at West Valley,
New York - A Study of Bedding - Plane Fractures Induced in Shale
for Waste Disposal, Open-file Report 74-365, U.S. Dept. of the
Interior Geological Survey, Dec. 1974.

Location:

West Valley, New York

Measurement Technique:

Hydraulic Fracturing

Measurements:

Depth		P_b		P_{ISIP}		Comments
(ft.)	(m)	(psi)	(MPa)	(psi)	(MPa)	
1450	440	2028 2203 2229	14.0 15.2 15.4	1748 1738	12.1 12.0	Additional Fracturing? $P_o = 403$ psi
1450	440	2328	16.1	1928	13.3	
1226	374	2061	14.3	1431	9.9	
1010	308	1537	10.6	1169	8.1	
500	152					

* Values are bottom-hole pressures

** $P_{ISIP} = \sigma_v$ (neglecting LEFM considerations)

Reference:

Sbar, M.L., Sykes, L.R., Contemporary Compressive Stress and Seismicity in Eastern North America: An Example of Intra-Plate Tectonics, G.S.A. Bul., v. 84, p. 1861-1882, 1973.

(a)

Location:

Nyack, New York

Measurement Technique:

Overcoring

Measurements: (Hooker & Johnson, 1967)

Depth - <50m in diabase

$\sigma_1 = 175 \text{ psi}$ (1.2 MPa) at N2E

$\sigma_3 = 75 \text{ psi}$ (.5 MPa)

(b)

Location:

Gibsonville, Ohio

Measurement Technique:

Overcoring

Measurements: (Rough & Lambert, 1971)

Depth - <50m in sandstone

$\sigma_1 / \sigma_3 = 1.7$

σ_1 at N78E

(c)

Location:

Morgantown, Pa.

Measurement Technique:

Overcoring

Measurements: (Agarwal, R., 1972)

Depth - 700 m (2295 ft.)

 $\sigma_1 = 7400 \text{ psi}$ (51.0 MPa) at N27E $\sigma_3 = 580 \text{ psi}$ (4.0 MPa)

(d)

Location:

Alma Township, N.Y.

Measurement Technique:

Hydraulic Fracturing

Measurements: (Haimson & Stahl, 1969)

Depth - 512 m (1680 ft.)

 $\sigma_1 = 3250 \text{ psi}$ (22.3 MPa) at N77E $\sigma_3 = 2130 \text{ psi}$ (14.7 MPa)

(e)

Location:

Falls Township, Ohio

Measurement Technique:

Hydraulic Fracturing

Measurements: (Haimson and Stahl, 1969)
(Overbey and Rough, 1971)

Depth - 815 m (2680 ft.)

σ_1 = 4050 psi (28.0 MPa) at N64E

σ_3 = 2200 psi (15.0 MPa)

(f)

Location:

Illinois

Measurement Technique:

Hydraulic Fracturing

Measurements: (Haimson & Stahl, 1969)

4 Fractures in a Carbonate Reservoir

Depth - 95 m (311 ft.)

σ_1 = 1100 psi (7.5 MPa) at N62E

σ_3 = 650 psi (4.6 MPa)

(g)

Location:

Bradford, Pa.

Measurement Technique:

Hydraulic Fracturing

Measurements: (Overbey & Rough; 1971)Orientation of σ_1 - N70E

(h)

Location:

Southern Illinois

Measurement Technique:

Fault Plane Solution

Measurements:Thrust Fault

<u>σ_1</u>	<u>Trend</u>	<u>Plunge</u>
-	N85W	15W
-	N80W	15E

(i)

Location:

Blue Mountain Lake, New York

Measurement Technique:

Fault Plane Solution

Measurements:Thrust Fault

σ_1	<u>Trend</u>	<u>Plunge</u>
-	N80E	5W

(j)

Location:

Lake Hopatcong, N.J.

Measurement Technique:

Fault Plane Solution

Measurements:Normal Fault

σ_3	<u>Trend</u>	<u>Plunge</u>
-	N88E	4W

Reference

Aggson, J.R., Report on In-Situ Determination of Stresses, Mather Mine,
Ish-peming Michigan, USBM Progress Report.

Location:

Ish-peming, Mich.

Measurements:

Depth - 3200 ft. (964 m)

$\sigma_v = 2692$ psi (18.5 MPa)

$\sigma_{Hmin} = 3740$ psi (25.8 MPa)

$\sigma_{Hmax} = 4626$ psi (31.9 MPa)

Reference

Roegiers, J.-C. (unpublished)

Location:

Clarendon, N.Y.

Measurement Technique:

Hydraulic Fracturing

Measurements:

Depth - 900 ft. (271 m)

σ_{Hmax} = 822 psi (5.6 MPa) at N63E

Reference:

- (1) McLennan, J.D., Roegiers, J.-C., Stress Conditions Around The Niagara Gorge, Proc. 3rd Symp. Eng. Appl. of Solid Mechanics, Univ. of Toronto, June 1976.

(a)

Location:

Ontario Power Generating Station, Niagara Falls, Ontario.

Measurement Technique:

Overcoring

(Measurements Performed by Dr. K-Y Lo)

Measurements (Representative):

Formation/Member	σ_1		Orientation
	(psi)	(MPa)	
Goat Island Dolomite	2180	15.0	N13E
Gasport Limestone	866	6.0	N16E
Decew Dolomite	1515	10.4	N22E
Eramosa Dolomite	1867	12.8	N12E
Rochester Shale	1610	11.0	N16E
(*) Topographic Control is exerted by the proximity of the Niagara Gorge)			

(b)

Location:

American Falls, Niagara Falls, N.Y.

Measurement Technique:

Overcoring

(Measurements Performed by U.S. Army Corps of Engineers)

Measurements:

Formation/Member	σ_1		Orientation
	(psi)	(MPa)	
Eramosa Dolomite	860	5.9	N40E
Goat Island Dolomite	1500	10.3	N37E

Reference :

Eisbacher, G.H., Bielenstein, H.U., Elastic Strain Recovery in Proterozoic Rocks Near Elliot Lake, Ontario, J.G.R., v. 70, pp. 2012-2021, 1971.

Location:

Elliot Lake, Ontario. 46.24N, 82.41W

Measurement Technique:

Doorstopper

Measurements:

Measurements were made in the basal conglomerate and sandstone units of the Proterozoic sedimentary succession. The maximum stress was approximately parallel to the strike of the joint planes.

Depth		σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}	Comments
(m)	(ft)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)		
300/400	983/1311	1640	11.2	2680	18.4	3120	21.4	E	Southern Limit
300	983	1640	11.2	2970	20.4	5500	37.8	N45E	Northern Limit of
700	2300	2500	17.4	3420	23.5	5500	37.8	E	Quirke Syncline

Reference:

Engelder, T., The Nature of Deformation within the Outer Limits of the Central Appalachian Foreland Fold and Thrust Belt in New York State,
Preprint for Tectonophysics.

Location:

- (a) The Onondaga Limestone in Northwestern New York State
- (b) The Grimsby Sandstone in Northwestern New York State

Measurement Technique:

Measurements of Residual Strain using Surface Overcoring

Measurements:

In general a NNW expansion was observed varying from a maximum of 200 $\mu\epsilon$ in the Grimsby to a minimum of approximately 50 $\mu\epsilon$ in the Onondaga.

Reference

Franklin, J.A., Hunger, O., Rock Stresses in Canada; Their Relevance to Engineering Projects, 25th Geomechanical Colloquy, Salzburg, Austria, Oct. 1976.

(a)

Location:

Mississauga, Ontario

Measurement Technique:

Overcoring

Measurements: (Lo et al, 1975)

In shale

Depth - 11-15 m (36 - 49 ft.)

σ_{Hmax} - up to 6.9 MPa (1000 psi)

Orientation - Variable

(b)

Location:

Pickering, Ontario

Measurement Technique:

Overcoring

Measurements: (Lo et al, 1975)

In shale

Depth - 18-24 m (59-79 ft.)

σ_{Hmax} - Up to 6.9 MPa (1000 psi)

Orientation - Variable

(c)

Location:

Wesleyville, Ontario

Measurement Technique:

Overcoring

Measurements: (Lo et al, 1975)

In Trenton limestone

Depth - 37 m (122 ft.)

σ_{Hmax} - 8.3-13.1 MPa (1200-1900 psi) at 165°

σ_{Hmin} - 4.8-10.3 MPa (700-1500 psi)

(d)

Location:

Quebec City, Quebec

Measurement Technique:

Flatjacks

Measurements: (Roctest, unpublished)

In Canajoharie Shale

Depth - 143 m (470 ft.)

σ_{Hmax} - 7.9 MPa (1145 psi)

σ_{Hmin} - 7.8 MPa (1130 psi)

(e)

Location:

Scarborough, Ontario

Measurement Technique:

Doorstopper

Measurements: (Franklin, 1975)

In Shale

Depth - 70 m (230 ft.)

σ_{Hmax} - 1.7 MPa (250 psi) at 90°

σ_{Hmin} - 1.6 MPa (230 psi)

(f)

Location:

Ottawa, Ontario

Measurement Technique:

Overcoring

Measurements: (Coates & Grant, 1966)

Depth - 15 m (49 ft)

σ_{Hmax} - 2.3 MPa (330 psi)

(g)

Location:

North Bay, Ontario

Measurement Technique:

Overcoring

Measurements: (Coates & Grant, 1966)

Depth - 15 m (49 ft.)

 σ_{Hmax} - 7.6 MPa (1100 psi)

(h)

Location:

Sudbury, Ontario

Measurement Technique:

Doorstopper and CSIR Triaxial Cell (Overcoring)

Measurements: (Herget et al, 1975)

In Metagabbro

Depth		σ_{Hmax}		σ_{Hmin}		Orientation of σ_{Hmax}
(m)	(ft)	(MPa)	(psi)	(MPa)	(psi)	
1220	4000	80.7	11700	38.6	5600	N63E
1710	5600	128.7	18700	100.7	14600	N69E
2130	7000	70.5	11500	61.2	8900	E

(i)

Location:

White Pine, Michigan

Measurement Technique:

Overcoring

Measurements: (Parker et al, 1966)

In Precambrian Shale

Depth - 150 m (492 ft.)

 σ_{Hmax} - 13.8 MPa (2000 psi) at 140° (j) Post Pleistocene Faults

Location	Formation	Rock	Dip	Strike
Claireville, Ontario	Georgian Bay	sh/siltst	17W	360°
Zimmeman, Ontario	Queenston	"	30E	360°
Oakville, Ontario	Queenston	"	54NW	240°
Oakville, Ontario	Georgian Bay	"	70SW	315°

(k) Post-Pleistocene Folds and Pop-ups

Location	Formation	Rock	Azimuth
Toronto Gore, Ontario	Georgian Bay	sh/siltst	70 ⁰
Woodbridge Ontario	"	"	128 ⁰
Oakville, Ontario	Queenston/ Georgian Bay	"	340 ⁰
Burlington, Ontario	Queenston	"	276 ⁰
Oakville, Ontario	Georgian Bay	"	280 ⁰
Chippewa Bay, N.Y.	Potsdam	Quartzite	332 ⁰

Reference:

Haimson, B.C., Stahl, E.J., Hydraulic Fracturing and the Extraction of Minerals Through Wells, 3rd Northern Ohio Geol. Soc. Salt Symp., v. 2, pp. 421-432. 1970.

Location:

Laurel Gas Storage Field, Hocking County, Ohio
(Falls Township) 39.20 N, 81.75 W

Measurement Technique:

Hydraulic Fracturing

Measurements:

3 Fractures in the Clinton Sandstone
Depth - 799 - 817 m (2590 - 2650 ft.)
 σ_{Hmin} - 15.3 MPa (2200 psi)
 σ_{Hmax} - 28.1 MPa at 064 ± 4

Reference

Hainson, B., The Hydrofracturing Stress Measuring Technique - Method and Recent Results in the U.S., Proc. Symp. I.S.R.M., Sydney, Aust., 1976.

(a)

Location:

Gratiot County, Mich.

Measurement Technique:

Hydraulic Fracturing

Measurements:

Depth		Formation	σ_v		σ_{Hmax}		σ_{Hmin}	
(m)	(ft)		(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)
1230	4040	Devionian Amherstburg	4000	27.7	7000	48.0	4300	29.5
2806	9230	Prairie du Chien Dolomite	9150	63.1	8150	56.0	6100	42.0
3660	12020	Mt. Simon Sandstone	12000	82.4	13100	90.0	9000	62.0
5110	16800	Precambrian Red Silty Shale	16700	115.0	19600	135	13800	95.0

(b)

Location:

Montello, Wisconsin 43.80N, 89.33W

Measurement Technique:

Hydraulic Fracturing

Measurements:

5 Fractures were created in Precambrian granite between a depth of 75-188 m (276 - 617 ft.)

$$\sigma_v = 1.9 - 4.7 \text{ MPa (275 - 680 psi)}$$

$$\sigma_{Hmin} = 6.2 - 8.2 \text{ MPa (895-1190 psi)}$$

$$\sigma_{Hmax} = 14.0 - 20.0 \text{ MPa (2030 - 2900 psi) at N63E } \pm 20$$

(c)

Location:

The uppermost part of Oconee County, S. Car. For the Bad Creek Pumped Storage Project, located along the Southeastern edge of the Blue Ridge escarpment.

Measurement Technique:

Hydraulic Fracturing

Measurements:

In Toxaway gneiss.

Values from graph of stress variation with depth.

Depth		σ_v		σ_{Hmax}		σ_{Hmin}	
(m)	(ft)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
150	493	4.5	655	12.5	1810	9.0	1300
175	575	5.5	800	17.0	2460	12.0	1730
200	656	6.0	870	18.0	2610	14.0	2000
250	820	7.0	1000	24.0	3480	17.0	2460

MISCELLANEOUS

(a)

Location:

Immel Mine, Knoxville, Tennessee

Measurements:

Depth - 925 ft. (278 m)

σ_v = 1421 psi (9.9 MPa)

σ_{Hmin} = 1025 psi (7.1 MPa)

σ_{Hmax} = 3481 psi (24.1 MPa) at N58E

Reference

Zoback, M., Healy, J., Interim Reprt on In-Situ Measurements in Clubhouse
Corners #2, Near Charleston, S.C., 1977.

Measurement Technique:

Hydraulic Fracturing

Measurements:

In Lower Tertiary Shale/siltstone

Depth		σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(m)	(ft)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	
194	638	640	4.4	4400	30.3	6900	47.5	N51E
210	690	695	4.8	4680	32.3		?	

Reference:

Jones, A.H., Abou-Sayed, A.S., Rogers, L.A., Rock Mechanics Aspects of MHF Design in Eastern Devonian Shale Gas Reservoirs.

Location:

Lincoln County, West Virginia

Measurement Technique:

Hydraulic Fracturing

Measurement:

Depth	- 2745 ft (824 m)
Overburden Stress	- 3210 psi (22.1 MPa)
σ_{Hmin}	- 2360 psi (16.2 MPa) at N40W to N45W
σ_{Hmax}	- 4390 psi (30.3 MPa) at N45E to N50E

Comments:

"Although it is not known whether or not basement faults penetrate into the Devonian shales in this area, Overbey's measurements (1976) suggest a correlation of principal stress directions with the basement structure. At locations which fall outside the projection of the Rome Trough, the measured directions of σ_{Hmax} are oriented generally east-west and are normal to the predominantly north-south strike of the thrust faults and folds of the Appalachian Mountains. Measured directions of σ_{Hmax} which fall within the projection of the Rome Trough are N45E to N50E, or parallel to the strike of the basement faults and in agreement with the directions reported here."

Reference:

- (1) Abou-Sayed, A.S., Brechtel, C.E., Clifton, R.J., In-Situ Stress Determination by Hydrofracturing - A Fracture Mechanics Approach.

Location:

Rome Basin, West Virginia

Ira McCoy Well 20403

Measurement Technique:

Depth - 837 m (2740 ft.)

(in Upper Gray Zone of Devonian Shales)

$\sigma_v = 3200$ psi (22.1 MPa)

$\sigma_{Hmin} = 2400$ psi (16.3 MPa)

$\sigma_{Hmax} = 4400 - 5600$ psi (30.3 - 38.5 MPa) at N45-50 E

Comments:

- (a) Based on the classical approach of exceeding a critical tensile

stress: $\sigma_{Hmax} = T_o + P_I - P_b - P_o$

- (b) Based on an LEFM approach:

$$\sigma_{Hmax} \cong 3P_I - ZP_b + \frac{K_{IC}}{(\pi L)^{1/2} (0.6)} \quad L/a \ll 1$$

Where:

T_o - Tensile Strength

L - Fracture length

P_I - Instantaneous Shut-in Pressure

a - Borehole Radius

P_b - Breakdown pressure

P_o - Formation Pore Pressure

K_{IC} - Fracture Toughness (Mode I)

Reference

Letter from D.U. Deere to M.H. Wahl of
(Dupont Inc.), Feb. 1970

Location:

In rock underlying the Tuscaloosa Formation (PR7 Hole)
The Savannah River Plant

Measurement Technique:

Hydraulic Fracturing

Measurements:

Depth - 986 ft. (297 m)

$P_b = 2100 \text{ psi (14.5 MPa)}$

$P_p = 2900\text{-}3300 \text{ psi (20-22.8 MPa)}$

Reference

Hooker, V.E., Johnson, C.F., Near Surface Horizontal Stresses Including
The Effects of Rock Anisotropy, USBM, R.I. 7224, 1969.

(a)

Location:

Barre, Vermont 44.2N, 72.50W

Measurement Technique:

Overcoring (2 measurements)

Measurements:

In Barre Granite

Depth - 45 m (251 ft.)

$\sigma_{Hmin} = 0.5 \pm 0.5 \text{ MPa } (70 \pm 70 \text{ psi})$

$\sigma_{Hmax} = 12.0 \pm 8.4 \text{ MPa } (1740 \pm 1220 \text{ psi})$ at $012 \pm 20^\circ$ *

* Reported elsewhere as N14E

(b)

Location:

Rapidan, Virginia 38.32N, 78.07W

Measurement Technique:

Overcoring (5 measurements)

Measurements:

Depth - 8.6 ft. (2.6 m)

$$\sigma_{Hmin} = 9.5 \pm 3.0 \text{ MPa } (1370 \pm 435 \text{ psi})$$

$$\sigma_{Hmax} = 11.6 \pm 1.9 \text{ MPa } (1680 \pm 275 \text{ psi}) \text{ at } N14E \pm 20^*$$

* Reported elsewhere as N6E

(c)

Location:

Proctor, Vermont 43.66N, 73.03W

Measurement Technique:

Overcoring (2 measurements)

Measurements:

Depth - 0.3 m (1.2 ft.)

$$\sigma_{Hmin} = 3.6 \pm 0.4 \text{ MPa } (520 \pm 60 \text{ psi})$$

$$\sigma_{Hmax} = 9.2 \pm 1.8 \text{ MPa } (1330 \pm 260 \text{ psi}) \text{ at } 354 \pm 16^*$$

* Reported elsewhere as N4W

(d)

Location:

St. Peters, Pa. 40.19N, 75.73W

Measurement Technique:

Overcoring (2 measurements)

Measurements:

In French Creek Norite

Depth - 1.4 m (4.6 ft.)

$$\sigma_{Hmin} = 2.3 \pm 0.1 \text{ MPa } (335 \pm 15 \text{ psi})$$

$$\sigma_{Hmax} = 5.9 \pm 0.2 \text{ MPa } (855 \pm 30 \text{ psi}) \text{ at } N10E \pm 4^*$$

* Reported elsewhere as N14E

(e)

Location:

Mt. Airy, North Carolina 36.42N, 80.61W

Measurement Technique:

Overcoring (6 measurements)

Measurements:

In Granite

Depth - 6-16 m (19.7-52.6 ft)

$$\sigma_{Hmin} = 8.2 \pm 3.3 \text{ MPa } (1190 \pm 480 \text{ psi})$$

$$\sigma_{Hmax} = 17.0 \pm 5.1 \text{ MPa } (2470 \pm 740 \text{ psi}) \text{ at } 100 \pm 23^*$$

* Reported elsewhere as N87E

(f)

Location:

Tewksbury, Mass. 42.61N, 71.23W

Measurement Technique:

Overcoring (4 measurements at each depth)

Measurements:

Depth		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(m)	(ft)	(MPa)	(psi)	(MPa)	(psi)	
0	0	1.0	145	3.1	450	N5E
14	46	5.5±1.0	800±145	9.5±1.8	1370±260	N1W±16

(g)

Location:

West Chelmsford, Mass. 42.60 N, 71.50W

(Oak Hill Quarries)

Measurement Technique:

Overcoring (11 measurements between 2 and 77 m (6.5 - 21.2 ft.))

Measurements:

Depth - 61.9 ft. (18.6 m)

 $\sigma_{Hmin} = 7.7 \pm 4.5$ MPa (1100 ± 650 psi) $\sigma_{Hmax} = 14.7 \pm 8.3$ MPa (2140 ± 1200 psi) at N71E ± 27*

* Reported elsewhere as N56E

Reference

Lo, K-Y, Palmer, J.H.L, Lee, C.F., Quigley, R.M., Report on Stress Relief and Time-Dependent Deformation of Rocks, NRC Special Project No. 7307, Dec. 1975.

Location:

Thorold, Ontario

Measurement Technique:

Overcoring

Measurements:

In Limestone

Depth - 62.5 ft. (18.8 m)

$\sigma_{Hmin} = 1200 \text{ psi (8.3 MPa)}$

$\sigma_{Hmax} = 2100 \text{ psi (14.4 MPa) at N58E}$

Reference

Obert, L., In-Situ Determination of Stress in Rock, Mining Eng., Aug. 1962.

Location:

Barberton, Ohio 41.01 N, 81.64 W

Measurement Technique:

Overcoring (U.S.B.M. Deformation Gauge)

Measurements:

In a horizontally bedded limestone (0.6 - 5.5 m thick)

Depth - 700 m (2310 ft.)

$$\sigma_v = 3000 \text{ psi (20.8 MPa)} \text{ } ^{*1}$$

$$\sigma_{Hmin} = 4000 \text{ psi (27.7 MPa)} \text{ } ^{*2}$$

$$\sigma_{Hmax} = 5500 \text{ psi (38.3 MPa) at N77E} \text{ } ^{*3}$$

*¹ Reported elsewhere as 23.5 MPa

*² Reported elsewhere as 24.0 MPa

*³ Reported elsewhere as 45.0 MPa at 90°

Reference

Nichols, T.C. Jr., Savage, W.Z., Brethauer, G.E., Deformation and Stress Changes that Result from Quarrying the Barre Granite of Vermont, Proc. Am. Nuc. Soc., Topical Meeting: Energy and Mineral Recovery Research, Golden Co., April 1977.

Location:

Wetmore and Morris Quarry 44.20N, 72.50W

Measurement Techniques:

USBM Borehole Deformation Gauge

USGS 3-D Borehole Probe

Resistance Strain Gauges

Measurements:

In Devonian Granite

Depth - 0-8m (0-24 ft.)

$\sigma_{Hmin} = 2.56 \text{ MPa (370 psi)}$

$\sigma_{Hmax} = 4.35 \text{ MPa (630 psi) at N40E}$

Reference

Palmer, J.H.L, Lo, K.Y., In-Situ Stress Measurements in Some Near-Surface Rock Formations in Thorold, Ontario. Can. Geotech. J., v. 13, pp. 1-7, 1976.

Location:

Thorold, Ontario

183 m (600 ft.) W of Welland Canal

366 m (1200 ft.) S of Thorold Tunnel

Measurement Technique:

Overcoring (USBM - 3 component deformation gauge)

Measurements:

Formation/ Member	Depth		σ_{Hmax}		σ_{Hmin}		Orientation of σ_{Hmax}
	(m)	(ft)	(psi)	(MPa)	(psi)	(MPa)	
Goat Island	12.5	41.7	1880	13.0	1750	12.1	N27W
"	15.3	51.0	1260	8.7	1260	8.7	
"	15.3	51.0	1310	9.1	756	5.2	N88W
"	15.9	53.1	959	6.6	959	6.6	
"	15.9	53.1	1180	8.1	956	6.6	N82W
Gasport	17.0	56.6	992	6.8	992	6.8	
"	17.0	56.6	1300	9.0	966	6.7	N76E
"	18.1	60.0	2130	14.7	1600	11.0	N60E
"	18.3	61.0	2130	14.7	1620	11.2	N58E
"	19.5	65.0	2000	13.8	961	6.6	N56E
Decew	24.3	81.0	1520	10.5	990	6.8	N60E

Reference

Nichols, T.C. Jr., Deformation Associated with Relaxation of Residual Stresses in a Sample of Barre Granite from Vermont, USGS Prof. Paper No. 875, 32 pp. 1975.

Location:

Wetmore and Morris Quarry

Measurement Technique:

Strain-Relief Overcoring of a Detached cube 22 cm/side

Measurements:

Sample from a depth of 67 m

$$\sigma_{\min} = 3.2 \text{ MPa (475 psi)}$$

$$\sigma_{\max} = 6.3 \text{ MPa (915 psi) at N06W}$$

Reference

Holzhausen, G., Ph.D. Thesis, Stanford U., 1977

(a)

Location:

Fletcher Quarry, Westford Township,
Middlesex County, Mass. 71°25'W, 42°32'N

(a) Measurement Technique:

Mechanical Extensometers

Measurements:

Depth		σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(m)	(ft)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
15	49	0	0	0	0	55	8000	N45E
18	59	0	0	0	0	49	7100	N35E

* The foregoing results are influenced by stress concentrations associated with the quarry geometry.

(b) Measurement Technique:

Overcoring of Surface Bonded Strain Gauges

Measurement:

In Chelmsford Granite at 60 m below the original ground surface.

σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
0	0	21	3050	36	6220	N48E
0	0	27	3920	42	6100	N44E
0	0	24	3470	35	5060	N46E

(b)

Location:

Val Stone Quarry, Westford Township, Mass.

71°26'W 42°38'N

Measurement Technique:

Overcoring of strain gauges cemented to surface

Measurements:

In Chelmsford granite, on quarry floor - 5 m below original ground level.

σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
0	0	14.0	2030	17.5	2540	N59E
0	0	12.5	1810	16.5	2400	N64E

(c)

Location:

Lomasurier Quarry

Measurement Technique:

(as above)

Measurements:

σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
0	0	18.0	2620	24.0	3480	N8E
0	0	15.5	2250	19.5	2830	N84E

* Measurements perturbed by quarry geometry

(d)

Location:Snake Meadow Hill, Mass. $71^{\circ}28'30''W$, $42^{\circ}36'N$ Measurement Technique:

Overcoring of Surface Bonded Strain Gauges.

Measurements:

σ_v		σ_{Hmin}		σ_{Hmax}		Orientation of σ_{Hmax}
(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
0	0	24.5	3550	27.5	4000	N16E
0	0	18.0	2600	28.5	4120	N6E
0	0	22.0	3200	28.0	4060	S22E

APPENDIX F

HYDRAULIC FRACTURING MEASUREMENTS: WEST VALLEY, NEW YORK

APPENDIX F - HYDRAULIC FRACTURING MEASUREMENTS:
WEST VALLEY, NEW YORK

This appendix contains a discussion of the hydraulic fracturing measurements performed at West Valley.

TEST ONE

Date: October 9, 1969.

Depth: 1450 feet

Rock Description: At this level, the rock is well-bedded petroliferous shale, qualitatively classified as being FAIR for the formation of horizontal fractures. A zone of vertical joints was geophysically detected from 1440 ft. to 1450 ft.

Injection History: Injection started at a very low rate (a very few gpm).

The injection pressure increased rapidly. After 22 minutes the wellhead pressure was 1400 psi and flow was detected on the flow meter. The injection wellhead pressure dropped to 1040 psi and increased to 1100 psi as the pumping rate sped up to 16.5 gpm. The rate was then slowly increased to 30 gpm with no detectable increase in the injection pressure. Increasing the rate to 50 gpm led to an increase in wellhead pressure to approximately 1400 psi. The elapsed time to this stage was about 1 hr. Next a regular pumping schedule was established. Flow rates were maintained at 100, 200 and 400 gpm successively, each rate being held for one-half hour. This pattern was systematically repeated. After 6 hours and the injection of 59000 gal. of water, pumping was stopped for 45 minutes at which time it resumed with the regular injection pattern (beginning at 400 gpm). Pressures were consistently higher, especially at rates of 200 and 400 gpm. After

588 min. and the injection of 114,282 gal. of water the well was shut in and pressure decay was measured for eight days subsequent to this.

Figure F-1. Variation of Bottom-hole Pressure
with Elapsed Time

Critical Pressures:

Pressure (psi) ^{*1}	Injection Rate (gpm)	Elapsed Time (min)
2028	trace	22
2203	100 gpm	68
1748 ^{*2}	0	332
2229	400 gpm	379
1738 ^{*2}	0	588

*1 - Bottom-hole pressure

*2 - instantaneous shut-in pressure

The Influence of Flowrate:

Assuming that flow through the fracture is laminar and obeys Darcy's Law, the injection pressure at the well should be linearly proportional to the injection rate. On this basis, using linear regression, Sun found:

$$P = 1735 + 0.22 Q \quad (1)$$

where:

P - Bottomhole injection pressure (psi)

Q - Injection rate (gpm)

After the 45 minute pause:

$$P = 1735 + 0.55 Q \quad (2)$$

Estimation of Tensile and Cohesive Strength:

Sun differentiates between the tensile strength in the vertical direction of the "intact" rock (T_z) and the cohesive strength resisting extension of an existing fracture ($f \cdot T_z$).

An estimate of the overburden pressure is:

$$\sigma_z = 1581 \text{ psi} \quad (3)$$

(This is based on the specific gravity and vertical extent of the overlying material.) A horizontal fracture allegedly will be initiated if:

$$P_b \geq \sigma_z - T_z \quad (4)$$

where:

P_b - Breakdown Pressure

σ_z - Calculated Overburden Pressure

T_z - Tensile Strength (considered negative)

(a) For $P_b = 2028 \text{ psi}$ (bottomhole)

$$T_z = 1581 - 2028 = \underline{-447 \text{ psi}} \quad (5)$$

$$fT_z = \sigma_z - P_{isip} \quad (6)$$

where P_{isip} - Instantaneous Shut-In Pressure
(Bottomhole, psi)

(b) After injection of 700 gals a second breakdown occurred at 2203 psi suggesting the formation of additional fractures. For $P_b = 2203 \text{ psi}$, $T_z = \underline{-602 \text{ psi}}$.

- (c) After the 45 minute break in pumping $P_b = 2229$ psi and
 $T_z = -568$ psi.

Analysis of Pressure Decay Curves:

The groundwater level at the injection well is at a depth of approximately 80 ft. Consequently, the formation pore pressure, P_o , at a depth of 1450 ft. is:

$$P_o = .4331 (1450 - 80) = 593 \text{ psi} \quad (8)$$

A log-log plot of $P - P_o$ versus t (time) shows two straight lines intersecting at 450 minutes, a point corresponding to $P - P_o = 980$ psi.

If there is more than one discontinuity on a plot of this nature it may indicate more than one set of directional fractures.

For $P - P_o = 980$ psi and $P_o = 593$ psi the fracture pressure at shutin is $980 + 593 = 1573$ psi which is very close to the estimated overburden pressure of 1581 psi. This would tend to indicate a horizontal fracture, although it does not preclude the possibility of the opening of existing vertical joints.

TEST TWODate: June 25, 1970Depth: 1450 ft.Rock Description: As for test one.Injection Fluid: 112,250 gal. of radioactively tagged water.

Injection History: Pumping started slowly, increasing consistently to 300 gpm after 150 min. Breakdown apparently occurred at 2328 psi (1700 psi at wellhead) at a slow rate of injection, after 13 minutes. Following breakdown, the injection rate was increased to 34 gpm and maintained at this value for 70 minutes. With an additional increase in the injection rate the bottomhole pressure rose and peaked at 3516 psi with $Q = 160$ gpm. This peak may manifest the formation of additional fractures. After 300 minutes the pressure stabilized around 2000 psi and an injection rate of 285 gpm.

Figure F-2. Variation of Bottom-Hole Pressure
with Elapsed Time

Critical Pressures:

Pressure (psi) *1	Injection Rate (gpm)	Elapsed Time (min)
2328	very slow	37
2548	34	38
3516	160	113
1928 *2	0	569

*1 - Bottom-hole pressure

*2 - Instantaneous shut-in pressure

The Influence of Flowrate:

$$P = 2024 + 2.05 Q \quad (9)$$

Before this second injection at 1450 feet a residual pressure of 150 psi was measured at the wellhead, suggesting a residual pressure in the fracture of $150 + 1450 \times .4331 = 778$ psi.

Estimation of Tensile and Cohesive Strength:

For $P_b = 2328$ psi, T_z is calculated to be 562 psi and for $P_s = 1928$ psi, f is calculated to be 0.29.

Analysis of Pressure Decay Curves:

Calculated Overburden Stress - $\sigma_z = 1581$ psi

Overburden Stress Estimated from log-log plot of

$$P - P_o \text{ versus } T \quad - \quad \sigma_z = 1513 \text{ psi}$$

Observation Wells (Gamma Ray Activity)

Well	Horizon where Activity Detected	Comments
North	1430'-1450'	(maximum of ~ 6000 API GR _{max}) (measured 10 days after injection)
West	1440'-1460'	(maximum of ~ 4000 API GR _{max}) (measured 10 days after injection)
North	Approximately same	(measured after 2 months)
West	"	"
South	1450'-1470'	" (~ 1600 API GR _{max})

TEST THREE

Date: August 17, 1970

Depth: 1226 ft.

Rock Description: At this level, the rock is thin-bedded shale interbedded with very thin layers of siltstone. Cores and geophysical logs showed joints at this horizon. There is a silty shale a few feet below the injection depth. The thin-bedded shale has been categorized as GOOD for the formation of horizontal fractures.

Injection Fluid: 90,600 gal. of radioactively tagged water.

Injection History: Injection started at a very low rate and gradually increased to nearly 230 gpm in 100 minutes. Breakdown occurred quickly (after 4 minutes) at 1500 psi after which time the pressure dropped to between 800 and 900 psi, which was maintained for the remainder of the test.

Figure F-3. Variation of Bottom-hole Pressure
with Elapsed Time

Critical Pressures:

Pressure (psi) *1	Injection Rate (gpm)	Elapsed Time (min)
1931	slow	4
2061	17	5
1431 *2	0	457

*1 - Bottom-hole pressure

*2 - Instantaneous shut-in pressure

The Influence of Flow Rate:

$$P = 1435 + 0.10 Q \quad (10)$$

Estimation of Tensile and Cohesive Strength:

σ_z (calculated) - 1329 psi

T_z (calculated) - -602 psi

for $P_b = 1931$ psi

T_z (calculated) - -624 psi

for $P_b = 2061$ psi

f - 0.18

Analysis of Pressure Decay Curves:

P_o (calculated) - 496 psi

This plot displayed two discontinuities.

First Discontinuity

t - 82 min

$P_A - P_o$ - 880 psi

P_A - $880 + 496 = 1376$ psi (as compared to σ_z (cal.)
= 1329 psi)

Second Discontinuity

t - 6600 min

$P_B - P_o$ - 580 psi

P_B - $580 + 496 = 1076$ psi

Comments

P_A probably indicates the closure of a horizontal fracture while P_B may be the least horizontal stress normal to the walls of a joint(s).

Observation Wells (Gamms Ray Activity)

In general, the wells indicated flow along bedding planes through a zone approximately 5 feet thick. However, the south wall showed activity spreadover a zone nearly 60 feet thick, suggesting joint travel at least in the vicinity of this well.

TEST FOUR

Date: May 10, 1971

Depth: 1010 ft.

Rock Description: The rock at this level is massive bedded shaley siltstone interbedded with thin layers of shale, classed as POOR for the formation of horizontal fractures.

Injection Fluid: 98,700 gal. of radioactively tapped water.

Injection History: For the first several minutes pumping was at a low rate. Within 10 minutes, however, the pumping rate had been increased to 300 gpm. The injection rate was held at 350 gpm during the remainder of the fracturing operation. The pressure went up to 1537 psi (P_b - bottom hole) and fell to between 800 and 850 psi which was maintained.

Figure F-4. Variaton of Bottom-Hole Pressure with Elapsed Time

Critical Pressures:

Pressure (psi) *1	Injection Rate (gpm)	Elapsed Time (min)
1537	0	3
1169 *2	0	300

*1 - Bottom-hole pressure

*2 - Instantaneous shut-in pressure

Estimation of Tensile and Cohesive Strength

For σ_z (calc.) = 1085 psi and $P_b = 1537$ psi... T_z is calculated to be -425 psi. For $P_s = 1169$ psi, f is calculated to be .18.

Analysis of Pressure Decay Curves

"A close examination of the pressure data indicates that the injection pressure needed to overcome the fractional loss of one unit of injection rate between 10 and 245 min is only 60% that during the period after 245 min. Therefore, it can probably be concluded that there was injection into two different fracture systems". (Sun and Mongan, 1974)

P_o (calculated) - 403 psi

The log-log plot of $P - P_o$ versus t consisted of three straight line segments.

At the First Discontinuity:

$t = 6$ min

$P_A - P_o = 665$ psi

$P_A = 1068$ psi which corresponds closely to the estimated overburden stress of 1085 psi indicating that at least part of the fracture system was probably horizontal.

At the Second Discontinuity:

$$t = 7600 \text{ min}$$

$$P_B - P_o = 305 \text{ psi}$$

$P_B = 708 \text{ psi}$ which may be the value of the least horizontal stress normal to the joint walls (implies $\sigma_{Hmin}/\sigma_z = .43$)

Observation Wells (Gamma Ray Activity)

Well	Description
West	Single small peak at 1014'
North	Single small peak at 1008'
South	Single small peak at 1009'
*East	Single small peak at 1001' and large peak at 1395' (1375' according to Sun and Morgan)

de Laguna attributed the usual situation in the east well to ... "The injection had fractured vertically downward from 1010 ft. to 1395 ft., and then had turned horizontal and had moved out to the east."

Sun and Mongan dispute de Laguna's claim on the basis of:

- (i) The difficulty in inducing a 375 foot vertical fracture in such an anisotropic medium unless numerous vertical joints (few of which were seen in the core or logged in the hole) were present.
- (ii) The inherent difficulty for a vertical fracture to propagate downward.

(iii) In order to propagate a horizontal fracture at 1395' the pressure must exceed the overburden pressure (1500 psi). Observed bottomhole pressures were never over 1500 psi except during the first four minutes.

Sun and Morgan argue for contamination of the east hole due to the poor integrity of the casing of this hole.

TEST FIVE

Date: May 29, 1971

Depth: 500 ft.

Rock Description: The rock at this level is thin-bedded silty shale interbedded with siltstone. It is classified as GOOD for the formation of horizontal fractures.

Injection Fluid: 51,000 gal. of water

Injection History: The pumping rate was low for the first 60 min., after which time it was increased to 450 psi. Breakdown was at 617 psi.

Figure F-5. Variation of Bottom-hole Pressure Elapsed Time

Critical Pressures:

Pressure (psi) *1	Injection Rate (gpm)	Elapsed Time (min)
617	0	0
629	278	135
551 *2	0	225

The Influence of Flowrate:

$$P = 563 + 0.10 Q \quad (B-11)$$

Estimation of Tensile and Cohesive Strength:

For σ_z (calc.) = 511 psi and $P_b = 617$, T_z (calc.) = -106 psi

For $P_s = 551$ psi, $f = .49$

Analysis of Pressure Decay Curves:

The stress calculated normal to the fracture using this technique is 499 psi which compares favourably with the estimated overburden stress of 511 psi.

TEST SIXDate: July 23, 1971Depth: 500 ft.Rock Description: Same as Test FiveInjection Fluid: Water and then grout, 41,000 gal.

Injection History: There was no clearly defined breakdown during the early part of injection probably because the existing fracture was merely being inflated. Most of the pumping was at well-head pressures between 325 and 350 psi. Higher pressures at later stages of pumping probably reflect the information new fractures.

Figure F.6. Variation of Bottom-Hole Pressure with Elapsed Time

Critical Pressures:

$$P_s = 580 \text{ psi (bottom hole)}$$

Low pressure during the latter part of the injection in some cases lower than P_s would suggest the possibility of the fluid entering open joints.

Observation Wells (Gamma Ray Activity)

A zone (15 ft.) of bedding plane fractures formed at least within a radius of 150 feet from the injection well.

REFERENCE

Sun, R. J. and C. K. Morgan, 1974, "Hydraulic Fracturing in Shale at West Valley, New York, A Study of Bedding Plane Fracture Induced in Shale for Waste Disposal, USGS. Open File Report 74-365.

APPENDIX G

ENHANCEMENT OF HORIZONTAL CRACK INITIATION BY JETTING

APPENDIX G - ENHANCEMENT OF HORIZONTAL CRACK INITIATION BY JETTING

This appendix contains a description of the methods for horizontal crack enhancement initiated by the jetting technique.

HORIZONTAL CRACK INITIATION ENHANCEMENT BY JETTING

Sand slurry jetting has been used in recent years to perforate casing or notch formations in special circumstances where it is needed.

Abrasijet^{*} service consists of pumping a fluid containing an abrasive solid against the surface of a desired downhole target. Pumped through specially designed jets under high differential pressure, the solids-laden fluid cuts away the target (casing, cement, formation, scale or debris) as the erosive jet stream impinges against the target.

The fluid and abrasive solid used in abrasijet service is dependent upon job design. The fluid is generally chosen to be compatible with the formation and can be gelled or ungelled water, acid, light oils, etc. Round 20-40 mesh sand is commonly used as the abrasive solid; however cutting rates can be slightly improved with sub-angular sand.

The principal applications for abrasive jetting are perforating, casing and open-hole jetting for clean up, under-reaming, cutting casing, and initiating fractures.

Open hole jetting can be used to under-ream, as shown in Figure G-1, to selectively stimulate production in open hole completions that have alternate barren and oil-bearing intervals.

FIGURE G-1

*Dowell Trademark

An obvious application for abrasive jetting is cutting casing for removal or in conjunction with fracturing operations to initiate fractures (Figure G-2). By rotating the jet gun while forcing the sand-laden jet stream through the orifices, casing can be cut cleanly and easily. When making horizontal cuts, a rotating hydraulic hold-down is generally recommended to eliminate vertical movement of the tubing string during the cutting operation. Vertical slots can be obtained by moving the tubing vertically in one-inch increments.

A fracture can be selectively initiated in casing or open hole by obtaining a cut into the formation which weakens the particular zone of interest, thus making it more susceptible to fracturing. In addition, breakdown pressures are generally reduced when the fracture is first initiated by abrasive jetting.

FIGURE G-2

Essentially, the gun used for abrasijet service consists of a steel case containing jet orifice inserts of special abrasive-resistant material. Different tools with various diameters, in both single and two-stage types, are

available with different orifice spacings. The tool shown in Figure G-3 is a conventional single stage gun with four jets in one horizontal plane. This tool can be modified to perforate from one to four holes at a time, as required. The single stage gun can be made up in tandem or series to form almost any jet pattern desired.

The jet gun is normally attached to the bottom of tubing or drill pipe and lowered to the desired depth. The sand-fluid slurry is then pumped down and out through the orifices. The power required to perform this work is supplied to the sand-laden fluid by high-pressure pumps through the orifices to the casing or formation against which the jet stream impinges. The force of the jet is held constant, increased or decreased, by controlling the differential in the bottom of the gun or series of guns and sealed by a ball during the jetting operations. This opening is used to reverse circulate sand from the hole after jetting is completed.

FIGURE G-3

The two-stage gun is used when a large number of cuts are to be made and when cutting time will exceed the life of one set of jets. There are special pump down guns available for use so that abrasive jetting can be applied effectively and economically to all types of wells. In use, the gun is dropped or pumped down the tubing and lands on a standard seating nipple. Dropping a ball closes the bottom of the tool and jetting can be performed through two orifices. The tool is removed from the well by reverse circulation or by wireline.

Abrasijet service can also be used in tubingless completion wells employing 2-inch or 2- $\frac{1}{2}$ inch tubing as casing. A 1- $\frac{1}{2}$ inch O.D. jetting gun run on 1-inch or 1- $\frac{1}{2}$ inch tubing has been applied to a number of wells. One application used this small gun successfully to perforate into the formation through 2-inch tubing that had been cemented in 4- $\frac{1}{2}$ inch casing.

Positioning an abrasive jet gun in the hole at the proper depth is most important if a successful job is to be performed. In addition, the motion of a string of tubing (due to changes of temperature and pump pulsation) and stretch (due to pressure) must be recognized and allowed for in placing the jetting tool at the desired location. Once all the variables have been determined and the tool properly placed, every effort should be made to maintain the exact predetermined surface pressure throughout the treatment. This will help prevent the tubing from stretching and contracting and moving the tool out of position. This is very important in deep wells, provided a hold-down tool is not used.

Figure G-4 and G-5 are illustrations of a job hook up which illustrates how a typical abrasijet job is performed and, more importantly, how the gun can be

placed and held in the proper position. The collar locator is one method to accurately determine the depth of the tool. The hold-down tool (swivel or rotating type) should be used to prevent any up and down movement during all horizontal notching operations. It is also useful when perforating if later stimulation treatments are designed to use perforation ball sealers. Generally, this motion is not desirable in any actual casing cutting work since it would require more metal to be removed from the casing.

Up and down movement of the tool is normally present when a hold-down tool is not used. This movement is a result of the pulsation of the surface pumping unit. In perforating, this motion becomes helpful if penetration alone is desired. The motion of the tool will make an elliptical hole in the casing which results in easier return of the fluid from behind the pipe. This minimizes stream break-up and increases penetration as well as penetration rate.

FIGURE G-4

FIGURE G-5

- (1) Swivel
- (2) Power tongs set to rotate @ 4 RPM
- (3) Manual slips
- (4) Rotary Bearing
- (5) Huber Head w/wiper rubber

The standard abrasijet tools and service available from Dowell are capable of performing the type work described above.

Communication with Dowell personally indicated that the typical operating conditions that would be expected in a properly designed system is as follows:

Nozzles - Two 3/16" diameter
Sand - 20/40 mesh
Sand Concentration - 1½ lb./gal.

Fluid - gelled water
Pressure Differential - 3000 psi @ nozzle
Flow Rate - 58 gpm each nozzle
Horse Power - 235
Operating Time - 30 minutes

Total requirements per notch would be approximately 100 barrels gelled water and 5000 pounds of sand. Additional water and time would be required for flushing.

In accordance with their work experience, they do not recommend the above described system for creating a deep notch unless the following conditions are met:

1. 5½ Casing size minimum
2. Compressive strength of formation not greater than 10,000 psi.

Smaller casing does not provide enough diameter to properly control fluid flow conditions, internal to the gun, nor the use of nozzles designed to be effective at several inches stand-off. Rock having a compressive strength above 10,000 psi has been found to erode very slowly, particularly when subject to hydrostatic back-pressure by fluid in the annulus.

Some basic statistical information from past testing programs are illustrated in Figures G-6, G-7 and G-8 to assist in the evaluation of the use of the jetting system

Figure G-6 is a typical time vs. penetration curve on sandstone. Approximately 15 seconds is required for the jet to pierce the casing wall.

Figure G-7 shows the effects of hydrostatic back pressure vs. penetration. The tendency of penetration to decrease with increasing back pressure is clearly shown. The effect of fifty feet of head is almost as significant as that of 5000 feet.

Figure G-8 illustrates the effect of compressive strength of a rock vs penetration which illustrates the rate of rock failure between different types of rocks.

It is concluded that the jetting technique can be used in formation slotting to assist in initiation of horizontal hydrofractures. It should be emphasized, however, that further interaction may be needed with Dowell prior to job performance.

APPENDIX H

DESCRIPTION OF FINITE ELEMENT PROGRAM FOR ANALYSIS OF CRACK PROPAGATION

APPENDIX H - DESCRIPTION OF FINITE ELEMENT PROGRAM FOR ANALYSIS OF CRACK PROPAGATION

This appendix contains a description of the finite element program for analysis of crack propagation and isotropic test cases used in this study.

H-1 - Program Description

The original version of the Finite Element Model used for the analysis of crack propagation for this study was developed by Vanderglas (1977). This code was extended at Acres to include material property anisotropy, as described below.

The program may be divided into two sections. The first is a stress analysis by finite elements and the second is a computation of the energy release rates for crack propagation.

The stress analysis program is formulated for 2-D static elastic (transversely isotropic) problems in plane stress or plane strain. The normal to the plane of isotropy may be rotated in the analysis. Five material properties are required: E_1 , E_3 , ν_{12} , ν_{13} and G_{13} where 3 is the normal direction.

The elements available are the basic isoparametric 8-noded quadrilateral and degenerate 4-, 6- and 7-noded quadrilaterals formed by deleting nodes from the basic 8-noded element. Other elements, a constant strain triangle and Rice and Tracy's crack tip triangle, were deleted from the code when anisotropy was added. The crack tip stress singularity is approximated by moving the mid-side nodes to the quarter point nearer the crack tip. A true singularity in stress occurs at the tip itself and the distribution away from the tip resembles the true one. This has been found to be efficacious in simulating the singularity and facile in its simplicity (Vanderglas, 1977; Ingraffea et al, 1977).

At nodes, zero displacements and loads may be specified in the coordinate directions.

An accelerated relaxation solver is employed with limits set on the number of solution passes and a tolerance on the

residuals (unbalanced loads) at nodes. Only nonzero matrix terms are stored and the solution is performed entirely in core storage.

Output includes all input data, solver characteristics, nodal displacements, stresses (x-y and principal) and strains (x-y) at selected points, reactions (and residuals) and applied and strain energies.

The crack propagation computation involves the determination of G_x and G_y by the stiffness derivative method. Two coordinate virtual displacements are given to the crack tip and the resultant values of G are summed over a contour of elements. Vanderglas compares this and several other methods of computing G 's and finds this the most accurate, as well as simple in its execution. A particularly elegant feature of this method is that it is effective for material anisotropy as well, since the properties are handled implicitly in the calculation. $G(\delta)_{\max}$ and $\delta_{\max}$ are also evaluated. The complex criteria involving the anisotropy of fracture toughness are evaluated outside the program at present.

H-2 - Isotropic Test Cases

Isotropic test cases were devised using elastic properties and loads which are representative of the West Valley site. The mesh was identical to that used for the anisotropic cases tested.

The pseudo-isotropic elastic properties, as presented in Table G.1, were determined by averaging the wave velocities used for determining the anisotropic properties at each depth.

The overall average properties as presented were used in the following tests.

A nominal depth of 400 m (1,320 ft) was used, giving σ_V of 1,000 MPa (.025 MPa/m = 1.1 psi/ft).

Table G 2 shows the test cases run and the results determined for G_V , G_H , G_1 and G_2 , the energy release rates in the directions as shown in Figure 5.3. (Volume II). The results presented span the points at which G_1 turns positive and crack extension proceeds.

TABLE H-1 - PSEUDO-ISOTROPIC
ELASTIC PROPERTIES

Nominal Depth ft	E		v
	10 ⁶ psi	MPa	
850	5.6	38,600	.23
1,250	4.3	29,700	.23
average	4.93	34,000	.23

TABLE H-2 - TEST CASES AND ENERGY
RELEASE RATES

Case No.	σ_V MPa (psi)	σ_H MPa (psi)	p MPa (psi)	G_V Pam	G_H Pam	G_1 Pam	G_2 Pam
1 (a)	10 (1450)	11 (1595)	11.2 (1624)	-1431	- 118	-1435	- 189
1 (b)	10 (1450)	11 (1595)	12 (1740)	2135	86	2137	21
2 (a)	10 (1450)	16 (2320)	16.5 (2393)	-1843	750	-1803	- 841
2 (b)	10 (1450)	16 (2320)	17 (2465)	1400	867	1442	- 796
3 (a)	10 (1450)	21 (3045)	21.2 (3074)	-7261	1576	-7173	-1937
3 (b)	10 (1450)	21 (3045)	22.5 (3263)	3835	1864	3923	-1670

Table H-3 gives summary data for the three cases, presenting critical p for which G_1 turns positive, and the P intercepts and slopes for the various G 's in this region.

In all cases crack propagation occurs when p equals 1.05 times the normal stress (approximately σ_H). Theoretically, for an elliptical crack this point should occur at $p/\sigma_n = 1.0+$ or p slightly exceeding the normal stress for low G_c .

For cases 1, G_1 turns positive marginally before G_H , indicating a tendency to tangential crack extension (along the existing crack) for low σ_H/σ_v (equals 1.1) in the model. Theoretical results predict that near-horizontal cracking should occur for $\sigma_H/\sigma_v > 1.0$ and $p/\sigma_n = 1.0+$ for low G_c . Cases 2 and 3 agree with the theoretical, G_H turning positive well before G_1 (initiation of crack extension) indicating near-normal (horizontal) crack extension for larger σ_H/σ_v (1.6 to 2.1). The value of σ_H/σ_v above which the model predicts horizontal cracking is 1.12, by interpolation of results (which are quite linear). Tendency towards horizontal cracking for $\sigma_H/\sigma_v > 1$ is reproduced in the model.

The theoretical results for this comparison are for an elliptical crack. Since we have in this numerical model only one crack tip and the boundary conditions do not exactly correspond to the theoretical, the agreement of model and analytical results are found satisfactory.

TABLE H-3 - SUMMARY ISOTROPIC
PROPAGATION RESULTS

Case No.	P critical (MPa) ($G_1 = 0$)	P for $G = 0$ intercept $dG/dP (\mu m)$ for			
		G_V	G_H	G_1	G_2
1	11.52	11.52	11.66	11.52	12.67
		4458	255	4465	-31
2	16.78	16.78	13.30	16.78	25.84
		6486	234	6490	90
3	22.04	22.05	13.95	22.04	30.48
		8523	218	8523	209

REFERENCES

- Ingraffen, A. R., Henze, F. E., Ko, H. Y., and Gerstle, K. 1977, "An Analysis of Discrete Fracture Propagation in Rock Loaded in Compression" 18th U.S. Symposium of Rock Mechanics, pp A2-1 to A2-7.
- Vanderglas, M.L. 1977, "Finite Element Analysis of Two and Three Dimensional Elastic Cracks" (thesis), University of Waterloo, Ontario.

APPENDIX I

WELL DATA

APPENDIX I - WELL DATA

This appendix contains water well data from selected wells in the West Valley area.

TABLE I-1

WATER WELL RECORDS OF SELECTED WELLS IN THE WEST VALLEY AREA (Abstracted from Erie-Niagara Basin, Groundwater Resources - Table 6)

Well number: See text for explanation

Year completed: a - about
b - before

Type of well: Drl - drilled
Drv - driven

Depth of well: All depths below land surface.
a - about
r - reported
all others measured

Diameter of well: Diameters of dug wells are approximate.
Where two or more sizes of casings were used, they are shown
in descending order.

Depth to bedrock: All depths below land surface
a - about
m - measured
all others reported

Water-bearing material: Gravel, sand, silt, and till - glacial deposits of
Pleistocene age.
Camillus Shale - Camillus Shale of Silurian age.
Limestone - limestone unit consisting of the Onondaga Limestone of
Devonian age and the Bertie Limestone and Akron Dolomite of
Silurian age.
Lockport Dolomite - Lockport Dolomite of Silurian age.
Shale - Hamilton Group and Conesus Group of Chadwick (1934) and
intervening units, all of Devonian age.

Altitude above sea level: Estimated from topographic maps to nearest 5 feet.

Water level: All water levels are below land surface except those preceded by a (+) sign,
which are above land surface.
a - about
p - pumping effect is probable
Flow - water flows above land surface but static head could not be measured.
r - reported
all others measured by U.S.G.S. personnel

Method of lift: AL - air lift
Dw - deep well cylinder pump
Jet - deep well jet pump
Sub - submersible pump
Sw - shallow-well pump
Tur - turbine pump

Type of power is indicated as -- I - internal combustion engine
M - manual
all others are electrically powered

Estimated pumpage: Average daily pumpage supplied by owner, tenant, or operator, or computed
on basis of per capita consumption of 50 gpd per person or 20 gpd per
milk cow.

Use: A - abandoned In - institutional
Ag - agricultural Ir - irrigation only
C - commercial PS - public supply
D - domestic T - test
F - dairy farm U - unused
GT - gas test X - destroyed
I - industrial

Remarks: anal - chemical analysis in this report
dd - drawdown
est - estimated
gas - flammable gas issues from well
gpd - gallons per day
gpm - gallons per minute
H₂S - hydrogen sulfide gas present in ground water
iron - water has noticeable iron content
LS - land surface
OW - observation well, series of water-level measurements available
r - reported
swl - static water level
temp - temperature, in degrees Fahrenheit, measured by U.S.G.S. on same day water
level was measured unless otherwise noted

*Wells relevant to this report

Table I-1 (Cont'd)

Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
										Below land surface (feet)	Date				
217-851-1	Cattaraugus	T. Borrowdale	1900	Dug	15.1	30	--	Sand	1,410	8.9	5-15-63	--	--	A	
218-843-1	do.	E. Alexander	1943	Drl	r39.5	8	--	Sand and gravel	1,520	Flow	5-13-63	--	7,000	F	Anal; temp 50; flows perennially, estimated as 5 gpm, 0.5 ft above LS; water-bearing zone 0.5 ft thick (r).
219-843-1	do.	F. Telaak	1948	Drl	81.5	6	--	do.	1,500	p4.1	5-14-63	Sw	1,900	F	Anal.
219-851-1	do.	Village of Cattaraugus	1934	Drl	r218	8	--	Gravel	1,260	Flow	5-15-63	AL	--	PS	Anal; H ₂ S; temp 50.0; yield 200 gpm (r); flow 40 gpm, 3 ft below LS; rarely used.
220-845-1	do.	C. Minckime	1943	Drl	r90	6	--	Sand and gravel	1,355	+20	5-14-63	--	3,500	F	Anal; temp 50.2; flows 2.5 gpm from faucet 3 ft above LS; used for cooling milk only.
220-846-1	do.	C. Leng	1920	Drl	r96	4	--	do.	1,340	Flow	5-14-63	--	3,500	F	Anal; temp 49.8; flow 2.5 gpm from discharge pipe in milk room continuously.
220-847-1	do.	do.	1950	Drl	135	6	--	Sand	1,340	+9	5-14-63	--	5,500	D	Anal; temp 49.8; flows 3.8 gpm, 3 ft above LS; well is cased to 152 ft and partly filled in by sand entering at bottom (r); blue clay overlies water-bearing sand (r).
220-850-1	do.	L. Gregory	1955	Drl	67.2	6	25	Shale	1,240	11.8	5-15-63	--	--	A, D	Anal; inadequate yield for domestic supply.
221-841-1	do.	R. Weishan	1962	Drl	163	6	--	Sand	1,920	69.5	4-29-63	--	--	C	Yield 10 gpm baller test (r); drilled to supply campsite under construction at time of visit.
-2	do.	--	--	Dug	2.8	30	--	Sand and gravel	1,840	.5	5-2-63	--	50,000	A, F	Anal; temp 44.4; flow 37 gpm from lateral discharge pipe 2.8 ft below LS.
221-849-1	do.	J. Frank	1961	Drl	r135	7	105	Shale	1,340	p67.7	5-5-63	Sub	100	D	Anal; iron; yield 6 gpm baller test (r).
222-848-1	do.	R. Stevens	1959	Drl	r315	6	--	Gravel	1,330	p1.5	5-22-63	Sub	1,500	F	Anal; temp 50; clay, silt, and very fine sand overlie water-bearing gravel (r).
-2	do.	R. Minckime	1960	Drl	r374	6	374	do.	1,340	p+.9	5-22-63	Sub	1,500	F	Anal; iron; gas; temp 49.0; flow 0.25 gpm, 0.8 ft above LS.
* 223-836-1	do.	West Valley Crystal Water Co.	--	Drl	r230	6	130	Shale	1,600	16.4	7-22-63	--	--	A	Anal; sand 0-130 ft (r); never used because yield is insufficient for requirements.
* -2	do.	do.	--	Dug	6.0	--	--	Sand and gravel	1,605	4.9	7-22-63	--	14,000	PS	Anal; temp 48.2; flow 10 gpm (est) from lateral discharge pipe 4.9 ft below LS; concrete casing is 3.3 X 5 ft in dimension; 1 of 3 similar so-called "springs" which are source of company's supply.
223-847-1	do.	R. Wisocki	1962	Drl	r255	7	--	Gravel	1,345	r+1	12-62	Sw	2,000	F	Anal; iron; gas; yield 32 gpm, dd 21, Dec. 1962 (r); gray clay overlies water-bearing pebble gravel (r); shallow water-bearing gravel at 16 ft depth yielded 12 gpm, but was cased off.
223-848-1	do.	D. Denkert	1948	Drl	r438	8	450	do.	1,340	Flow	5-21-63	Jet	1,500	F	Anal; gas; temp 50.2; flows 1.5 gpm (est), 1 ft below LS; cased to 438 ft, drilled to 450 ft but casing would not drive.
-2	do.	H. Tegler	1952	Drl	r300	7	>425	do.	1,340	rFlow	9-52	Sw	2,500	F	Anal; gas; water level was higher than 20 ft above LS 9-52 (r); flows when not pumped; drilled 425 ft in glacial deposits; casing set at 300 ft; silt and clay overlie water-bearing gravel.
* 224-836-1	do.	West Valley School District	--	Drl	r360	--	--	--	1,540	--	--	Tur	--	In	Anal; H ₂ S.
* 224-838-1	do.	H. Feldman	1961	Drl	88	6	68	Shale	1,760	p56.3	11-7-61	Jet	--	F	Yield 15 gpm baller test (r).
224-848-1	do.	R. Hebner	1960	Drl	r438	8	--	Sand and gravel	1,360	--	--	--	--	D	

Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
										Below land surface (feet)	Date				
224-850-1	Cattaraugus	E. Ball	1950	Dr1	r78	6	15	Shale	1,700	r40	1961	Jet	100	D	Water-bearing zone is near bottom of well (r).
* 225-836-1	do.	C. Conrad	--	Dr1	78	6	m71	do.	1,460	7.7	7-22-63	--	--	A, F	H ₂ S; formerly used for watering cattle; water was pumped by hand.
* 225-838-1	do.	R. Codd	--	Dr1	r250	5	--	do.	1,450	r15	1961	Sub	1,500	F	Yield 10 gpm (r); dd 145 ft (r).
* 225-839-1	do.	S. Kwicfen	--	Dr1	22.6	24	--	Till	1,660	21.0	12- 8-60	Sw M	100	D	Abandoned drilled well in shale, 140 ft deep on same property.
* 225-840-1	do.	M. Skinner	--	Dug	11.9	48	11.9	do.	1,845	3.9	4-21-62	Sw	--	D	
* 225-841-1	do.	L. Barbeti	1964	Dr1	148	7	118	Shale	1,415	Flow	9-17-64	--	900	C	Anal; temp 51.7; flow 0.6 gpm, 2 ft above LS; yield 10 gpm bailer test.
226-825-1	do.	Kirkby	1927	Dr1	156	8	24	do.	1,690	Flow	6- 5-64	AL	7,000	U, C	Anal; temp 48.0; flow 5 gpm (est) 0.6 ft below LS.
226-827-1	do.	--	--	Dug	36.7	40	--	Sand and gravel	1,720	35.2	6- 5-64	Dw M	--	A	
* 226-836-1	do.	B. Hadley	--	Dug	11.9	36	9	Till; shale	1,450	4.1	4-30-62	Sw M	20	D	
* 226-837-1	do.	S. Heary	--	Dr1	92.4	6	--	Shale	1,570	58.4	4-28-62	Jet	1,200	F	
* -2	do.	P. Simko	--	Dug	14.7	36	--	Sand and gravel	1,420	p7.7	4-30-62	Sw	--	D	
* 226-838-1	do.	State of New York	--	Dr1	37.5	3	--	Till	1,280	24.0	12- 1-60	Dw M	--	A	
* -2	do.	do.	--	Dr1	219	6	--	--	1,350	182.7	11- 2-61	--	--	A	
* -3	do.	do.	1961	Drv	22	4	--	Till	1,380	10.0	10- 9-61	--	--	A	OW.
* -4	do.	do.	1962	Drv	21	1 1/4	--	Sand and gravel	1,380	7.3	4-27-62	--	--	T	Anal; 19 ft of till overlies sand and gravel; screened from 18 to 21 ft.
* -5	do.	do.	1961	Drv	11	1 1/4	--	Till	1,380	10.1	10-20-61	--	--	T	Anal.
* 226-839-1	do.	do.	--	Dug	6.1	24	--	Sand and gravel	1,450	4.3	12- 8-60	Sw	--	A	Anal; temp 40.5, 4-19-62.
* -2	do.	do.	--	Dug	16.5	36	--	Till	1,490	10.7	12- 8-60	Sw M	--	A	
* -3	do.	do.	--	Dug	11.4	30	--	do.	1,400	9.5	12- 8-60	Sw	--	A	Anal; OW.
* -4	do.	do.	1960	Dr1	156	7	103	Shale	1,395	91.5	10-16-61	--	--	A	Anal; yield 12 gpm bailer test (r); OW.
* -5	do.	do.	--	Dug	19.4	38	--	Till	1,770	13.0	4-27-62	--	--	A	
* 226-840-1	do.	Cyro	--	Dug	17.8	36	17.8	do.	1,780	10.2	4-20-62	Sw M	--	A	
* -2	do.	G. Rachic	--	Dug	5.3	24	5.3	do.	1,800	2.8	4-21-62	Sw	200	D	
226-851-1	Erie	F. Colligan	1962	Dr1	r137	6	a85	Shale	1,240	25.9	5-24-63	Jet	250	D	Anal; yield 5 gpm bailer test (r); silt and fine sand overlie shale.
227-826-1	Cattaraugus	Baldwin	1962	Dr1	r80	6	a40	do.	1,610	r10	10-62	--	250	D	
227-828-1	do.	H. Herman	--	Dr1	33.5	5	--	Sand and gravel	1,620	32.0	6- 5-64	--	--	A	Well may be partly backfilled.
* 227-837-1	do.	Frank Green	--	Dr1	r90	6	--	Shale	1,515	Flow	4-30-62	Sw	--	D	Water flows over top of casing, 1 ft above LS.
* -2	do.	H. Kester	1957	Dr1	r166	6	164	do.	1,500	9.1	11- 8-61	Jet	--	D	
* -3	do.	E. Zimmerman	1961	Dr1	r100	6	a90	do.	1,510	5.8	5- 1-62	Sub	--	F	Yield 14 gpm bailer test (r).
* -4	do.	State of New York	--	Dr1	169	6	--	--	1,540	147.2	11- 3-64	--	--	A	
* 227-838-1	do.	C. Zeffers	a1940	Dr1	161.3	6	--	Shale	1,450	24.3	5- 1-62	--	1,000	F	

Table I-1 (Cont'd)

Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
										Below land surface (feet)	Date				
* 227-838-2	Cattaraugus	State of New York	1962	Drv	11	1 1/4	--	Till	1,370	2.1	4-19-62	--	--	T	Anal; screen, 8-11 ft.
* 227-839-1	do.	do.	--	Dug	16.6	30	--	do.	1,560	6.7	4-18-62	--	--	A	
* -2	do.	do.	1961	Dr	112	6	110	Shale	1,580	56.0	4-18-62	--	--	A	Yield 20 gpm bailer test (r).
* -3	do.	do.	--	Dug	15.9	36	--	Till	1,430	2.4	4-28-62	--	--	A	
* -4	do.	do.	1961	Dr	160	7	180	Shale	1,410	82.9	4-18-62	--	--	F, X	Well also draw from unconsolidated deposits overlying shale; yield about 5 gpm (r).
* 227-840-1	do.	R. Custer	--	Dug	10.1	24	10.1	Till	1,730	4.1	4-21-62	--	--	D	
* -2	do.	L. Cobo	1930	Dr	140	6	15	Shale	1,555	4.5	4-20-62	Sw	--	F	Yield is inadequate for farm; a drilled well 70 ft deep is used along with this well.
* -3	do.	--	--	Dr	41	4	--	do.	1,525	19.2	10-21-61	Dw M	--	A	
* -4	do.	R. Miller	--	Dr	48.5	6	--	do.	1,525	6.5	4-21-62	--	--	A	
* -5	do.	Et. Carl	1947	Dug	6.4	24	--	Till	1,560	1.0	4-26-62	Sw	--	D	
227-851-1	Erie	C. Johnson	--	Dug	17.6	24	--	Sand and silt	1,330	9.3	5-24-63	--	--	A	Temp 44.8; domestic supply is obtained from a spring downslope from well; an attempt to drill a well was abandoned because only fine-grained materials were penetrated for considerable depth.
227-852-1	do.	Ross	1962	Dr	33.0	6	--	Sand and gravel	1,280	13.0	5-24-63	Sw	2,000	F	Anal; gravel was placed at bottom of well by driller (r).
227-856-1	Cattaraugus	Village of Gowanda	1928	Dr	1376	12, 8	377	do.	780	152.4	4-4-63	Tur	300,000	PS	Anal; gas; temp 55.0, 2-20-63; shutter screen 8-inch diameter, 6-gage, from 336-376 ft; gravel packed, when drilled swl was +7 ft and yield was 550 gpm with dd of 92 ft (r); yield 210 gpm, pumping water level 186 ft on 2-20-63 after redevelopment of well; generally pumped from May to October (estimated pumpage is for this period).
-3	do.	Moench Tanning Co. Division of Brown Shoe Co.	1934	Dr	1329	18, 12	--	do.	790	--	--	Tur	200,000	I	Gas; Arisco iron screen, 12-inch diameter, 6-gage, from 299 to 329 ft; gravel packed; yield was 275 gpm on 8-31-62 after redevelopment (r); yield when drilled was 585 gpm (r).
-4	do.	do.	1948	Dr	1332.5	18, 12	--	do.	790	1192	2-18-63	Tur	300,000	I	Gas; screen, 12-inch diameter from 302.5-332.5 ft; gravel packed, yield 510 gpm, swl 141.7 ft, dd 39.4 ft on 12-14-68, periodic redevelopment necessary to maintain yield.
-5	do.	do.	1963	Dr	1350	8	347	do.	790	200	11-27-63	--	--	T	
-6	do.	Village of Gowanda	1920	Dr	1299.5	7	--	do.	795	176.3	11-3-64	--	--	A, PS	Anal; gas, temp 56.2, 1-17-63; yield about 20 gpm.
228-827-1	do.	M. Herman	1958	Dr	1110	8	--	Sand	1,500	17.9	6-5-64	Jet	200	D	Drilled to 115 ft but cased only to 110 ft (r).
* 228-837-1	do.	A. Nisita	--	Dr	83.1	6	--	Shale	1,465	26.2	10-23-61	--	--	A	
-2	do.	do.	--	Dr	41.5	8	--	do.	1,560	9.5	10-23-61	Dw M	--	A	
* 228-838-1	do.	M. Felt	--	Dr	16.2	20	--	Sand and gravel	1,410	10.6	10-21-61	Sw	--	D	H ₂ S.
* -2	do.	S. Emerson	1960	Dr	1130	6	80	Shale	1,360	--	--	Sub	--	F	Yield 5 gpm (r).
* -3	do.	E. Hansen	--	Dr	61.7	5	--	do.	1,410	9.5	10-24-61	Dw M	--	U	
* -4	do.	G. Smith	1960	Dr	73.0	6	65	do.	1,490	50.5	11-7-61	Sub	--	D	
* -5	do.	R. Codd	--	Dug	16.4	36	--	Till	1,475	11.8	5-1-62	--	--	A	

	Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
											Below land surface (feet)	Date				
*	228-839-1	Cattaraugus	F. Waterstram	--	Dug	11.0	48	--	Sand and gravel	1,330	9.0	10-21-61	Sw	--	F	
*	228-840-1	do.	F. Felton	1958	Drv	12.4	1 1/4	--	do.	1,280	10.0	10-24-61	--	--	A	About 1 ft away from driven well used for farm supply.
*	-2	do.	H. Kelley	--	Dr1	53.1	6	--	Shale	1,370	12.4	4-20-62	Jet	--	D, Ag	Iron, supplies a chicken farm.
*	-3	do.	French	1961	Dr1	54.4	6	32	do.	1,370	3.9	4-20-62	--	--	U	Yield 3 gpm baller test (r).
	228-846-1	Erie	D. Byblie	1955	Dug	8.6	24	--	Sand and gravel	1,230	6.8	5-29-63	Sw	450	D	Anal, temp 48.0.
	228-851-1	do.	B. Skuse	1932	Dr1	110	6	--	Shale	1,120	--	--	Jet	1,500	F	Anal, Iron.
	228-857-1	Cattaraugus	Seneca Nation of Indians	1964	Dr1	298	8	78	do.	870	111.3	8-26-64	--	--	A	Gas, yield less than 1 gpm (r); "shot" with 39 sticks of dynamite which did not improve yield.
	-2	do.	do.	1964	Dr1	447.6	8	470	do.	870	442.7	8-26-64	--	--	A	Temp 55.4; yield is negligible, "shot" with 39 sticks of dynamite which did not improve yield.
	229-819-1	do.	Earl Thomas Estate	1920	Dr1	37.9	6	--	Sand and gravel	1,820	21.6	5-13-64	Dw M	--	A	OW.
	-2	do.	do.	--	Dug	35.0	36	--	do.	1,820	21.0	5-13-64	--	--	A	Goes dry.
	-3	do.	C. Owens	1947	Dr1	39.2	6	--	do.	1,815	20.4	5-15-64	Jet	100	D	Anal, perennial supply.
	229-822-1	do.	Village of Arcade	1954	Dr1	175.9	18, 12	--	do.	1,660	123.5	10-11-54	Tur	600,000	PS	Screen, 12-inch diameter, 100-slot, from 65.9-75.9 ft, gravel packed, yield 425 gpm, on initial test, swl 21.0 ft, dd 30.5 ft, pumpage rate is prior to addition of well 231-825-2 to Arcade system.
	-2	do.	do.	--	Dr1	154	12	--	do.	1,660	--	--	Tur	15,000	PS	Screen, yield 60 gpm, supplies community of Sanjusky.
*	229-841-1	Erie	R. Gentner	--	Dug	16.6	24	--	do.	1,360	13.3	5-7-64	Sw	--	F	
*	229-842-1	do.	do.	1959	Dr1	132.5	6	--	--	1,340	--	--	--	--	A	Dry hole, sand and gravel 0-15 ft, clay and sand 15-32.5 ft, filled with trash.
	229-846-1	do.	D. Kessler	1953	Dug	11.0	30, 12	--	Sand	1,400	2.0	5-29-63	Sw	200	D	Anal, temp 46.0, yield about 10 gpm pump test.
	229-849-1	do.	Town of Collins, Water District No. 3	1959	Dr1	160	10, 6	--	Sand and gravel	1,220	Flow	--	--	40,000	PS	Flows about 30 gpm through header 3 ft above LS into main of water system, flow provides sufficient supply for weekdays, screen, 6-inch diameter, 100-slot, 51-60 ft.
	-2	do.	do.	1959	Dr1	156	18, 10	--	do.	1,220	Flow	--	Tur	--	PS	Iron, screen, 18-inch diameter, 100-slot, 51-56 ft; gravel packed, yield 150 gpm, generally pumped only on weekends.
	229-856-1	do.	Town of Collins, Water Districts Nos. 1 & 2	1959	Dr1	135	18, 10	--	do.	820	119	4-16-58	Tur	--	PS	Screen, 18-inch diameter, 100-slot, 30 3-35.3 ft, gravel packed, pumping test, 150 gpm dd 9 5 ft.
	229-857-1	do.	H. Gates	1964	Dr1	142	6	--	Sand	820	31	9-14-64	--	--	D	Screen, 5-inch diameter, .030-slot, 32-42 ft, yield 10 gpm baller test with no appreciable drawdown.
	230-829-1	Cattaraugus	W. Delaney	1962	Dr1	1244	8, 6, 4	--	Gravel	1,400	1430	2-11-63	--	3,000	F	Anal, H2S, supplies house and barn by artesian pressure, when drilled flow was 200 gpm, estimated by driller.
	230-833-1	Erie	E. Korowski	1954	Dr1	56.2	6	--	Sand	1,265	40.6	8-5-64	Jet	100	D	Anal.
	230-835-1	do.	R. King	1955	Dr1	57.8	6	--	Sand, silt, clay	1,245	12	8-5-64	--	--	A	Yield is inadequate for domestic supply
	-2	Cattaraugus	W. Winkey	--	Dug	20.2	36	--	Sand and gravel	1,390	17.9	8-6-64	Sw	--	F	
*	230-837-1	Erie	L. Ruffolo	1941	Dr1	33.7	6	--	Gravel	1,365	14.7	8-5-64	Sw	3,500	F	Anal, cased to 40 ft; partly backfilled with crushed stone.

Table I-1 (Cont'd)

	Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
											Below land surface (feet)	Date				
*	230-838-1	Erie	B. Mooney	--	Drv	14.1	1 1/4	--	Sand and gravel	1,380	3.8	5-6-64	--	--	A	OW.
*	230-840-1	do.	Village of Springville	1931	Dr1	r139	18, 6	--	do.	1,350	16	7-31	--	--	A, FS	Originally finished with shutter screen, 12-inch diameter from 121-135 ft; pumping test 830 gpm, dd 25 ft; gravel packed liner with 6-inch diameter screen from 119.5-135 ft, then installed to reduce amount of sand pumped from well; abandoned about 1944 because of sand pumping.
*	-2	do.	do.	1944	Dr1	r137	18, 12	--	do.	1,350	pr27	1-29-63	Tur	200,000	PS	H ₂ S; pumping rate 630 gpm; screen, 12-inch diameter from 122-137 ft; gravel packed; pumping test on 8-5-44, 672 gpm, swl 27.4 ft, dd 16.4 ft after 8 hours pumping (swl at this time probably was affected by pumping from wells 230-840-1 and -3).
*	-3	do.	do.	1942	Dr1	r159	18, 10	--	do.	1,350	p31.5	1-29-63	Tur	200,000	PS	H ₂ S; pumped at 600 gpm; screen, 10-inch diameter, 100-slot from 144-149 ft; 80-slot from 149-159 ft; gravel packed; pumping test 5-14-42, 513 gpm, swl 37.7 ft, dd 20.6 ft (swl probably affected by pumping of well 230-840-1).
*	230-842-1	do.	G. Kroll	1962	Dr1	125	6	19	Shale	1,335	p46	7-28-64	Jet	200	D	Anal; Iron; yield 1 gpm (r).
*	230-843-1	do.	C. Munt	1964	Dr1	r330	6, 4	--	Sand	1,385	199	8-11-64	--	--	D	Yield 5 gpm (r); casing backfilled with washed gravel to 310 ft.
	230-845-1	do.	F. Schue	1961	Dr1	37.9	6	--	Gravel	1,390	20.6	8-28-64	Sw	200	D	Yield 5 gpm.
	230-856-1	do.	Town of Collins, Water Districts Nos. 1 & 2	1948	Dr1	r42	18, 10	--	do.	835	r17	1948	Tur	--	PS	Pumping rate 150 gpm; construction details are reported to be similar to those of well 229-856-1.
	-2	do.	Don Gernatt Gravel Products, Inc.	1956	Dr1	r36	--	--	Sand and gravel	830	--	--	Tur	100,000	I	Anal; supplies gravel plant, use is seasonal; yield 400 gpm.
	-3	do.	do.	1962	Dr1	30.3	18	--	do.	840	3.7	8-12-64	Tur	2,000	I	Anal; supplies cleaner at asphalt plant, use is seasonal; casing perforated from 26-30 ft; pumping test, 150 gpm, swl 4 ft, dd 7 ft.
	231-825-1	Wyoming	Village of Arcade	1962	Dr1	r50	12	--	Gravel	1,490	r16	3-26-62	--	--	T	Screen and gravel pack, 38-48 ft; pumping test, 150 gpm, swl 16 ft, dd 3.
	-2	do.	do.	1962	Dr1	r49	20, 12	--	Sand and gravel	1,490	r17	11-28-62	Tur	--	PS	Screen, 12-inch diameter, 100-slot, 39-49 ft; gravel packed; pumping test 500 gpm, swl 17 ft, dd 7.1 ft after 24 hours pumping.
	231-830-1	Cattaraugus	M. Schaper	1956	Dr1	200	6	--	do.	1,355	10.5	8-7-64	Jet	300	D	On same property two wells, 60 ft deep, penetrated clay and were dry; a well 400 ft deep flowed but yielded sulfurous water and was destroyed.
	-2	do.	C. Klima	1959	Dr1	450	6	454	do.	1,375	Flow	8-7-64	Sub	3,000	F	
	231-831-1	Erie	W. Schiener	1962	Drv	r22	1 1/4	--	do.	1,410	--	--	Sw	400	D	
	231-833-1	do.	A. Zisser	1964	Dr1	280	6, 4	--	Sand	1,390	8.1	8-5-64	Sub	--	D	Yield 2 1/2 gpm (r).
	-2	do.	J. Rung	1959	Dr1	59.3	6	--	Gravel	1,430	39.7	8-5-64	Jet	350	D	Anal; yield about 25 gpm baller test.
	-3	do.	C. Butler	1962	Dr1	94.4	6	--	do.	1,430	p47.2	8-5-64	Jet	3,000	F	Iron; cased to 150 ft (r, driller); yield 25 gpm baller test when drilled; yield was inadequate in summer 1964; well may be partly filled in with sand entering at bottom of casing.
	231-835-1	do.	P. Schuster	1958	Dr1	99.7	6	--	Sand and gravel	1,445	p90.8	8-6-64	Sub	100	D	Anal.
*	231-838-1	do.	G. Lancaster	--	Drv	17.6	1 1/4	--	do.	1,400	3.5	5-12-64	--	--	A, Ag	Screened from 14.9-17.6 ft; OW.
*	231-839-1	do.	K. Ploetz	1956	Dr1	29.0	6	--	do.	1,400	18.8	5-6-64	Jet	200	D	

Well number	County	Owner	Year completed	Type of well	Depth of well (feet)	Diameter (inches)	Depth to bedrock (feet)	Water-bearing material	Altitude above sea level (feet)	Water level		Method of lift	Estimated pumpage or flow (gallons per day)	Use	Remarks
										Below land surface (feet)	Date				
231-844-1	Erie	H. Kobler	1961	Drv	12	--	--	Sand and gravel	--	--	--	Sw	150	D	Iron.
231-858-1	do.	Seneca Nation of Indians	1964	Dr1	288	8, 6	--	--	810	--	--	--	--	T	Casing stuck in hole; sand, 0-130 ft; sandy clay, 130-230 ft; sand and gravel, 230-288 ft.
-2	do.	do.	1964	Dr1	385	8	366	Shale	810	94	3-65	--	--	D	Water-bearing zone at 370 ft; pumping test, 23 gpm, dd 156 ft.
231-900-1	Cattaraugus	do.	1964	Dr1	76.9	8	50	do.	715	31.1	8-12-64	--	--	D	Ballier test, 25 gpm, swl 35 ft, dd 25 ft (r).
-2	do.	do.	1964	Dr1	76.1	8	49	do.	715	29.8	8-12-64	--	--	D	Do.
232-825-1	Wyoming	Village of Arcade	1953	Dr1	r53	12, 8, 10	--	Sand and gravel	1,480	--	--	Tur	650,000	PS	Anal; screen, 10-inch diameter, 100-slot, from 44-49 ft; gravel packed; pumping test of 11-53, 305 gpm, swl 7.1 ft, dd 6.9 ft.
232-827-1	do.	do.	1961	Dr1	r149	10, 8, 6	--	do.	1,460	Flow	--	--	--	X, T	Temp 49 (r) 8-16-61; screen, 6-inch diameter, 125-slot, 139-144 ft; flow 60 gpm (r); pumping test 185 gpm, water level 29.7 ft after 24 hours pumping.
232-828-1	Erie	K. Wertz	1958	Dr1	28.7	6	--	Gravel	1,435	18.3	6-25-64	Sw	--	C	
232-830-1	do.	M. Hogan	1963	Dr1	175	6	--	Sand and gravel	1,405	11.4	8-11-64	Sub	150	D	Anal; H ₂ S.
232-831-1	do.	P. Loggans	1961	Dr1	r87	r6	--	do.	1,435	r32	--	Jet	100	D	Anal.
232-838-1	do.	R. Schweikert	1963	Dr1	129	6	--	Sand	1,430	32.6	5-5-64	--	--	D	
232-839-1	do.	F. Knowlton	--	Dug	21	30	--	Sand and gravel	1,400	17.7	5-7-64	--	--	A	Well has been partly backfilled by owner.
232-857-1	do.	Seneca Nation of Indians	1964	Dr1	r76	8	14	Shale	845	5.8	8-12-64	--	--	D	Original depth 48.1 ft; no improvement in yield after deepening; yield 7.5 gpm ballier test; cased to 27 ft because of caving shale; water enters at bottom of casing.
-2	do.	do.	1964	Dr1	50.8	8	16	do.	840	6.1	8-12-64	--	--	D	Gas; caving shale; casing slotted from 27-30 ft and set into shale and gravel packed.
-3	do.	do.	1964	Dr1	55.7	8	16	do.	845	6.3	8-12-64	--	--	D	Gas; yield 1.5 gpm ballier test; water enters from caving shale at 28 ft.
-4	do.	do.	1964	Dr1	r148	8	14	do.	--	--	--	--	--	A	Yield less than 2 gallons per hour.
233-828-1	do.	Chafee Water Works, Inc.	1900	Dr1	20.4	8	--	Sand and gravel	1,460	13.5	2-11-63	Sw	15,000	PS	Pumping rate is about 100 gpm.
-2	do.	Greatwood	1960	Dr1	50.7	6	--	Sand	1,435	20.0	6-25-64	Sub	100	D	Yield 40 gpm.
233-838-1	do.	Miller	1963	Dr1	86.5	6	45	Shale	1,455	18.6	5-7-64	--	--	A	Yield is a few gallons per minute.
-2	do.	do.	1963	Dr1	55.6	6	--	Sand and gravel	1,450	29.0	5-7-64	--	--	F	
-3	do.	do.	1960	Dr1	101.9	6	--	Shale	1,460	46.6	5-12-64	--	--	A, F	Insufficient yield; CM.
-4	do.	R. Wiede	1959	Dr1	126.3	6	--	do.	1,440	24.0	11-8-64	Jet	150	D	Anal; iron; H ₂ S; can be pumped dry.
233-839-1	do.	J. Buzak	1963	Dr1	r528	7	--	Gravel	1,430	r200	4-3-63	Sub	250	D	Anal; gas; iron.
233-840-1	do.	D. Zittel	1960	Dug	r18	24	--	do.	1,435	16	--	Sw	4,000	F	Use includes 2,000 gpd for cooling.
233-844-1	do.	J. Pharner	--	Dr1	55.5	6	--	Shale	1,470	27.0	7-28-64	--	--	D	
234-823-1	Wyoming	W. Lewandowski	1935	Dr1	r3,403	12	--	Shale?	1,600	Flow	--	--	2,000	GT	Anal; gas; salty taste; temp 53.8, 5-4-64; flow 1-2 gpm, 6.5 ft above LS, 5-4-64; water is presumed to enter well through break in casing at relatively shallow depth.

TABLE I-2

CHEMICAL ANALYSES OF GROUNDWATER
FROM THE ERIE-NIAGARA BASIN

Well Number	Depth of Well (feet)	Water-bearing Material	Date of Collection	Temperature (°F)	Silica (SiO ₂)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	Dissolved Solids (residue at 180°C)	Hardness at CaCO ₃ Calcium Magnesium Noncarbonate	Specific conduct- ance (micromhos at 25°C)	pH	Color	Alkyl benzene Sulfonate (ABS)	Turbidity
226-839-4	156	Sh	7.27-62	54	5.5	.53	.10	17	4.0	48	2.3	174	12	12	.3	.1	193	59 0	334	7.7	9	1	2
235-904-1	r55	Sh	7-9-63	52	13	.29	.03	47	15	56	1.4	290	.2	52	.3	.1	341	179 0	590	7.3	3	.1	.6
241-855-1	r22	Sh	8-15-63	55	17	.44	.02	75	26	25	1.9	388	6.9	18	.2	.1	377	294 0	668	7.2	7	.0	2

Depth of well: All depths below land surface.

r - reported

All others measured.

Remarks: All analyses made by U.S. Geological Survey, Water Resources Division.
From Erie-Niagara Basin Groundwater Resources Table 8

(Results in parts per million except specific conductance, pH, color and turbidity)

TABLE I-3

Survey, water resources
From Erie-Niagara Basin Groundwater
Resources' Table 9

CHEMICAL ANALYSES OF SELECTED CHEMICAL CONSTITUENTS
AND CHARACTERISTICS OF GROUNDWATER FROM THE ERIE-NIAGARA BASIN

Site Number	Depth of Well (feet)	Water Bearing Material	Date of Collection	Sulfate (SO ₄)	Chloride (Cl)	Calcium, magnesium- Hardness (as CaCO ₃)	Specific Conductance (micromhos at 25°C)	pH
220-850-1	67.2	Sh	5-15-63	16	16	106	5251	7.2
221-849-1	r135	Sh	5-14-63	22	8.4	153	322	7.6
223-836-1	r230	Sh	7-22-63	4.9	6.5	52	187	7.6
225-841-1	148	Sh	9-17-64	16	242	108	1,400	8.0
226-851-1	156	Sh	6-5-64	9.6	3.4	138	298	8.0
226-851	r137	Sh	5-24-63	3.5	2.0	80	322	8.3
228-251	r110	Sh	5-24-63	22	2.0	149	341	7.7
230-842-1	125	Sh	7-28-64	27	119	157	1,080	7.5
233-838-4	126	Sh	8-11-64	328	16	78	470	7.8
234-823-1		Sh	5-4-64	4.8	220	90	1,200	7.4
235-848-1	38	Sh	8-27-63	80	19	270	585	8.0
236-848-1	19	Sh	8-26-63	71	14	170	470	7.2
237-850-1	r65	Sh	8-26-73	24	56	147	628	7.2
239-826-1	r46	Sh	7-17-63	7.6	50	167	411	7.7
239-841-1	61	Sh	8-12-64	11	66	285	764	7.5
239-854-1	60	Sh	8-15-63	29	23	99	343	7.4
239-855-1	52	Sh	8-15-63	57	12	236	462	7.6

Depth of well: All depths below land surface
r - reported
All other measured.

TABLE I-3 (Cont'd)

<u>Site Number</u>	<u>Depth of Well</u> (feet)	<u>Water Bearing Material</u>	<u>Date of Collection</u>	<u>Sulfate</u> (SO ₄)	<u>Chloride</u> (Cl)	<u>Calcium, magnesium-Hardness</u> (as CaCO ₃)	<u>Specific Conductance</u> (micromhos at 25°C)	<u>pH</u>
240-823-1	57	Sh	7-17-63	39	7.0	232	445	7.5
240-826-1	107	Sh	7-17-63	36	1,000	520	3,600	7.0
241-841-2	r44	Sh	8-12-64	17	64	244	641	7.2
241-844-1	56	Sh	4-23-64	8.8	56	140	458	7.0
244-830-1	47	Sh	7-18-63	37	18	218	437	7.5
244-846-1	65	Sh	7-23-63	42	35	247	511	7.4
244-848-1	65	Sh	7-24-63	.8	94	317	948	7.4
245-817-1	44	Sh	8-10-63	21	2.8	182	370	7.5
246-818-1	132	Sh	8--2-63	15	12	193	420	7.5
246-824-1	24	Sh	8-10-63	53	17	300	605	7.5
246-830-1	76	Sh	8-2-63	54	28	198	658	7.1
248-818-1	r140	Sh	8-12-63	12	9.0	170	432	7.5
248-825-1	r112	Sh	8-2-63	34	11	149	387	7.1
248-828-1	r112	Sh	8-2-63	32	9.0	219	443	7.2
248-829-1	36	Sh	8-2-63	38	48	195	476	8.0
249-818-1	59	Sh	8-12-63	16	3.8	251	463	7.5
249-823-1	82	Sh	8-9-63	19	2.4	242	469	7.7
249-826-1	r70	Sh	8-2-63	61	14	223	518	7.6
250-810-1	62	Sh	6-9-64	.4	46	200	849	7.3

Iron (Fe) = 0.79 ppm, in solution when collected
 Specific conductance in micromhos per centimeter except specific conductance and pH

APPENDIX J

DESCRIPTION OF FINITE ELEMENT PROGRAM FOR GROUNDWATER FLOW ANALYSIS

APPENDIX J - DESCRIPTION OF FINITE ELEMENT
PROGRAM FOR GROUNDWATER FLOW ANALYSIS

This appendix contains a description of the finite element program for the groundwater flow analysis used in this study.

1 - INTRODUCTION

This appendix describes a two-dimensional, planar and axisymmetric transient (or steady state) finite element saturated groundwater flow code developed at Acres in early 1976. The available elements are an isoparametric quadratic head (total potential) triangle (6 nodes), a quadratic gap (fracture) element (6 nodes), and a loading element (3 nodes). The model starts from a specified arbitrary set of initial conditions and proceeds stepwise through a number of solutions during the course of a run. Boundary conditions include specified head at node, nodal load (source or sink), element internal load and surface loads. The surface loads are specified normal seepage velocity and specified head outside a film. All specified values and loads are variable linearly over time spans consisting of one to several time steps and can be started and stopped independently whenever desired. Gradient fluxes (pore velocities) are computed in a post-processor attached to the main program itself and plotting of meshes, equipotential lines and pore velocities is accomplished by a follow-up program FINI 510 that accesses several of the disc files produced by the main code.

2 - BASIC EQUATIONS AND BOUNDARY CONDITIONS

The basic equation for two-dimensional saturated groundwater flow, as used in the model, is:

$$K_{km} \frac{\partial^2 \phi}{\partial x_k \partial x_m} + Q - nc \frac{\partial \phi}{\partial t} = 0, \quad (1)$$

where ϕ = total potential (head),

x = linear dimension,

n = porosity (fractional),

K = hydraulic conductivity = $\rho g \frac{k}{\mu}$,

ρ = fluid density, k = intrinsic permeability,

g = gravitational constant, μ = dynamic viscosity,

Q = volumetric source rate,

c = specific capacity or storage = $\rho g (\beta_f + \beta_s/n)$,

β_f = fluid compressibility, β_s = solid compressibility

and t = time.

In the finite element discretization of the modeled region, the physical space is broken up into elements, in each of which the temperature field is described by a simple relationship:

$$\phi = \phi_i N_i. \quad (2)$$

The ϕ_i are the solution values at specified discretization points or nodes and the N_i are distribution functions associated with each node.

The ϕ_i are also assumed to vary linearly over time steps so that accounting for the time variation expands equation (2) into:

$$\phi = \phi_i^k M_k N_i \quad (3)$$

in which the M_k are time distribution functions associated with the old and new solutions spanning the time interval in question.

A weighted-residual method may be used with finite elements to formulate a set of linear algebraic equations representative of the modeled system. In this model we use Galerkin weighting in which the residual, multiplied by the distribution functions previously mentioned, is integrated and set equal to zero over the whole region of study.

The form of the Galerkin pseudo-functional is:

$$\chi_G = \int_R \left(K_{km} \frac{\partial^2 \phi}{\partial x_k \partial x_m} + Q - nc \frac{\partial \phi}{\partial t} \right)^* \phi \, dR \quad (4)$$

*The residual is not varied in the derivation of the matrix equation below. Integration-by-parts and the divergence theorem yield a quadratic formulation:

$$G = \int_R \left(-K_{km} \frac{\partial \phi^*}{\partial x_k} \frac{\partial \phi}{\partial x_m} + Q^* \phi - nc \frac{\partial \phi^*}{\partial t} \phi \right) dR + \int_S \left(K_{km} \frac{\partial \phi}{\partial x_k} \phi \, i_m \right) dS, \quad (5)$$

where the second term is a boundary flux term used to express natural boundary conditions or imposed seepage velocities and specified head outside a film. i_m is the outward facing normal to the surface S . This term is omitted for impermeable boundaries or boundaries with fixed potential and is replaced for other boundaries by:

$$\int_S [q - \alpha (\phi - \phi_a)]^* \phi \, dS, \quad (6)$$

where the imposed seepage velocity q is positive for water inflow. α is the film transfer coefficient and ϕ_a is the ambient potential outside the film.

The load film with transfer coefficient α and specified external potential may be used for very thin layers of resistance to groundwater flow e.g. shallow (surface) grouting in a cavity with specified head. It may also be used for a type of substructured model wherein a local model is constructed but, the boundary condition is specified head well outside the model boundaries. In this case, $\alpha = K * L$, where K is the conductivity of the external medium and L is the distance from boundary to point of specified head, ϕ_a . When this approximation can be applied, it eliminates the need to model all the flow region with a mesh.

An additional important boundary condition is the phreatic surface with specified infiltration (vertical seepage velocity), $q/\cos(\theta)$, where θ is the angle between the surface normal and vertical. In steady state runs, the phreatic surface may be determined by iteratively moving the mesh to approximations of the true surface until the vertical pore velocity at the surface point equals $q/\cos(\theta)/n$. At each iteration ϕ = vertical coordinate at each surface node. This mesh distortion must be performed manually between successive iterations, but may be automated in a future version of this program if use warrants.

In transient analysis, similar time steps with moving phreatic surface may be taken. The vertical velocity of the surface would be:

$$V_s = q/\cos(\theta)/n - V_y \quad (7)$$

where V_y is the vertical pore velocity.

Generally in unconfined transient flow of this type, the compression (storage) effects in equation (1) may be neglected compared to the storage occurring at the phreatic surface.

When the first variation of this pseudo-functional is taken:

$$\frac{\partial \chi_G}{\partial \phi_i} = 0 \quad (8)$$

the following matrix equations result at time step ℓ
(Δt = step length):

(a) For fixed α

$$\begin{aligned} \left[\frac{2}{3} (\bar{K} + \bar{\alpha}) + \frac{\bar{C}}{\Delta t} \right] \phi_j^\ell &= \left[-\frac{1}{3} (\bar{K} + \bar{\alpha}) + \frac{\bar{C}}{\Delta t} \right] \phi_j^{\ell-1} \\ &+ \frac{1}{3} [\bar{Q} + \bar{q} + \bar{\alpha} \phi_a]^{\ell-1} \\ &+ \frac{2}{3} [\bar{Q} + \bar{q} + \bar{\alpha} \phi_a]^\ell \end{aligned} \quad (9a)$$

(b) For variable α

$$\begin{aligned} \left[\frac{2}{3} \bar{K} + \frac{\bar{C}}{\Delta t} \right] \phi_j^\ell &= \left[-\frac{1}{3} \bar{K} - \bar{\alpha} + \frac{\bar{C}}{\Delta t} \right] \phi_j^{\ell-1} \\ &+ \frac{1}{3} [\bar{Q} + \bar{q} + \bar{\alpha} \phi_a]^{\ell-1} \\ &+ \frac{2}{3} [\bar{Q} + \bar{q} + \bar{\alpha} \phi_a]^\ell \end{aligned} \quad (9b)$$

(c) For steady-state solutions we have:

$$[\bar{K} + \bar{\alpha}] \phi_j = \bar{Q} + \bar{q} + \bar{\alpha} \phi_a \quad (9c)$$

The component matrices are:

$$\bar{K} = \sum^e \int_e K_{km} N_{j,x_k} N_{i,x_m} dR, \text{ where } \sum^e \text{ is a sum over all elements,}$$

$$\bar{\alpha} = \sum^e \int_e \alpha N_j N_i dS, \text{ where } S \text{ is the external boundary on the element}$$

$$\bar{\alpha} = \sum^e \int_e \alpha N_i dS$$

$$\bar{C} = \sum^e \int_e nc N_j N_i dR,$$

$$\bar{Q} = \sum^e \int_e Q N_i dR + Q_i, \text{ where } Q_i \text{ is a nodal load (source), and}$$

$$\bar{q} = \sum^e \int_e q N_i dS.$$

These matrices are presented for the general case. In 2-D planar (dR) is ($dx dy$). For the axisymmetric, replace ($dx dy$) by ($2\pi r dz dr$), (dS) by ($2\pi r dS$) and (Q_i) by ($2\pi r Q_i$).

2.1 - Units

The program is written in dimensionless form so that any compatible set of units for the input data will be acceptable. The units, however, are never listed in the output so the user must remember what they are.

As an example consider the following: In metric units, the desirable units of length and time may be the metre and second respectively. The value of K , n and c must therefore be given in input data so that the diffusivity K/nc has units m^2/sec or

length²/time. K in [m/sec], n dimensionless and c in [m^{-1}] will achieve this and are compatible. The constituent units for K are: k in [m^2], μ in [kg/m sec], ρ in [kg/m³] and g in [m/sec²]. Similarly, the additional constituent units for c are: β_f and β_s in [Pa^{-1} or $m \text{ sec}^2/kg$]. It is important to note that the nodal locations must be given in the length unit desired e.g. [m] in this example. Also, loading units must be compatible, e.g.: volumetric source Q in [sec^{-1} , actually $m^3/m^3 \text{ sec}$], boundary normal seepage velocity q in [m/sec], film coefficient α in [sec^{-1}], film external potential ϕ_a in [m] and nodal source Q_i in [m^3/sec].

As an example in English units, consider length in feet and time in hours. Compatible units are then K in [ft/hr], n dimensionless and c in [ft^{-1}]. The constituent units for K are: k in [ft²], μ in [slug/ft hour], ρ in [slug /ft³] and g in [ft/hr²]. The additional constituent units for c are: β_f and β_s in [ft hr²/slug]. The loading units in the given English system are: Q in [hr⁻¹], q in [ft/hr], α in [hr⁻¹], ϕ_a in [ft] and Q_i in [ft³/hr].

Failure to get all units right (compatible) will invalidate results but will not terminate the run.