**GEOHYDROLOGIC STUDY OF THE MICHIGAN BASIN FOR THE APPLICABILITY
OF JACK W. MCINTYRE'S PATENTED PROCESS FOR SIMULTANEOUS GAS
RECOVERY AND WATER DISPOSAL IN PRODUCTION WELLS**

DISCLAIMER

**By
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March 1994

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Work Performed Under Jack McIntyre/DOE Contract No. DE-FG46-92R699202

**For
Jack W. McIntyre
Fort Stockton, Texas**

And

**U.S. Department of Energy
Office of Scientific and Technical Information (OSTI)
Oak Ridge, Tennessee**

**By
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MASTER

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CONTENTS

ABSTRACT	2
INTRODUCTION	2
GEOLOGIC SETTING	2
STRUCTURE AND STRATIGRAPHY	4
STRUCTURE	4
STRATIGRAPHY	6
Precambrian Eras	17
Mesozoic Era	20
HYDROCARBON OCCURRENCE	20
Coal and Coal-Bed Methane	20
Oil and Gas	21
DEVONIAN SHALE GAS OCCURRENCE, CHARACTERISTICS AND RESERVES	25
SHALE GAS OCCURRENCE AND CHARACTERISTICS	25
Antrim Shale Gas Generation	25
Porosity and Permeability of the Antrim Shale	27
Antrim Shale Gas and Water Production	27
SHALE GAS RESERVES	28
Antrim Shale-Estimated Gas in Place	28
HYDROGEOLOGIC SYSTEM	28
AQUIFERS	28
Glacial Drift Aquifer System	28
Bedrock Aquifers	29
CONFINING FORMATIONS	29
GROUNDWATER QUALITY	29
UNDERGROUND INJECTION	32
Formations Accepting Disposal of Produced Water	32
SUMMARY	33
ACKNOWLEDGEMENT	34
DISCLAIMER	34
REFERENCES	35

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ABSTRACT

Geraghty & Miller, Inc. of Midland, Texas conducted a geohydrologic study of the Michigan Basin to evaluate the applicability of Jack McIntyre's patented process for gas recovery and water disposal in production wells. A review of available publications was conducted to identify, 1) natural gas reservoirs which generate large quantities of gas and water, and 2) underground injection zones for produced water. Research efforts were focused on unconventional natural gas formations.

The Antrim Shale is a Devonian gas shale which produces gas and large quantities of water. Total 1992 production from 2,626 wells was 74,209,916 Mcf of gas and 25,795,334 bbl of water. The Middle Devonian Dundee Limestone is a major injection zone for produced water. "Waterless completion" wells have been completed in the Antrim Shale for gas recovery and in the Dundee Limestone for water disposal. Jack McIntyre's patented process has potential application for the recovery of gas from the Antrim Shale and simultaneous injection of produced water into the Dundee Limestone.

INTRODUCTION

A process patented by Jack W. McIntyre has potential economic and environmental advantages over conventional methods of surface treatment and disposal of produced water from gas wells. The process was tested in the Michigan Basin. The process enables a gas well to be used for both production and water disposal. During production, formation fluids enter the wellbore and gas rises to the surface while water moves down into the disposal zone either by gravity or mechanical pumping. This method allows separation of gas and simultaneous disposal of the formation water without the economic cost and environmental liability associated with bringing the water to the surface. A description and discussion of

Jack W. McIntyre's gas recovery/water disposal process (US Patent No. 4,766,957) is summarized in the compendium of the seven basins studied under this contract.

The objective of this investigation was to identify the geologic and hydrologic parameters associated with the production of unconventional natural gas resources in the Michigan Basin and to evaluate potential applicability of Jack McIntyre's patented process. The investigation was conducted by reviewing available publications and literature for information about stratigraphy, structure, hydrocarbon production and hydrologic conditions. No field acquisition of data was performed for this investigation by Geraghty & Miller, Inc.. No testing or evaluation of the effectiveness of Jack McIntyre's gas recovery/water disposal process is presented.

GEOLOGIC SETTING

The Michigan Basin is an interior cratonic basin located in the Great Lakes region of the United States and Canada. The major portion of the circular sedimentary basin is located in the lower peninsula of Michigan. The lower peninsula is in the Central Lowland physiographic province (Figure 1). The Superior Uplands physiographic province borders the northern perimeter of the Michigan Basin.

Topography of the Central Lowlands consists of gently rolling to flat lowlands. Elevations range from about 180 to 1600 feet above sea level. Primary surface drainage is to Lake Superior, Lake Huron and Lake Erie. Low-lying glaciated terrain is filled with many lakes, marshes and bogs.

Figure 1. Physiographic Provinces of the Great Lakes Region (from Weist, 1978).

STRUCTURE AND STRATIGRAPHY

STRUCTURE

The Michigan basin is a circular-shaped bowl with a 16,000 foot accumulation of predominantly Paleozoic rocks (sandstones, marine carbonates, evaporites and shales) resting on Precambrian crystalline and sedimentary basement. The basin is centrally located in the lower peninsula and measures 80,000 square miles in area. Outcrops and subcrops are concentric and progress from older formations at the basin perimeter to younger formations towards the basin center (Catacosinos and others, 1990).

The outer portions of the basin extend into parts of Wisconsin, Illinois, Indiana, Ohio, Ontario, Canada and the Upper peninsula of Michigan (Catacosinos and others, 1990). Regional structures bounding the Michigan Basin are the Kankakee Arch (southwest), Wisconsin Dome and Arch(west), the Canadian Shield (north), the Algonquin Axis (southeast) and the Findlay Arch (south-southeast) (Figure 2).

Faults and fractures trend northwest and southwest. The Howell Anticline, located in the southeast corner of the basin, trends northwest. Some oil and gas field patterns also trend in the same directions (Newcombe, 1933; Catacosinos and others, 1990). A buried rift of Precambrian age has been interpreted from a gravity anomaly (Hinze et al., 1975; Fowler and Kuenzi, 1978;). The rift is associated with over 5,000 feet of Precambrian red clastics and is bounded by crystalline Precambrian rock (Lilienthal, 1978). The rift trends generally northwest-southeast through the center of the basin (Fowler and Kuenzi, 1978; Catacosinos and others, 1990). According to Lilienthal (1978), the Michigan Basin began forming in Precambrian time and continued downwarping through the Paleozoic. Silurian-Salina and Devonian-Detroit River times are believed to be major periods of downwarping.

Figure 2. Regional Structure Map (from Vugrinovich, 1986).

STRATIGRAPHY

The stratigraphic nomenclature used for this report is from the Stratigraphic Succession in Michigan, Chart 1, 1964 published by the Michigan Department of Natural Resources (Figure 3) and nomenclature used by Lilienthal, 1978, Stratigraphic Cross-Sections of the Michigan Basin, Report of Investigation 19, MI DNR, and Briggs, (1968). The Geologic Bedrock Map of Michigan (Kelley, 1968) illustrates the concentric bands of subcrop/outcrop of the basin and includes a generalized cross-section (Figure 4). Figure 5 is an index map for stratigraphic cross-sections from Lilienthal, 1978, and Figures 6 through 12 are the selected cross-sections (From Lilienthal, 1978). The figures selected show the Precambrian through Jurassic stratigraphy from central Michigan and north through Otsego County. Otsego County is the predominant location where Antrim Shale gas activity is occurring. The cross-sections centered around the deepest well drilled in Michigan, (the McClure Oil Company - Sparks, Eckelbarger, Whightsil No. 1-8, Gratiot County) which was advanced to a total depth of 17,466 feet. The logs depict porosity, density, conductivity and lithology of the sedimentary strata. Abundant porosity zones were noted in the Traverse Limestone, the Dundee Limestone and the Lucas Formation of the Devonian System (Lilienthal, 1978).

Time-stratigraphic strata in the Michigan Basin, in ascending order, are the Precambrian basement rocks, the Paleozoic rocks composed of the Cambrian, Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian Systems, the Mesozoic rocks (Jurassic System) and Cenozoic rocks of Quaternary age.

The stratigraphic section in the Michigan Basin is composed of six basic lithologic groups:

- Precambrian granites, gneiss, metasedimentary clastics and metavolcanic.
- Cambrian sandstones, sandy dolomites, dolomites and shales.

Chart 1).

Figure 4. Geologic Bedrock Map of Michigan (from MIDNR, 1968, small scale Map 2)

Figure 5. Index Map Showing Lines of Cross Section (from Lilienthal, 1978).

PLATE 14

B

Figure 7. Stratigraphic Cross Section A-B of the Upper & Middle Ordovician of the Michigan Basin (Lilienthal, 1978).

Figure 8. Stratigraphic Cross Section A-B of the Middle & Lower Silurian of the Michigan Basin (from Lilienthal, 1978).

Figure 9. Stratigraphic Cross Section A-B of the Middle & Lower Devonian & Upper Silurian of the Michigan Basin (from Lilienthal, 1978).

Figure 12. Stratigraphic Cross Section A-B of the Lower Mississippian & Upper & Middle Devonian of the Michigan Basin (from Lillienthal, 1978).

- Ordovician to Middle Devonian carbonates with interbedded evaporites, shaly carbonates, shales and sandstones.
- Late Devonian to Pennsylvanian rocks composed of primarily shale interbedded with sandstone, siltstone and carbonates, and thinly bedded evaporites.
- "Red Beds" of Jurassic Age which lie unconformably on the eroded Pennsylvanian bedrock. The Jurassic "Red Beds" were dissected and eroded during a pre-Pleistocene glacial event.
- Unconsolidated sands, gravels, tills and clays deposited during Pleistocene glacial events (Vugrinovich, 1986).

Precambrian Eras

Through 1978, 30 test holes have been drilled into the Precambrian basement rocks of the Lower Peninsula and most encountered granitic rocks. By 1984, 42 test holes encountered the Precambrian basement in the Lower Peninsula. Depths to the Precambrian basement ranged from 3,342 to 12,176 feet (Catacosinos and others, 1991). Geophysical surveys suggest mafic rocks are widespread in the Precambrian basement of the Michigan Basin (Hinze and Merritt, 1969; Lilienthal, 1978). Briggs' (1968) generalized columnar section of Michigan showed lavas, conglomerate, iron formations, schist, gneiss and granites as Precambrian rocks. Four major provinces are found in the Lower Peninsula of Michigan. They are the Grenville, Central, Penokean and the rift zone (Hinze and Merritt, 1969). Over 5,000 feet of red beds were encountered beneath the Mt. Simon sandstone during the McClure Oil Company deep test. The red beds are believed to be of late Keweenawan Age (Lilienthal, 1978).

A generalized stratigraphic succession overlying the Precambrian basement with general lithology and maximum general thickness is presented below.

Cambrian System

Jacobsville Sandstone - Sandstone - 1100 ft.

Lake Superior Group**Munising Formation**

Mt. Simon - Sandstone - 1100 ft.

Eau Claire - Sandstone, limestone - 100 ft.

Dresbach - Sandstone - {90 ft.}

Franconia - Sandstone - {included in Dresbach}

Trempealeau Formation - Dolomite - 750 ft.

Ordovician System

Prairie du Chien Group - Dolomite, sandstone - 400 ft.

Oneota Dolomite

New Richmond Sandstone

Shakopee Dolomite

St. Peter Sandstone (Chazyan) - Sandstone - 200 ft.

Black River Group - Limestone, dolomite - 500 ft.

Trenton Group - Limestone, dolomite - 500 ft.

Richmond Group (Richmond-Maysville) - Shale, limestone - 450 ft.

Utica Shale - Shale - 500 ft.

Silurian System

Cataract Group - Dolomite, shale - 200 ft.

Niagaran Group - (Clinton) - Dolomite, shale - 1000 ft

Salina Group - Salt, anhydrite, dolomite - 3150 ft.

A-1 Evaporite - Salt

A-1 Carbonate - Dolomite

A-2 Evaporite - Salt

A-2 Carbonate - Dolomite

B Evaporite - Salt

C Unit - Argillaceous dolomite

D Evaporite - Salt

E Unit - Dolomite

F Evaporite - Salt

G Unit - Argillaceous dolomite

Bass Islands Group - Dolomite, anhydrite - 700 ft.

Devonian System

Garden Island Formation - Dolomite, shale, sand - 100 ft.

Bois Blanc Formation - Dolomite, limestone, chert - 1100 ft.

Detroit River Group - Dolomite, anhydrite, salt, sandstone - 1700 ft.

Sylvania Sandstone

Amherstburg Formation

Lucas Formation

Dundee Limestone - Limestone - 800 ft.}

Rogers City Limestone - Limestone {included in Dundee}

Traverse Group - Shale, Limestone - 800 ft.

Bell Shale

Alpena Limestone

Squaw Bay Limestone

Antrim Shale - Shale, limestone - 600 ft.

Ellsworth Shale - Shale - 600 ft.

Mississippian System

Bedford Shale

Berea Sandstone

Sundbury Shale

Coldwater Shale - Shale, sandstone - 1300 ft.

Marshall Sandstone - Sandstone - 350 ft.

Grand Rapids Group

Michigan Formation - Shale, gypsum, dolomite - 600 ft.

Bayport Limestone - Limestone, dolomite - 150 ft.

Pennsylvanian System

Saginaw Formation - Shale, limestone, coal, sandstone - 550 ft.

Grand River Formation - Sandstone - 200 ft.

Mesozoic Era

Jurassic System

"Red Beds" - Sand, clay - 200 ft.

Cenozoic Era

Quaternary System

Glacial Drift - Boulder, clay, gravels - 850 feet

HYDROCARBON OCCURRENCE

Coal and Coal-Bed Methane

The Pennsylvanian Saginaw Formation contains coal seams that are thin and laterally discontinuous. Between 1835 and 1949, 46 million short tons of coal were produced in

Michigan (Cohee et al., 1950; Kalliokoski and Welch, 1977). One estimate of identified reserves of bituminous coal remaining in the Saginaw Formation is 205 million short tons (Averitt, 1974). Most of the coal is at shallow depths of less than 1,000 feet and covered with glacial deposits.

A review of available literature was conducted to determine if any coal-bed methane potential existed in the Saginaw Formation. No data indicating significant coal-bed methane potential was found.

The Michigan Basin was not identified as a coal-bed methane prospect in the Quarterly Review of Methane From Coal Seams Technology (ICF Resources, Inc., Vol. 7, No. 3, March, 1990).

Oil and Gas

Oil and gas production occurs in Mississippian to Ordovician-age formations. In the Mississippian formations, hydrocarbon production is primarily in sandstones such as the Stray and Berea. Reservoir/trap consist of a combination of stratigraphic and structural types. The Devonian shales, such as the Antrim, are of the combination stratigraphic/structural type reservoir/trap. Hydrocarbons in Devonian carbonates such as the Traverse and Dundee Limestones, are of the anticlinal reservoir/trap type. Hydrocarbons in Silurian carbonates, such as the Niagaran reefs, are of the stratigraphic reservoir/trap type. Ordovician carbonates have hydrocarbon accumulations in combination stratigraphic and structural reservoir/traps. The Trenton and Black River units are examples of this type. Hydrocarbons found in the Ordovician Glenwood and St. Peter Sandstones are in anticlinal reservoir/traps (Catacosinos and others, 1991).

Production records from the Michigan Department of Natural Resources and Michigan Public Service Commission were reviewed for natural gas formations which produce significant quantities of water and gas. Formations which produce both oil & gas,

or gas condensate and water were not considered for potential application of Jack McIntyre's patented process. Upon initial review, two producing intervals were identified for closer evaluation, the Ordovician Prairie Du Chien Group (PDC) and the Antrim Shale.

The PDC produces gas, gas condensate, oil and water, however some wells produce only gas and water. The PDC is stratigraphically the deepest gas producing zone in the Michigan Basin. Production records for the PDC indicate the majority of the gas wells produced little or no water (MI DNR, 1991 AWSUM, 1993). Evaluation of the PDC for potential application of Jack McIntyre's patented process would require a more localized study to identify individual wells which might benefit from application of the technology. The technology may also be of benefit to other specific wells in other fields. This report focused on a review of general field characteristics for the majority of production wells.

The Antrim Shale produces significant quantities of natural gas and water. Low thermal maturation of the organic rich black shale facies appears to have limited oil potential in the formation. Total Antrim Shale gas and water production for 1992 totaled 74,209,916 Mcf and 25,795,334 bbl, respectively (MSPC Antrim Gas Well Database, 1993) (Table 1).

The Stratigraphic Succession of Michigan Chart 1 shows oil and gas producing zones (Figure 3) except for the Devonian Antrim Shale (the shallow play) and the Ordovician St. Peter Sandstone, the overlying Glenwood Formation and underlying PDC (the deep play "Massive Sand").

Potential prospects in the Cambrian Munising Group includes the Galesville and Franconia formations. Shows were reported in the Galesville Sandstone, the Franconia Formation and the underlying Mt. Simon Sandstone. The Cambrian Mt. Simon Sandstone is a potential hydrocarbon exploration prospect (Catacosinos, 1979; Catacosinos and others, 1991).

MPSC ANTRIM GAS WELL DATABASE 1992

FIELD NAME	OPERATOR	WELLS IN FIELD	WELLS ON-LINE	MAX WELLS ON-LINE	FIELD PRODUCTION		MONTHLY AVERAGE PER WELL		DAILY AVERAGE PER WELL	
					GAS (MCF)*	WATER (BARRELS)	GAS (MCF)*	WATER (BARRELS)	GAS (MCFD)*	WATER (BARRELS)
BRADFORD LAKE ANTRIM	ANTRIM DEVELOPMENT	21	19	19	276830	97827	1223	426	40	14
DOODGE LAKE ANTRIM	ANTRIM DEVELOPMENT	20	19-20	20	277866	26886	1213	113	40	4
E-Z ANTRIM PROJECT	ANTRIM DEVELOPMENT	10	10	10	246851	12399	2066	103	87	3
TOWER ANTRIM PROJECT	ANTRIM DEVELOPMENT	24	21-24	24	681948	144840	2848	587	84	18
ASE #1 HAYES	ANTRIM GAS INC	13	12-13	13	239307	78818	1856	516	81	17
ASE #2, ASE #38	ANTRIM GAS INC	27	24-27	27	1078737	112201	3362	357	111	12
ASE #3A STATE	ANTRIM GAS INC	16	13-16	16	373415	45143	2138	259	70	8
ASE #4, ASE #48	ANTRIM GAS INC	17	13-17	17	363400	116738	2010	641	66	21
ASE #5, ASE #58	ANTRIM GAS INC	23	17-23	23	1233623	147768	5104	607	167	29
ASE #5C, ASE #12	ANTRIM GAS INC	13	11-13	13	958423	123011	6717	851	220	28
ASE #6, ASE #68	ANTRIM GAS INC	40	28-40	40	1931924	336754	4642	813	152	27
ASE #7, ASE #78	ANTRIM GAS INC	10	9-10	10	254788	45868	2318	420	76	14
ASE #7C	ANTRIM GAS INC	7	7	7	88866	15762	1058	188	35	8
NMAG #2, NMAG #3	ANTRIM GAS INC	34	32-34	34	704279	69942	1736	163	57	5
SCV	ANTRIM GAS INC	64	61-62	62	2845919	385807	3636	520	126	17
AXFORD PROJECT	DELTA OIL CO., INC.	20	0-20	20	261990	171212	2701	1827	88	60
BOUGHNER PROJECT	DELTA OIL CO., INC.	15	11-15	15	273364	167770	1856	1158	61	38
GARDNER PROJECT	DELTA OIL CO., INC.	28	21-28	28	641013	429532	2808	1438	92	47
KUBACKI PROJECT	DELTA OIL CO., INC.	19	15-19	19	412591	265331	2177	1395	71	46
SCHRAEDER PROJECT	DELTA OIL CO., INC.	32	32	32	835181	480735	2175	1252	71	41
JA BOTT ANTRIM	DEVOMAN ENERGY, INC.	18	13-18	18	734163	89327	4224	524	136	17
CHESTER 8	DON YOHE ENTERPRISES	29	29	29	581399	60154	1671	173	85	5
WINTER ANTRIM	DON YOHE ENTERPRISES	17	16-17	17	429170	244360	2203	1262	72	41
BAGLEY W ANTRIM	FPI ANTRIM ONE, INC	35	35	35	365831	444740	871	1059	29	35
CHESTER W ANTRIM	FPI ANTRIM ONE, INC	31	30-31	31	514917	74429	1426	208	47	7
NORTH BAGLEY ANTRIM	HR FRUEHAUF	36	30-36	35	2183414	0	5864	0	192	0
SOUTH (OTSEGO LAKE)	HR FRUEHAUF	29	24-28	28	2191807	0	6924	0	227	0
N VIENNA 27	JS INC	10	0-10	10	78808	205570	960	2570	32	84
LEO M RILEY	LEO M. RILEY COMPANY	7	7	7	263786	18151	3140	216	103	7
CHARLTON 14	MACK OIL CORPORATION	13	13	13	360383	103337	2310	662	78	22
MAYER	MACK OIL CORPORATION	13	13	13	291083	36480	1866	234	61	8
STATE-HAYES	MACK OIL CORPORATION	11	11	11	64008	47348	468	359	16	12
VIENNA-CHARLTON	MACK OIL CORPORATION	11	11	11	208775	58801	1582	446	52	15
FREDERIC I	MERCURY EXPLORATION	11	0-10	10	96453	22468	9645	2247	224	72
FREDERIC II	MERCURY EXPLORATION	11	0-11	11	23292	19283	2117	1753	68	57
FREDERIC III	MERCURY EXPLORATION	11	0-11	11	20833	18328	1867	1686	60	54
FREDERIC IV	MERCURY EXPLORATION	10	0-10	10	5973	37598	597	3760	19	121
FREDERIC PROJECT	MERCURY EXPLORATION	43	0-42	42	1110379	1048805	3663	3650	122	120
BASS LAKE	MUSKEGON DEVELOPMENT	22	20	20	816140	138296	3401	578	112	18
CAULKINS LAKE	MUSKEGON DEVELOPMENT	23	17	17	843171	539256	3153	2584	103	68
CRAPO LAKE	MUSKEGON DEVELOPMENT	34	34	34	740745	87549	1816	216	60	7
DOVER	MUSKEGON DEVELOPMENT	20	20	20	414113	341458	1728	1423	56	47
EAST HEART LAKE	MUSKEGON DEVELOPMENT	23	21	21	573772	179635	2277	714	75	23
EMERALD LAKE	MUSKEGON DEVELOPMENT	8	0-8	8	298395	69967	3391	761	111	25
GINGELL LAKE	MUSKEGON DEVELOPMENT	13	13	13	424888	118184	2724	758	86	28
HEART LAKE	MUSKEGON DEVELOPMENT	17	17	17	215305	71921	1055	353	35	12
HORICON 15	MUSKEGON DEVELOPMENT	12	12	12	452438	57854	3142	402	103	13
LITTLE CRAPO LAKE	MUSKEGON DEVELOPMENT	29	29	29	894208	125941	2570	362	84	12
LOWER CHUB LAKE	MUSKEGON DEVELOPMENT	19	19	19	728361	282623	3199	1240	105	41
MITCHELL LAKE	MUSKEGON DEVELOPMENT	8	8	8	42789	82972	713	1383	24	46
NO LAKE	MUSKEGON DEVELOPMENT	37	30	30	1050189	184237	2917	512	96	17
NORTH HIDDEN LAKE	MUSKEGON DEVELOPMENT	16	16	16	263727	210286	1498	1109	49	36
OPAL LAKE	MUSKEGON DEVELOPMENT	12	12	12	643130	116008	4486	808	147	29
OTSEGO LAKE	MUSKEGON DEVELOPMENT	32	30	30	1055101	27799	2931	77	96	3
PERCH LAKE	MUSKEGON DEVELOPMENT	9	0-8	8	22017	54519	2202	6452	72	178
PIGEON RIVER	MUSKEGON DEVELOPMENT	10	0-9	9	242450	209764	2449	2119	80	70
ROUND LAKE	MUSKEGON DEVELOPMENT	13	13	13	375715	183360	2408	1175	79	36
SOUTH HIDDEN LAKE	MUSKEGON DEVELOPMENT	22	15-20	20	478677	233856	2542	1230	63	40
TRAVERSE LAKES	MUSKEGON DEVELOPMENT	12	11	11	421712	216212	3195	1638	105	54
VRUNG LAKE	MUSKEGON DEVELOPMENT	13	13	13	233187	68096	1495	438	48	14
BAGLEY EAST	NOMECCO OIL & GAS CO.	24	17-24	24	407980	391805	1656	1579	54	52
CHESTER EAST	NOMECCO OIL & GAS CO.	17	7-11	11	846243	399326	8422	3676	276	131
HAYES 10	NOMECCO OIL & GAS CO.	28	18-23	23	336397	280292	1350	1122	44	37
BIG BASS LAKE ANTRIM	NORTHWESTERN	10	10	10	472715	354060	3639	2950	129	57
BAGLEY 17	OILFIELD INVESTMENTS	24	24	24	318179	94256	1105	327	36	11
CHESTER 12 (FOX)	OILFIELD INVESTMENTS	26	26	26	711482	123026	2280	394	75	13
ELMIRA 34	OILFIELD INVESTMENTS	18	14-18	18	153889	337118	750	1853	25	54
WARNER 36	OILFIELD INVESTMENTS	22	20-22	22	941452	800826	3671	3108	120	102
CHARLTON #3-88	SRW, INC.	16	16	16	556928	14794	2899	77	96	3
CHARLTON 16 PROJ1-88	SRW, INC.	16	15-16	16	581963	104955	3078	557	101	18
CHESTER 7/OTSEGO 12A	SRW, INC.	9	0-9	9	124744	29810	3581	880	116	28
OTSEGO 12-OPAL LAKE	SRW, INC.	9	8-9	9	461187	81840	9804	807	194	26
OTSEGO LAKE #1-88	SRW, INC.	26	26	26	891807	94898	1801	303	86	19

Table 1. MPSC Antrim Gas Well Database 1992.

ALBERT 16 GAS FIELD	TRENDWELL OIL CORP	22	21-22	22	464318	264663	1744	1616	87	34
CHARLTON 27 GAS	TRENDWELL OIL CORP	46	46	46	1242240	108881	2308	184	75	6
VIENNA 16 GAS FIELD	TRENDWELL OIL CORP	13	8-13	13	108283	402964	2306	6163	78	202
VIENNA 26 GAS FIELD	TRENDWELL OIL CORP	12	0-12	12	103310	406131	1118	4617	26	156
VIENNA 31 GAS FIELD	TRENDWELL OIL CORP	27	26-27	27	621088	235894	1846	743	64	24
S. CHARLTON 4	WARD LAKE DRILLING	12	12	12	682436	48676	4739	336	186	11
BAGLEY 23 FIELD	WARD LAKE ENERGY	18	14	14	258477	12228	1538	73	80	2
BAGLEY 23 H	WARD LAKE ENERGY	3	1-3	3	110653	13470	5586	673	183	22
BAGLEY 24 FIELD	WARD LAKE ENERGY	4	4	4	143786	5378	2986	112	98	4
CHAR 18/DOVER 13	WARD LAKE ENERGY	18	8-18	18	442753	292772	2143	1460	70	47
CHARLTON 11	WARD LAKE ENERGY	17	17	17	424004	67273	2078	330	88	11
CHARLTON 12 - WARD LK	WARD LAKE ENERGY	18	10-18	18	415568	80708	2561	508	84	17
CHARLTON 18 FIELD	WARD LAKE ENERGY	4	0	0	0	0	0	0	0	0
CHARLTON 19 FIELD	WARD LAKE ENERGY	19	19	19	481063	210765	1978	924	65	30
CHARLTON 2 FIELD	WARD LAKE ENERGY	20	20	20	661700	208548	2718	873	88	29
CHARLTON 21 FIELD	WARD LAKE ENERGY	22	22	22	446531	77682	1981	294	86	10
CHARLTON 32 FIELD	WARD LAKE ENERGY	17	0-17	17	588243	808688	2975	2710	97	88
CHARLTON 28	WARD LAKE ENERGY	6	6	6	178001	28637	2472	366	81	12
CHARLTON 30 FIELD	WARD LAKE ENERGY	10	10	10	264612	44494	2205	371	72	12
CHARLTON 31	WARD LAKE ENERGY	14	14	14	678166	86108	3442	382	113	12
CHARLTON 32 FIELD	WARD LAKE ENERGY	21	21	21	788426	64488	3122	288	103	8
CHARLTON 32 - B	WARD LAKE ENERGY	2	2	2	107873	9214	4487	384	147	13
CHARLTON 34	WARD LAKE ENERGY	6	0-6	6	78819	10807	1832	253	80	8
CHARLTON 36	WARD LAKE ENERGY	12	12	12	565560	88003	3635	867	129	22
CHARLTON 36 FIELD	WARD LAKE ENERGY	22	0-22	22	658993	255483	3173	1303	104	43
CHARLTON 7 FIELD	WARD LAKE ENERGY	22	22	22	403054	45956	1827	174	80	6
CHARLTON 8 FIELD	WARD LAKE ENERGY	8	8	8	209346	86895	2181	895	72	23
CHESTER 10 FIELD	WARD LAKE ENERGY	8	8	8	285514	48755	2874	508	98	17
CHESTER 18	WARD LAKE ENERGY	52	52	52	1273000	146191	2040	234	87	8
CHESTER 22	WARD LAKE ENERGY	20	20	20	569707	201386	2332	839	76	26
CHESTER 23	WARD LAKE ENERGY	25	25	25	634295	253381	2128	845	70	26
CHESTER 27	WARD LAKE ENERGY	5	5	5	208614	31783	3477	530	114	17
DOVER 24	WARD LAKE ENERGY	3	3	3	108044	63884	2948	2330	98	78
HAYES 12 FIELD	WARD LAKE ENERGY	10	10	10	125886	122387	1048	1020	34	33
N. CHARLTON 24	WARD LAKE ENERGY	28	28	28	747219	248600	2481	829	62	27
N. CHARLTON 31	WARD LAKE ENERGY	14	0-14	14	47963	20208	1778	770	56	26
S. CHARLTON 8 FIELD	WARD LAKE ENERGY	12	12	12	697371	77903	4543	638	158	18
ALBERT #1	TERRA ENERGY LTD	10	0-10	10	21722	37212	724	1240	23	41
ANTRIM RESOURCES #2	TERRA ENERGY LTD	18	11-13	13	198821	13411	1463	101	46	3
BAGLEY 14 ANTRIM	TERRA ENERGY LTD	6	6	6	373612	100729	5183	1388	170	48
BAGLEY 11 D	TERRA ENERGY LTD	4	0-4	4	160288	36172	6612	1580	213	82
BAGLEY 16 EAST	TERRA ENERGY LTD	1	0-1	1	8358	3468	1589	867	52	26
BAGLEY 22	TERRA ENERGY LTD	1	1	1	67348	2106	4779	178	157	6
BAGLEY 400	TERRA ENERGY LTD	22	22	22	381680	63622	1332	242	44	6
BAGLEY 700	TERRA ENERGY LTD	13	8-13	13	207802	243880	1770	2203	58	72
BART STAR	TERRA ENERGY LTD	9	0-9	9	2082	12295	344	2048	11	88
BLACK ANTRIM	TERRA ENERGY LTD	22	22	22	889580	641560	3370	2051	110	67
CHARLTON EAST	TERRA ENERGY LTD	30	24-30	30	1351853	213040	4526	714	148	23
CHARLTON WEST	TERRA ENERGY LTD	44	40-44	44	2147282	278165	4406	568	148	18
CHESTER 31	TERRA ENERGY LTD	5	5	5	251716	44736	4186	748	138	24
CHESTER 7-11	TERRA ENERGY LTD	13	13	13	458552	145674	2938	838	98	31
CORWITH	TERRA ENERGY LTD	25	0-12	12	58258	224922	885	3648	29	120
CUSTER/MANCELONA WEST	TERRA ENERGY LTD	31	31	31	228662	142305	808	383	20	13
DOVER ANTRIM SOUTH	TERRA ENERGY LTD	21	16-21	21	1143982	347128	5341	1688	175	86
DOVER ANTRIM WEST	TERRA ENERGY LTD	18	18	18	381509	418308	1831	2184	90	72
ELMER RUDD #1	TERRA ENERGY LTD	10	0-10	10	24787	364842	413	6082	14	188
LIVINGSTON	TERRA ENERGY LTD	4	0-3	3	870	4578	290	1825	9	49
LUCKY 18	TERRA ENERGY LTD	17	17	17	206308	128063	1021	626	33	21
MANCELONA EAST	TERRA ENERGY LTD	10	10	10	115518	102937	963	858	32	26
MID CHARLTON 1 SOUTH	TERRA ENERGY LTD	10	10	10	411805	35094	3430	292	112	10
MID CHARLTON PHASE 1	TERRA ENERGY LTD	17	15-17	17	1148738	174308	6748	884	189	29
MID CHARLTON PHASE 2	TERRA ENERGY LTD	29	17-29	29	1380553	505890	4378	1548	144	84
NADV #1	TERRA ENERGY LTD	7	7	7	86880	118846	794	1418	28	46
NADV #2	TERRA ENERGY LTD	9	9	9	33754	55985	313	515	10	17
NADV #3	TERRA ENERGY LTD	11	11	11	101752	107782	771	817	25	27
NADV #4	TERRA ENERGY LTD	20	20	20	82389	122862	280	511	8	17
NADV #7	TERRA ENERGY LTD	8	7-8	8	455666	971818	5684	7791	188	288
SAWDUST PROJECT	TERRA ENERGY LTD	6	0-6	6	419358	284498	6364	4492	208	147
SCHROEDER PROJECT	TERRA ENERGY LTD	10	10	10	383118	135882	3276	1133	107	37
SKIBA CAPLE	TERRA ENERGY LTD	11	11	11	208278	137219	1583	1040	51	34
SOUTH CAPLE	TERRA ENERGY LTD	24	24	24	298890	148918	1041	520	34	17
VIENNA #2	TERRA ENERGY LTD	18	13-18	18	464189	647310	2560	3751	63	123
VIENNA #3	TERRA ENERGY LTD	10	10	10	217341	186878	1811	1297	88	43
VIENNA #4	TERRA ENERGY LTD	6	0-6	6	63179	248831	1381	8407	45	176
CHESTER 1 CPP	WOLVERINE ENVIR PRO	17	17	17	981817	108348	2801	538	95	18
HARDWOOD ANTRIM	WOLVERINE ENVIR PRO	29	0-29	29	216704	414586	1714	3651	86	118
HIGHWAY 612 ANTRIM	WOLVERINE ENVIR PRO	6	0-6	6	46141	104813	1463	3431	48	112
MARSTRAND 34 ANTRIM	WOLVERINE ENVIR PRO	20	10-20	20	631120	347283	4728	2075	185	88
MIDCHARLTON 28 EAST	WOLVERINE ENVIR PRO	18	13-18	18	343773	27820	2023	182	98	5
MIDCHARLTON 28 WEST	WOLVERINE ENVIR PRO	13	10-13	13	387827	32388	2818	230	92	7
PAPPI ANTRIM	WOLVERINE ENVIR PRO	5	0-5	5	3763	21889	378	2179	12	79
SHERIDAN CREEK	WOLVERINE ENVIR PRO	5	0-5	5	5843	12900	684	1280	18	62
ST MAPLE FOREST/ANT	WOLVERINE ENVIR PRO	28	28	28	488888	382626	1856	1182	80	58

REPORT INTERVAL 1/82 TO 12/98

TOTALS

2788

2626

74288918

26798334

Table 1 (cont'd). MPSC Antrim Gas Well Database 1992.

DEVONIAN SHALE GAS OCCURRENCE, CHARACTERISTICS AND RESERVES

SHALE GAS OCCURRENCE AND CHARACTERISTICS

Antrim Shale Gas Generation

The Antrim Shale is composed of black, calcareous gray, clastic gray and green shale lithologies. Gas occurs in the two black shale facies which are rich in organics. These gas producing horizons are in the Lower Antrim. The Lower Antrim is found at depths between 1,400 and 1,600 feet in Otsego County (Manger, 1991; Lang and Oliver, 1991). The two black shale facies are commonly known as the "Upper" and "Lower Black Shales". A "Middle" gray shale lies between the "Upper" and "Lower Black Shales". The "Lower Black Shale" facies overlies a "Lower" gray shale (Manger and Curtis, 1991) (Figure 13).

According to Manger and Curtis, the Antrim Shale gas is thermogenic in origin and was generated in place by thermal maturation of kerogen. The kerogen is believed to be of marine origin. Deposition occurred in a reducing environment. The Antrim Shale is believed to be the source and reservoir of the gas. Most Antrim wells are completed in the Upper Black Shale facies. Some wells are completed in just the Upper or Lower Black Shale while other wells are completed in both facies.

Antrim Shale gas production occurs from gas desorption of the organic rich black shale facies along natural fracture systems. Gas storage in the black shales occurs in matrix porosity and by adsorption. In one study, laboratory measurements on core samples from the Lower Antrim's Upper Black facies resulted in a calculated gas concentration of 12 Bcf/section for a thickness of 80 feet. A calculated gas concentration of 4 Bcf/section was reported for core samples from the Lower Black Shale facies. A comparison of the measurements of the two intervals suggests that the Lower Black shale interval has a higher adsorbed gas capacity than the Upper Black. The total thickness of the Lower Black Shale in the area of study was approximately 20 feet (Lang and Oliver, 1991).

Figure 13. Antrim Shale Stratigraphy (from Manger and Curtis, 1991, GRI, Devonian Gas Shales Technology Review).

Porosity and Permeability of the Antrim Shale

Matrix porosity measurements of core samples from the Upper Black, Middle Gray and Lower Black, ranged from 7 to 12 %, 6 to 10 %, and 6 to 14 %, respectively. The average matrix porosity was on the order of 10% (Luffel, and others, 1991; Manger and Curtis, 1991).

Permeability of the Antrim Shale is along naturally occurring fractures. Dominant fracture orientations measured in one study trended northeast and southwest with some minor northwest to southeast orientations. The study also suggested that the number, intensity and the character of the fracture sets may be affected by mineralogy of the shale and structural features (Lang and Oliver, 1991). Permeability measurements of one well in Otsego County was 0.8 millidarcies (md) for gas and 20 md for water (Smith, 1991). Additional permeability measurements of wells in the Antrim Shale averaged 0.2 md and 0.6 md for gas and water, respectively (Reeves, and others, 1992).

Antrim Shale Gas and Water Production

1990 Antrim gas production reported from about 1,400 wells totaled more than 100 MMscfd. Water production in 1990 totaled about 60,000 BWPD. In December, 1990, the average well produced 74 Mscfd and 42 BWPD. The average depth of 814 conventional Antrim gas wells completed in 1990 was 1,672 feet. Initial potentials for the 814 wells averaged 45 Mcfd/d and 90 bwd. In 1990, 33 conventional brine disposal wells were drilled into the Dundee formation to an average depth of 2,480 feet. Also in 1990, 44 wells were drilled and permitted as combination production/disposal wells, i.e. "waterless" completions. These "waterless" completion wells were located in Antrim, Montmorency and Otsego Counties. Thirty-three of the wells are located in Otsego County. Thirty-five of the "waterless" completion wells drilled in 1990 have been reported to average initial potentials of 88 Mcfd/d (Roberts, 1991).

Total 1992 Antrim Shale production from 2,626 wells was 74,209,916Mcf of gas and 25,795,334 bbl of water (MSPC Antrim Gas Well Database, 1993).

SHALE GAS RESERVES

Antrim Shale-Estimated Gas in Place

The Antrim Shale was reported to have a potential for up to 80 scf of adsorbed gas per ton of shale and there is a reasonable expectation that there is potential for gas in the Antrim Shale outside of Otsego County (Manger and Curtis, 1991). The black shale facies is thought to cover an area of approximately 30,000 square miles. The estimated in-place gas resources of the Antrim Shale range from 16 bcf/square mile to over 35 bcf/square mile (Decker, 1992).

HYDROGEOLOGIC SYSTEM

AQUIFERS

The principal aquifers in the lower peninsula of Michigan are the glacial drift deposits and the consolidated Paleozoic bedrock formations.

Glacial Drift Aquifer System

Outwash, glaciofluvial, lacustrine sand and till deposits are the four types of glacial aquifers present over most of the basin. Most wells are less than 400 feet deep. Glacial deposits are up to 1,200 feet thick.

Bedrock Aquifers

The principal freshwater bedrock aquifers are in descending order the Pennsylvanian Saginaw Formation, the Mississippian Marshall Formation, Silurian-Devonian rocks, Cambrian-Ordovician rocks, and Precambrian sandstone that outcrop near the surface. The Precambrian sandstone aquifers are confined to the Upper Peninsula and are not in the area of study. Principal aquifers of Michigan are shown in Figure 14. Table 2 shows common well depths and yields.

Transmissivity of the Saginaw Formation ranges from 130 to 3,300 square feet per day. Transmissivity values for the Marshall Formation range from 2,700 to 67,000 square feet/day.

CONFINING FORMATIONS

The general boundary for the separation of the freshwater aquifers and the brine containing formations is the Coldwater Shale. The Marshall Formation overlies the Coldwater and except for the shallow outcrops of older formations which supply freshwater near the perimeter of the Michigan Basin, is the basal freshwater aquifer.

Several shale formations, such as the Sunbury, the Bedford, the Ellsworth and the Coldwater confine the lower Antrim Shale water and gas. The Dundee Limestone is confined by the Bell Shale and the Traverse Group.

GROUNDWATER QUALITY

Generally, freshwater is obtained from the glacial deposits and shallow Paleozoic limestone and sandstone formations that outcrop at the surface. Total dissolved solids (TDS) concentration of glacial aquifers ranges from 100 to 500 mg/L. Average TDS concentration of the Saginaw Formation is 1,600 mg/L. In some areas, TDS concentrations for the Saginaw Formation can range from 300 to 800 mg/L. The Marshall Formation

Figure 14. Principal Aquifers in Michigan (from USGS Water Supply Professional Paper 2275, 1985).

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U. S. Geological Survey and Michigan Department of Natural Resources, Geological Survey Division]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Glacial aquifers:					
Outwash and glaciofluvial deposits: Sand and gravel, contains silt and clay in places. Mostly unconfined.	25 - 200	400	1 - 1,000	2,000	Water generally hard; large iron concentrations common; deep wells may produce salty water in places.
Lacustrine sand: Sand, some gravel, and interbedded silt and clay. Mostly unconfined.	25 - 100	200	80 - 500	500	Used for domestic supplies in Saginaw Bay and Detroit areas; is salty in places at depth.
Till: Intermixed clay, silt, sand, gravel and boulders; sand and gravel lenses abundant in some areas. Confined and unconfined.	25 - 200	400	5 - 200	200	Primary source of domestic supply in western Upper Peninsula.
Bedrock aquifers:					
Saginaw Formation: Sandstone, siltstone, some shale, limestone, and coal. Mostly confined.	25 - 300	500	100 - 300	1,000	One of Michigan's most important bedrock aquifers; water generally hard; salty in places at depth.
Marshall Formation: Sandstone and siltstone. Mostly confined or semiconfined, unconfined at places.	25 - 200	400	100 - 500	1,500	Another of Michigan's important bedrock aquifers; salty in places and at depth.
Silurian-Devonian rocks: Limestone and dolomite; some shale and sandstone. Mostly confined.	25 - 150	200	10 - 300	500	Important aquifer in parts of eastern Upper Peninsula; water commonly hard.
Cambrian-Ordovician rocks: Sandstone, limestone, and dolomite. Mostly confined.	25 - 150	200	10 - 100	500	Important aquifer in eastern Upper Peninsula; water commonly very hard; salty in places and at depth.
Precambrian sandstone: Sandstone interbedded with siltstone. Mostly confined.	25 - 400	500	5 - 50	100	Important aquifer in western Upper Peninsula; salty in places.

Table 2. Aquifer and Well Characteristics in Michigan (from USGS Water Supply Professional Paper 2275, 1985).

usually has a TDS concentration of less than 500 mg/L. Silurian-Devonian aquifers generally have a TDS concentration of less than 500 mg/L. Cambrian-Ordovician aquifers have a TDS concentration range of about 150 to 2,000 mg/L. Groundwater quality deteriorates with depth and towards the center of the Michigan basin. Deeply buried aquifers contain saline or brine waters (USGS, Water-Supply Professional Paper 2275, 1985).

UNDERGROUND INJECTION

Formations Accepting Disposal of Produced Water

Many formations, primarily dolomites and sandstones, are used for injection of produced waters. Most shales and limestone sequences that are continuous and not fractured are good confining units. Records were reviewed for current injection zones for produced water from the Antrim Shale. Current Antrim Shale "Waterless Completions" Class II production/disposal wells are permitted to inject into the Middle Devonian Dundee Limestone. The Dundee has very good porosity and permeability where it is dolomitized (Western Michigan University, 1981). Permeabilities measured up to 650 md. The Dundee is known for a pronounced hydraulic low in the central area of the Lower Peninsula which is believed to be related to hydrocarbon production (Vugrinovich, 1986).

A potential injection zone for deep gas plays with significant water production is the Cambrian Mt. Simon Sandstone. The Mt. Simon Sandstone is believed to have the potential to accept a large quantity of fluids for disposal. Porosity ranges from 4 to 20 percent. Average permeability measured was 32 md. However the Mt. Simon is used for water supply in southwestern Michigan and in some areas of the basin, the cost of deep injection may not be economical (Briggs, 1968).

SUMMARY

The Michigan Basin is an interior cratonic basin with a Paleozoic sedimentary section up to 16,000 feet in total thickness. Quaternary glacial drift deposits extend across most of the basin and overlie Jurassic and Paleozoic bedrock formations.

Pennsylvanian coal seams of the Saginaw Formation are generally at shallow depths (<1000 feet), laterally discontinuous and were not reported to be a potential major resource for coal-bed methane gas. Oil and gas is produced from Mississippian to Ordovician-age formations. The majority of the fields produce oil and gas along with water and were not considered for this report. A more localized study of individual wells which produce gas and significant quantities of water may reveal potential application of Jack McIntyre's gas recovery/water disposal process.

The Devonian Antrim Shale is a major natural gas reservoir which produces significant quantities of gas and water. To date, over 2,700 wells have been completed in the Antrim Shale. Antrim Shale gas and water annual production for 1992 totaled 74,209,916 Mcf of gas and 25,795,334 bbl of water, respectively, for 2,626 on-line wells in 156 fields. The Middle Devonian Dundee Limestone is a major injection zone which is used for disposal of produced waters from the Antrim Shale. "Waterless Completion" wells are producing Antrim Shale gas and simultaneously disposing of water into the Dundee Limestone.

Jack W. McIntyre's patented process for gas recovery and water disposal has potential application for dewatering of the Antrim Shale into the Dundee Limestone in the Michigan Basin. "Waterless" completion wells are currently in use in the Antrim Shale gas reservoir and the Dundee Limestone injection zone.

ACKNOWLEDGEMENT

The authors express thanks to the United States Department of Energy (DOE) for funding this work. The grant was awarded to Jack W. McIntyre under DOE Contract No. DEJ-FG46-92R699202. Mr. McIntyre contracted Geraghty & Miller to perform this research. Greatly appreciated is the assistance and materials provided by the staffs of the Gas Research Institute, Michigan Public Service Commission, Michigan Department of Natural Resources, United States Geological Survey in Denver, Colorado and Lansing, MI, and the Petroleum Department of the Midland, Texas County Library. Special thanks go to Robert Miller, G&M project manager, and Hugh Robotham, G&M hydrologist, for technical review, and Sandra Elliott for editorial review. Thanks to Carol Ballard, Pam Covington and Rose Shive for word processing and reproduction.

DISCLAIMER

Mention of specific processes, brand names or models of equipment is for information only and does not imply endorsement of any particular process or brand.

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