ORO-5197-14

STUDY OF HYDROCARBON - SHALE INTERACTION

PROGRESS REPORT #14

April 1 - June 30, 1979

Paul D. Schettler, Jr., Principal Investigator

and Dale L. Wampler

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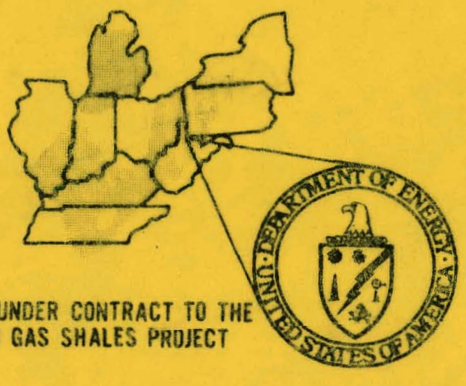

PREPARED UNDER CONTRACT TO THE
EASTERN GAS SHALES PROJECT

Contract No. DE-AS05-76MC05197

DISCLAIMER

QUARTERLY PROGRESS REPORT

April 1 - June 30, 1979

MASTER

Contract No. DE-AS05-76MC05197

Summary: Progress has been made on all assigned tasks. In particular we have concentrated on the high pressure apparatus.

A. Technical Progress

I. High Pressure Degasibility/Isotherm. The construction of the apparatus is complete and two demonstration runs have been made (Appendix A).

II. Low Pressure. Progress has proceeded normally.

Appendix B - Gas Chromatographic Analysis of Off-gassing from Wells KY#4-EGSP, PA#1-EGSP, PA#2-EGSP, OH#3-EGSP and IL#4-EGSP

Appendix C - Temperature Coefficients of Degasibilities and Isotherm Parameters in Devonian Shale (cont.)

Appendix D - Degasibility/Isotherm Data Summary

III. Models. A computer simulation of a matrix diffusion/fracture flow model in the radial case is discussed (Appendix E).

IV. Other Laboratory Studies. A small infrared/X-ray diffraction study is proceeding on selected samples (Appendix F).

B. Financial Progress. Formal accounting is sent by our business office on a monthly report. An informal summary is as follows.

Supplies		$ 899.22
Maintenance Contract on Computer		603.00
Salaries		10,325.91
Faculty	$8,919.66	
Student	1,406.25	
Indirect Costs		8,095.16
TOTAL		$19,923.29

APPENDICES

ORO-5197-14
Appendix A

STATUS REPORT: HIGH PRESSURE

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STATUS REPORT: HIGH PRESSURE

Construction of an apparatus to extend our degasibility/isotherm measurements to pressure of 1000 psi is complete. Initial checkout revealed some leaks which have now been repaired. An initial volume calibration has been completed for the various parts of the system within an accuracy of about 2%.

We plan next to make measurements on an inert (non-sorbing) substance as a standard against which to compare shale.

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Appendix B

GAS CHROMATOGRAPHIC ANALYSIS OF OFF-GASSING FROM WELLS

KY#4 - EGSP

PA#1 - EGSP

PA#2 - EGSP

OH#3 - EGSP

IL#4 - EGSP

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GAS CHROMATOGRAPHIC ANALYSIS OF OFF-GASSING FROM
WELLS KY#4-EGSP, PA#1-EGSP, PA#2-EGSP, OH#3-EGSP, IL#4-EGSP

Chromatographic analysis and subsequent treatment of data is the same as has been previously reported (1). The percent composition of the gas in the can with the sample, as determined by gas chromatography, is converted to the volume of gas off-gassed (STP) per unit volume of rock. The formula of conversion is

$$V_i = 0.916 \frac{V_C}{V_R}\left(P X_i - X_i^0\right)$$

where

V_i -- the computed volume of gas per volume of rock for component i.

0.916 -- converts gas volumes to standard temperature (0°C)

V_R -- the volume of rock (estimated by $(W - W_C)/2.55$)

V_C -- free volume in can (Volume of empty can - V_R)

P -- pressure (atm)

X_i -- fraction of gas which is component i as determined by GC

X_i^0 -- fraction of component i in air (i.e., 0.78 for nitrogen and etc.)

The results are shown in the accompanying table.

All samples showed a depletion of oxygen although for some samples (KY#4-EGSP:1503, PA#1-EGSP:3487, OH#3-EGSP:1161 and IL#4-EGSP:137) the amount of depletion is probably not significant. Several of the samples showed no oxygen at all. Extensive oxygen depletion seems to be related to the presence of carbon dioxide in the gas and/or the presence of significant amounts of methane. Possibly, in some cases the dose of oxygen is due to conversion to carbon dioxide (by bacterial or chemical action) while in other cases chemical reactions which do not yield gaseous products may be responsible.

The average amounts of methane and ethane outgassing for the five wells vary considerably. The KY#4-EGSP well samples showed by far the largest average amount of methane outgassing, 0.41 volume of methane per volume of rock. The two PA and the OH#3 wells showed average methane outgassing ranging from 0.16 to 0.10, while the IL#4 well showed no methane outgassing. Surprisingly, the PA#2 well samples revealed the largest amount of ethane outgassing, the average of 0.08 V/V being considerably larger than the 0.05 V/V exhibited by the most methane productive well samples, KY#4. The low methane/ethane degassing ratios for many of the PA#1 samples is puzzling, particularly the samples which showed no methane, but large quantities of ethane. All of the samples with very low methane/ethane ratio show reasonably large quantities of carbon dioxide and low oxygen content, suggesting possible conversion of some or all of the methane to carbon dioxide. An alternative explanation for the low methane values in some cases is selective diffusion through possible small leaks in the can.

Bibliography

1. L. Hoeflich, E. Jensen, D. Wampler, P. Schettler, "Analysis of Hydrocarbon Gases From Cores of Well #20403, Lincoln County, West Virginia," Progress Report #1, ORO-5197-1, under USERDA Contract No. E(40-1)5197.

TABLE I

VOLUMES OF GAS DESORBED PER VOLUME OF SHALE

SAMPLE ID	W(G)	P(ATM)	V(CH4)	V(C2H6)	V(C3H8)	V(CO2)	V(N2)	V(O2)
KY#4-EGSP:997	1587	1.005	0.016	0.000	0.000	0.043	0.061	-.115
KY#4-EGSP:1036	1583	1.297	0.668	0.067	0.019	0.000	-.182	-.211
KY#4-EGSP:1089	1557	1.424	0.634	0.075	0.021	0.000	0.002	-.200
KY#4-EGSP:1146	1536	1.010	0.454	0.068	0.024	0.000	-.296	-.212
KY#4-EGSP:1196	1550	1.521	0.768	0.080	0.026	0.000	-.002	-.214
KY#4-EGSP:1244	1545	1.314	0.657	0.070	0.024	0.000	-.126	-.226
KY#4-EGSP:1283	1541	1.000	0.156	0.030	0.012	0.065	-.105	-.158
KY#4-EGSP:1342	1565	1.743	0.804	0.089	0.023	0.000	0.189	-.182
KY#4-EGSP:1392	1560	1.167	0.279	0.044	0.011	0.000	0.015	-.140
KY#4-EGSP:1443	1565	0.998	0.067	0.017	0.000	0.073	0.082	-.241
KY#4-EGSP:1503	1561	1.000	0.011	0.000	0.000	0.000	0.004	-.015
PA#1-EGSP:3487	1519	0.986	0.000	0.012	0.000	0.000	-.003	-.028
PA#1-EGSP:4547	1560	1.034	0.000	0.065	0.079	0.035	0.126	-.262
PA#1-EGSP:4597	1501	0.978	0.000	0.084	0.085	0.048	0.034	-.280
PA#1-EGSP:4649	1548	1.028	0.117	0.132	0.070	0.000	-.045	-.238
PA#1:EGSP:4699	1540	0.964	0.000	0.021	0.020	0.097	0.042	-.226
PA#1-EGSP:4749	1548	0.999	0.000	0.046	0.063	0.065	0.090	-.266
PA#1-EGSP:4799	1512	1.120	0.218	0.119	0.071	0.000	0.028	-.277
PA#1-EGSP:4849	1519	1.129	0.294	0.097	0.041	0.000	0.008	-.272
PA#1-EGSP:4899	1546	1.033	0.148	0.090	0.042	0.000	0.026	-.264
PA#1-EGSP:4949	1513	1.276	0.446	0.190	0.084	0.000	-.086	-.271
PA#1-EGSP:5004	1518	0.998	0.167	0.062	0.020	0.000	-.092	-.159
PA#1-EGSP:5053	1544	1.004	0.000	0.047	0.053	0.080	0.091	-.267
PA#1-EGSP:5103	1569	1.007	0.044	0.062	0.051	0.070	0.041	-.260
PA#1-EGSP:5153	1547	1.005	0.000	0.093	0.088	0.047	0.018	-.239
PA#2-EGSP:6957	1534	1.043	0.228	0.039	0.000	0.061	-.002	-.270
PA#2-EGSP:7025	1557	1.020	0.203	0.041	0.000	0.059	-.015	-.263
PA#2-EGSP:7075	1554	1.033	0.250	0.047	0.000	0.000	0.009	-.264
PA#2-EGSP:7125	1527	1.003	0.171	0.026	0.000	0.000	-.015	-.178
PA#2-EGSP:7234	2257	1.010	0.022	0.013	0.000	0.025	0.068	-.122
PA#2-EGSP:7284	1554	0.975	0.084	0.019	0.000	0.039	0.024	-.198
PA#2-EGSP:7334	1553	0.976	0.057	0.050	0.000	0.043	0.083	-.264
PA#2-EGSP:7405	1549	1.010	0.198	0.054	0.000	0.000	0.026	-.266
PA#2-EGSP:7455	1545	1.021	0.211	0.078	0.000	0.000	-.008	-.253
OH#3-EGSP:567	1342	1.000	0.015	0.000	0.000	0.000	0.037	-.052
OH#3-EGSP:617	1578	1.000	0.098	0.017	0.000	0.070	0.070	-.256
OH#3-EGSP:667	1179	1.000	0.108	0.021	0.000	0.000	0.096	-.225
OH#3-EGSP:717	1081	1.000	0.018	0.000	0.000	0.000	0.044	-.061
OH#3-EGSP:761	1598	1.000	0.367	0.039	0.007	0.000	-.162	-.252
OH#3-EGSP:811	1001	1.000	0.196	0.035	0.000	0.000	-.037	-.194
OH#3-EGSP:856	1043	1.000	0.338	0.044	0.000	0.000	-.205	-.177
OH#3-EGSP:909	1365	1.037	0.155	0.038	0.000	0.000	-.028	-.108
OH#3-EGSP:959	1330	1.000	0.052	0.015	0.000	0.000	-.013	-.054
OH#3-EGSP:1061	604	1.000	0.140	0.063	0.000	0.000	-.067	-.137
OH#3-EGSP:1125	1030	1.000	0.338	0.074	0.017	0.000	-.233	-.195
OH#3-EGSP:1161	1328	1.000	0.000	0.000	0.000	0.000	0.029	-.029

TABLE __I__ (continued)

VOLUMES OF GAS DESORBED PER VOLUME OF SHALE

SAMPLE ID	W(G)	P(ATM)	V(CH4)	V(C2H6)	V(C3H8)	V(CO2)	V(N2)	V(O2)
OH#3-EGSP:1215	1153	1.000	0.000	0.000	0.000	0.000	0.034	-.034
ILL#4-EGSP:85	2265	0.968	0.000	0.000	0.000	0.064	0.039	-.121
ILL#4-EGSP:137	2571	0.999	0.000	0.000	0.000	0.000	0.004	-.004
ILL#4-EGSP:196	1497	1.022	0.000	0.000	0.000	0.052	0.039	-.062

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Appendix C

TEMPERATURE COEFFICIENTS OF DEGASIBILITY AND ISOTHERM PARAMETERS IN DEVONIAN SHALES (PART II)

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TEMPERATURE COEFFICIENTS OF DEGASIBILITY AND ISOTHERM PARAMETERS IN DEVONIAN SHALES (PART II)

Introduction

We previously reported (1) on the initiation of a study of the temperature dependence of degasibility and isotherm parameters for Devonian shales. Our earlier paper included the results of the study of three shale samples (2). We now are reporting on the results of the study of an additional samples, WV#5-EGSP:2935. We also are including graphical presentation of the analyses reported previously.

Experimental

Experimental procedures were the same as reported previously. Data were taken for the sample for seven temperatures ranging from -28.5 to 31.32°C. During the data gathering for the sample, it was noted that the circulator from the temperature control bath was not functional. The exact time of failure of the pump is not known. Inspection of the data revealed that the results for the two temperature settings run just previous to noting the failure were inconsistent with the other data. The data for these two temperature settings are not included in this analysis.

The data taken are summarized in Table I. The results of the data analysis are given in Table II. The graphical presentation of the analyses follow Table II.

Discussion

The heat of sorption calculated from the methane isotherm is -2.55 ± 0.13 Kcal/mole. This value is similar to those found for the three samples previously examined. of the four samples thus far examined, the heats of sorption for three, WV#5-EGSP:3035

(-2.72 ± 0.58 Kcal/mole), WV#5-EGSP:2935 (-2.55 ± 0.13 Kcal/mole) and 20403:2926.1 (-2.78 ± 0.23 Kcal/mole), appear the same within experimental error. The -3.44 ± 0.13 Kcal/mole value for the WV#6-MERC-IX:7474 sample seems significantly larger than that for the other three samples.

The systematic increase of the diffusion constant with temperature is consistent with a model of activated diffusion for the sample. A linear least squares analysis of $\ell n D$ versus 1/T gives a computed heat of activation of 2.48 ± 0.39 Kcal/mole.

The helium isotherm data revealed too much scatter to draw any conclusions about their temperature dependence.

References

1. Jay C. Nelson and Dale L. Wampler, "Temperature Coefficients of Degasibility and Isotherm Parameters in Devonian Shales," Progress Report #13, ORO-5197-13.

2. In our analysis of data from sample WV#5-EGSP:3035 we have inadvertently referred to the sample as WV#5-EGSP:3085 in several places. All references to WV#5-EGSP:3085 are actually for WV#5-EGSP:3035.

TABLE I

Data from the Study of Temperature Dependence of Isotherm and Degasibilities for Sample WV#5-EGSP:2935

T°C	Helium Isotherm x 10^{-5}	Methane Isotherm x 10^{-5}	Methane Degasibility x 10^{-7}	Methane Diffusion Constant x 10^{-6}
-28.5	10.28	72.77	1.14	0.077
-19.3	3.43	65.65	1.04	0.079
-10.1	9.02	50.47	1.01	0.126
0	4.51	43.70	0.863	0.123
16.5	4.11	32.97	0.748	0.162

TABLE II

Results of Linear Least Squares Analysis
of Data from Study of Temperature Dependence of Isotherms and Degasibilities
for Sample WV #5-EGSP:2935

Methane Isotherm Data

1/T	$(\ell n\ K_{CH_4})_{obs}$	$(\ell n\ K_{CH_4})_{calc}$	Δ
0.004087	-7.226	-7.196	-0.029
0.003939	-7.329	-7.387	0.058
0.003801	-7.592	-7.564	-0.028
0.003661	-7.736	-7.744	0.008
0.003452	-8.017	-8.013	-0.004

Slope = 1285 with a standard deviation of 65
$\Delta H_{sorption}$ = -2.55 ± 0.13 Kcal/mole

Methane Diffusion Data

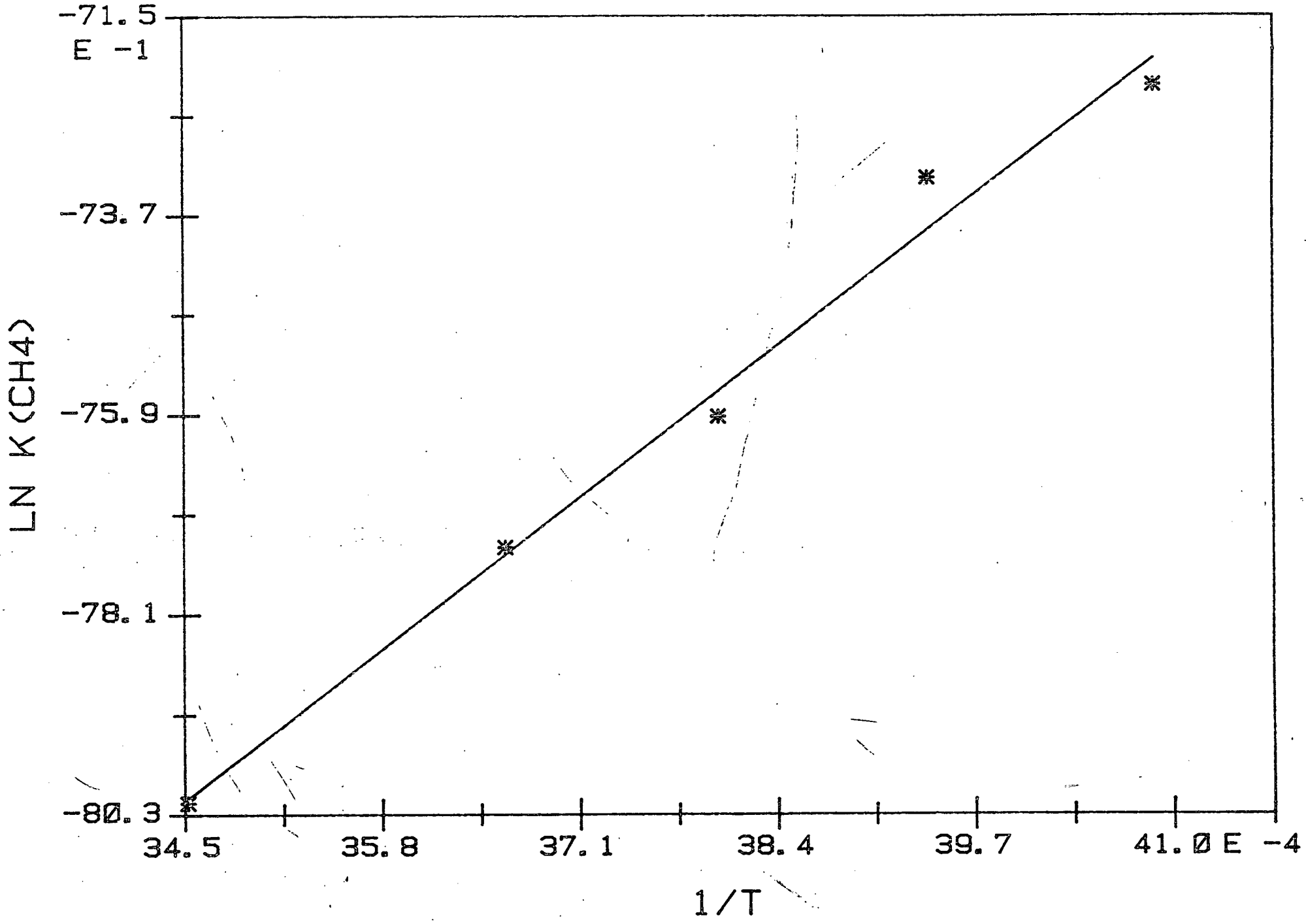
1/T	$(\ell n D)_{obs}$	$(\ell n\ D)_{calc}$	Δ
0.004087	-16.375	-16.404	0.029
0.003939	-16.358	-16.220	-0.138
0.003801	-15.887	-16.048	0.161
0.003661	-15.887	-15.873	-0.014
0.003452	-15.638	-15.613	-0.025

Slope = -1246 with a standard deviation of 197
$\Delta H_{activation}$ = 2.48 ± 0.39 Kcal/mole

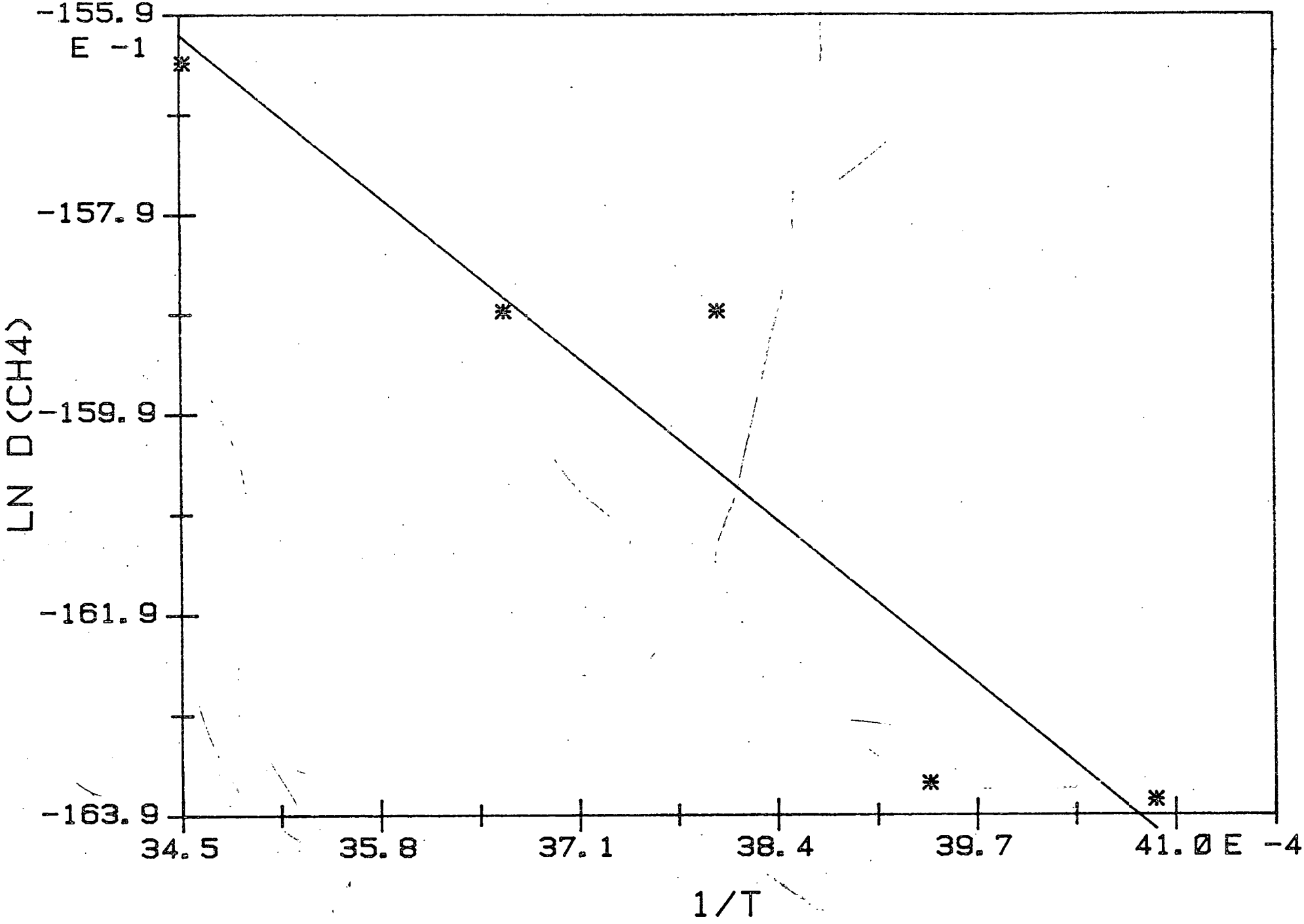
Helium Isotherm Data

1/T	$(\ell n\ K_{He})_{obs}$	$(\ell n\ K_{CH_4})_{calc}$	Δ
0.004087	- 9.18	- 9.47	0.29
0.003939	-10.28	- 9.62	-0.66
0.003801	- 9.31	- 9.76	0.45
0.003661	-10.01	- 9.91	-0.10
0.003452	-10.10	-10.12	0.02

Slope = 1016 with a standard deviation of 776



METHANE ISOTHERM TEMPERATURE STUDY FOR WV#5: 2935



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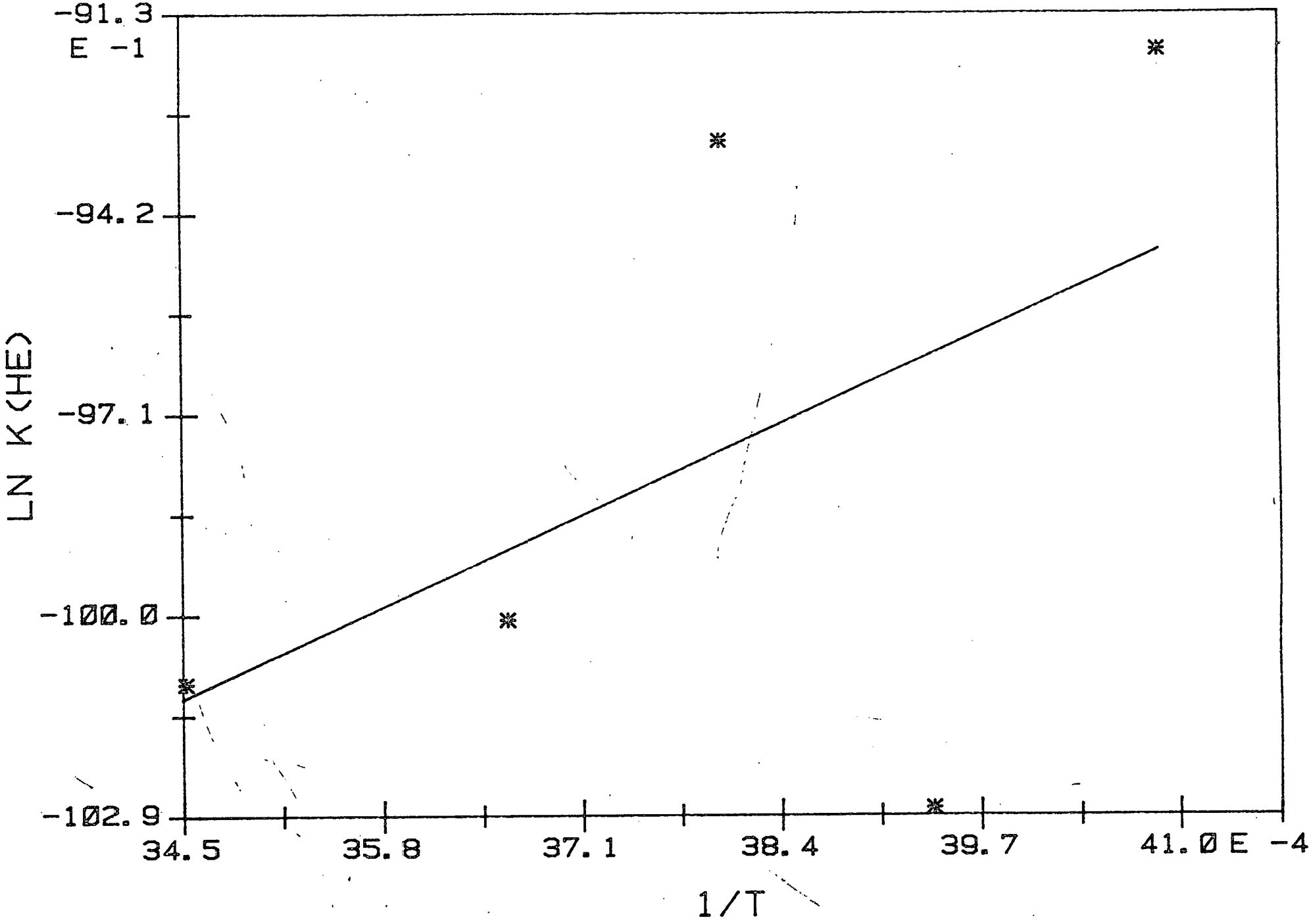
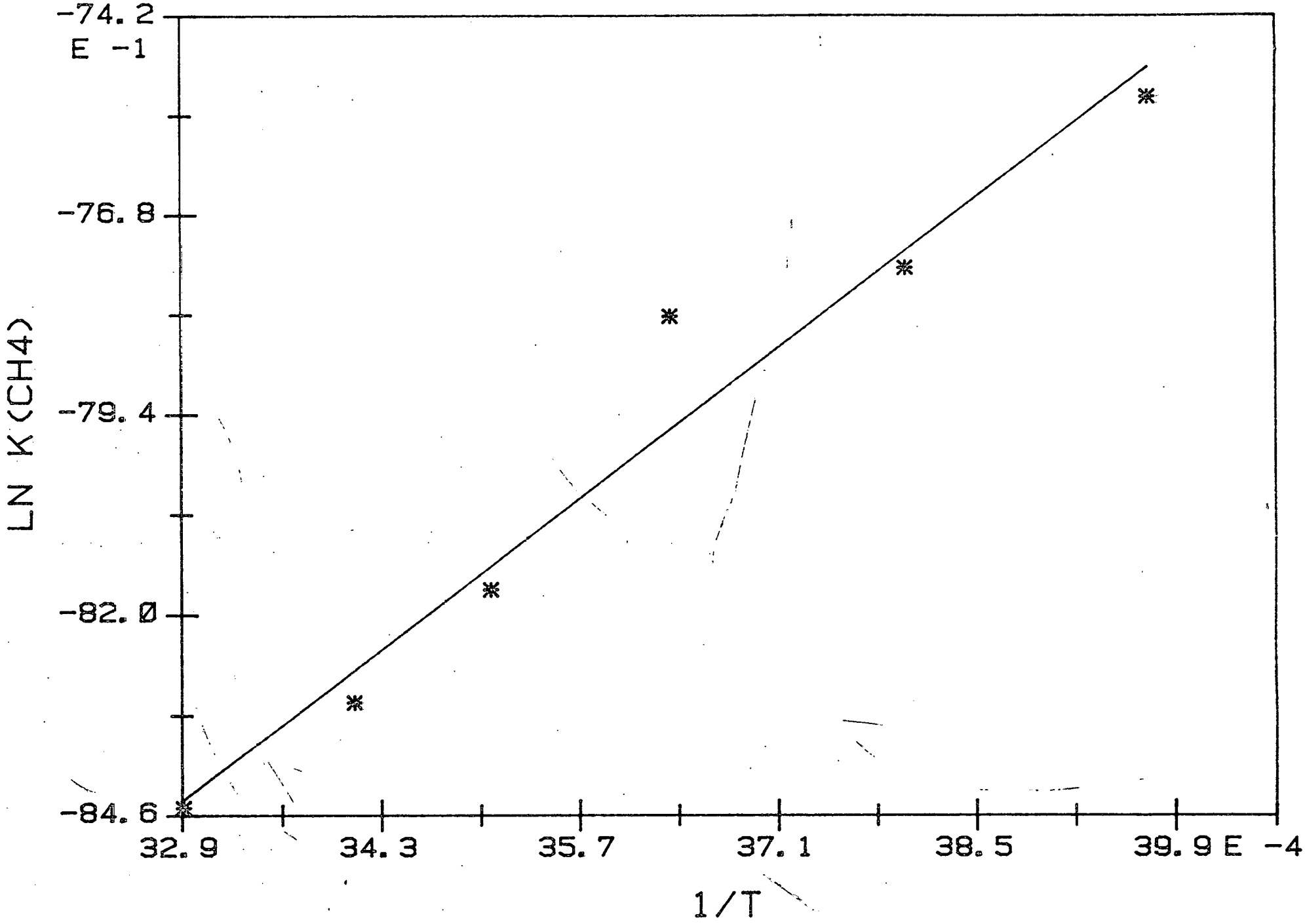
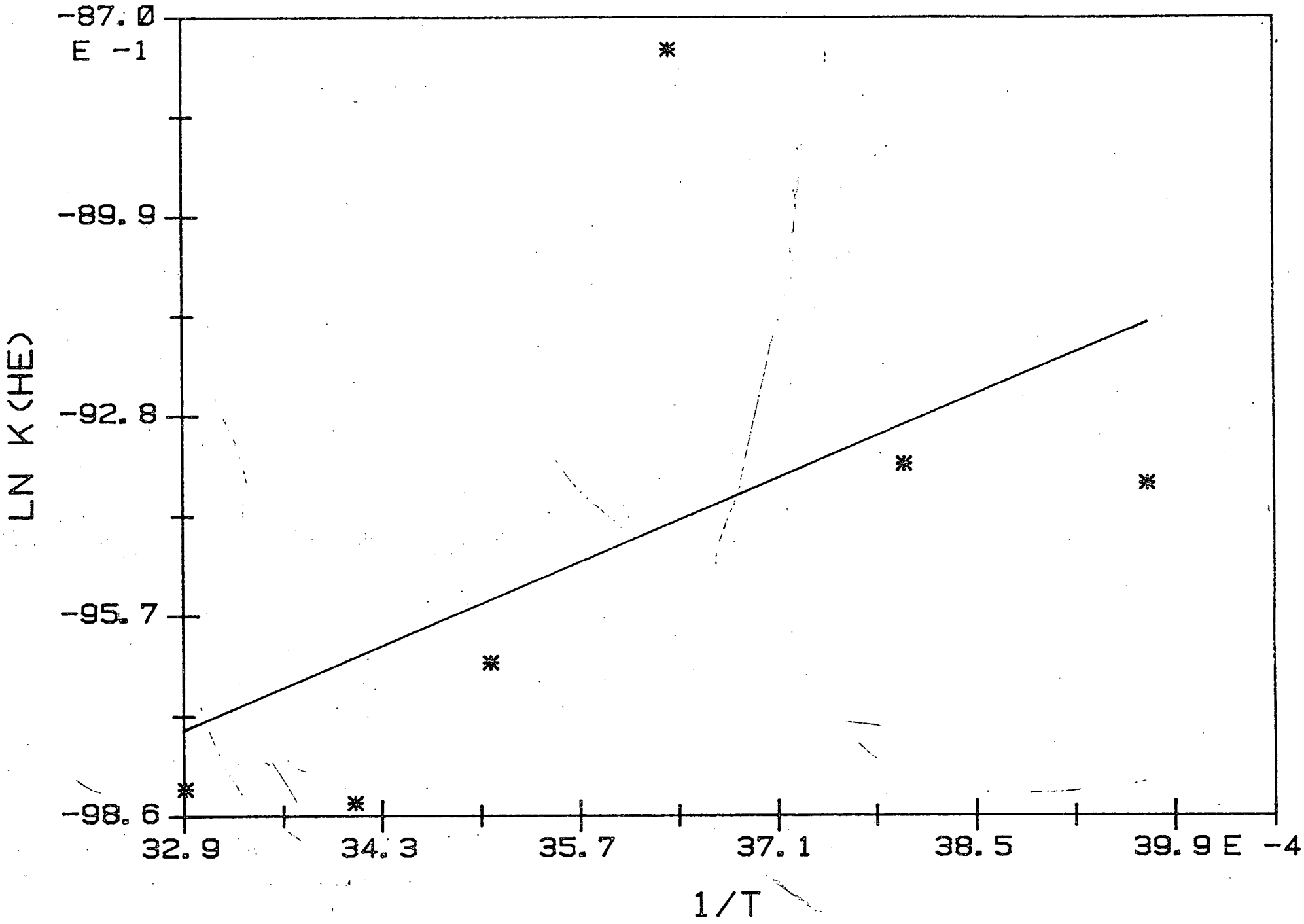


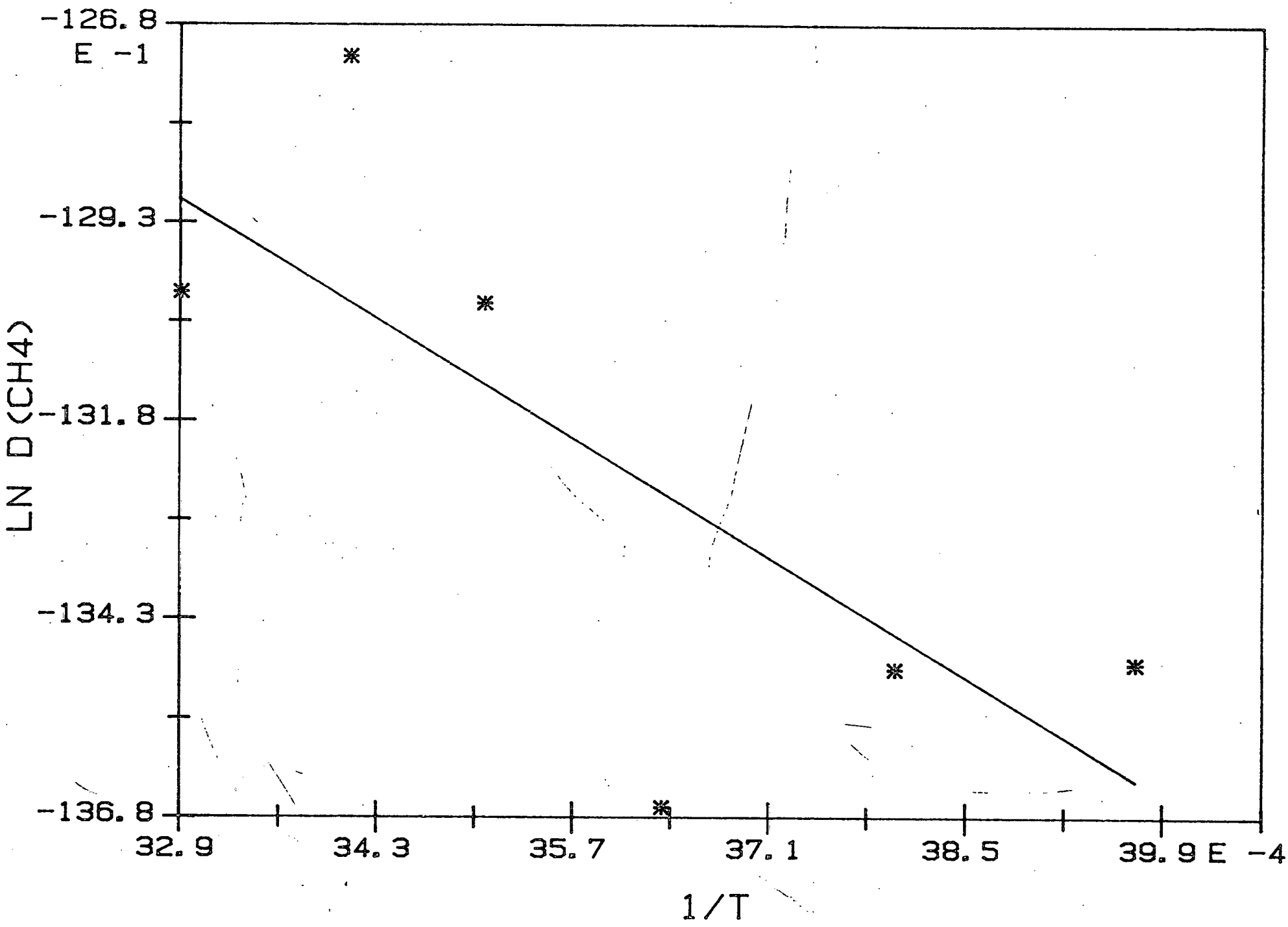
HELIUM ISOTHERM TEMPERATURE STUDY FOR WV#5: 2935



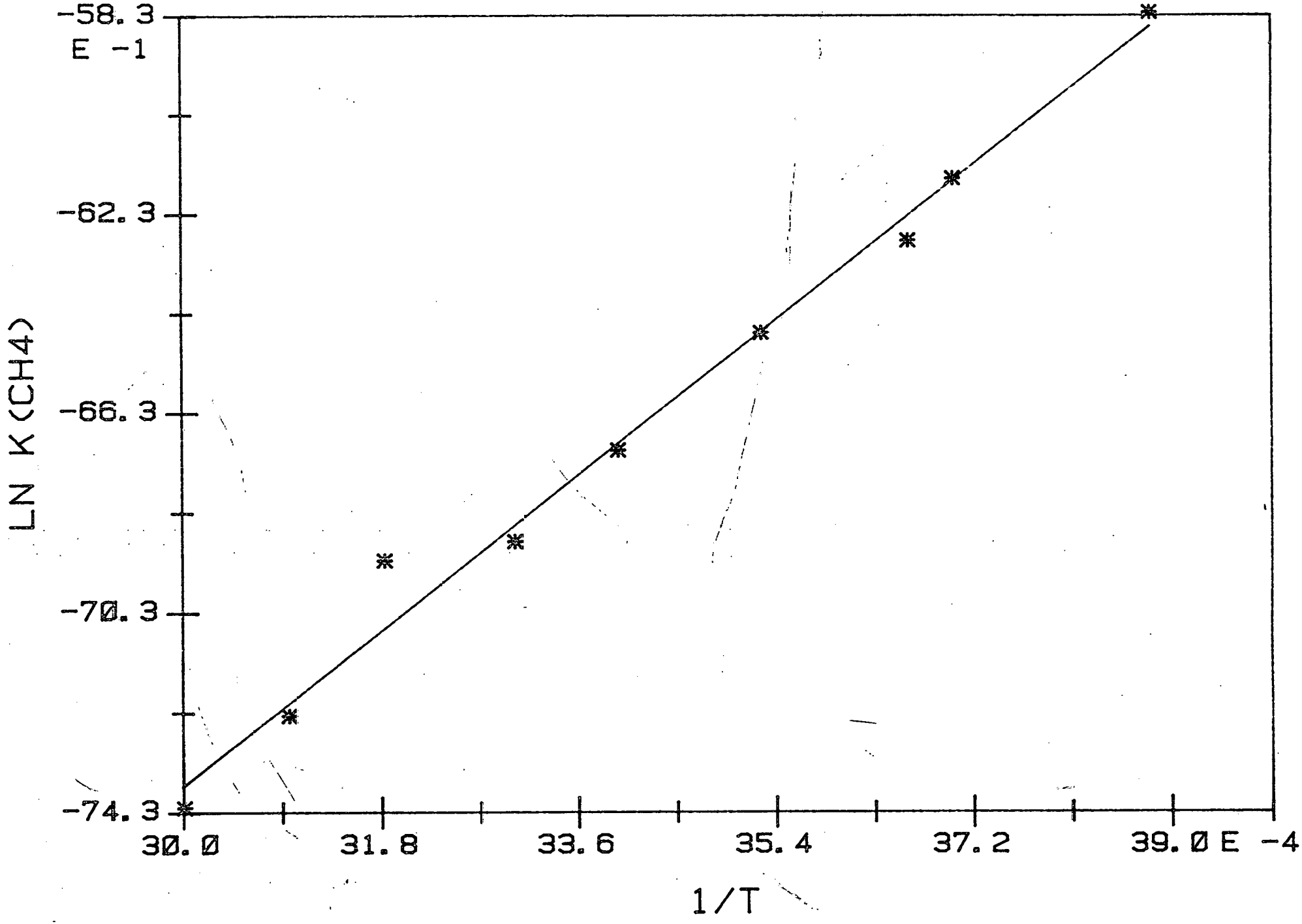
CH4 ISOTHERM TEMPERATURE STUDY FOR 20403: 2926.1



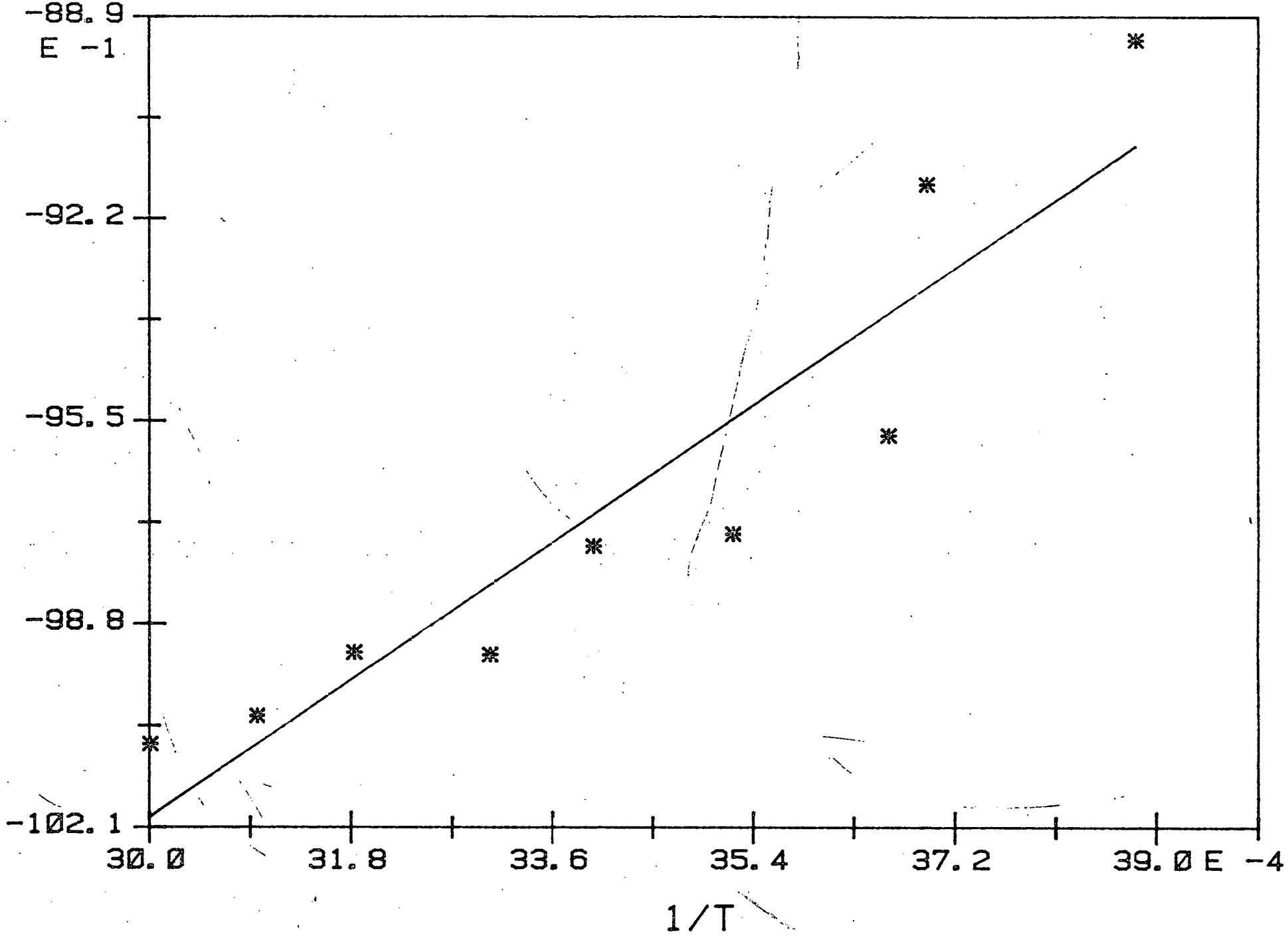
HELIUM ISOTHERM TEMPERATURE STUDY FOR 20403:2926.1



C10 CH4 DIFFUSION TEMPERATURE STUDY FOR 20403:2926.1



METHANE ISOTHERM TEMPERATURE STUDY FOR WV#6: 7474



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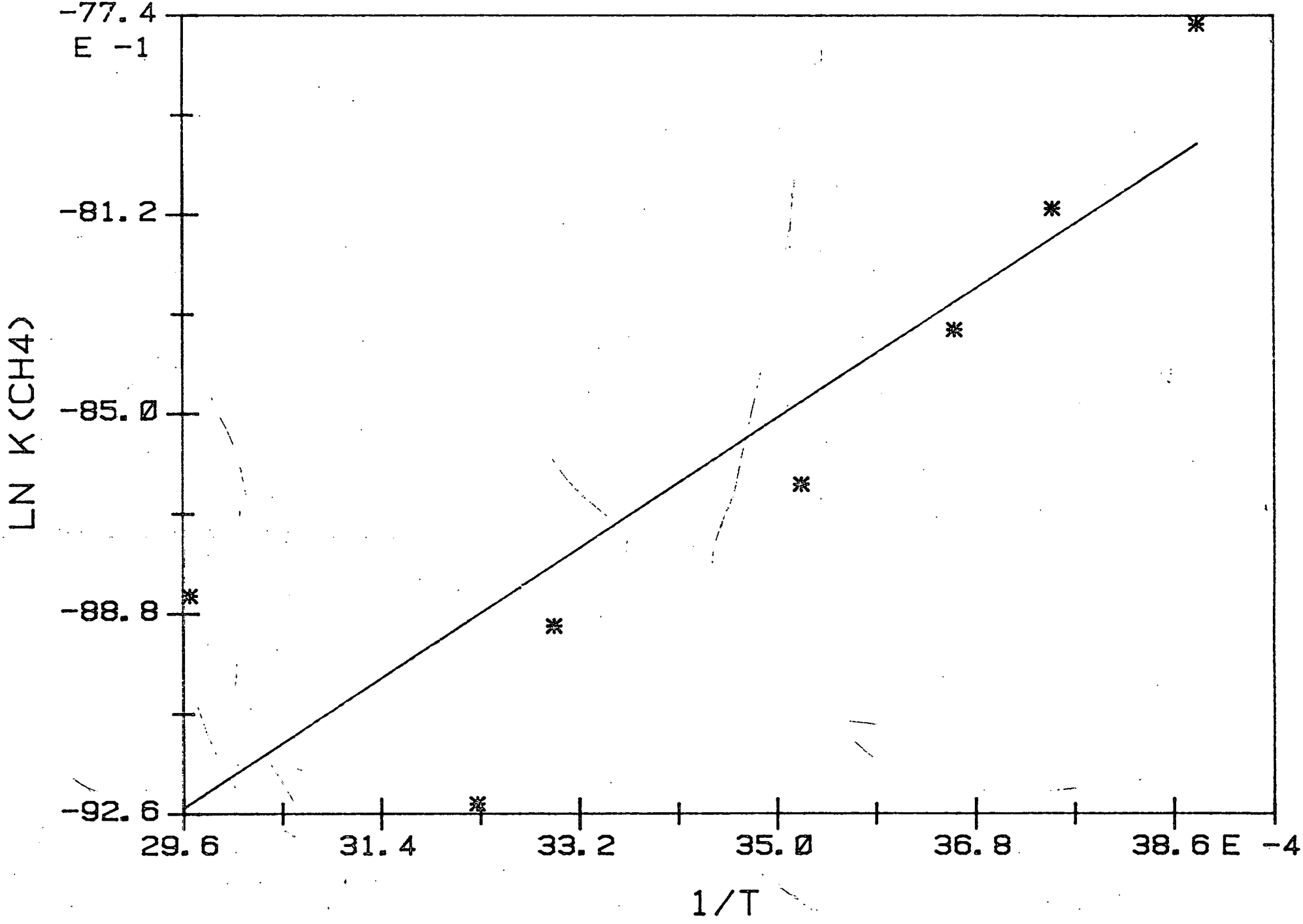

METHANE ISOTHERM TEMPERATURE STUDY FOR WV#5: 3Ø85

ORO-5197-14
Appendix D

DATA SUMMARY

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DATA SUMMARY

This compact presentation is designed to save production costs. Herein is a summary of all data on our data files. The * samples have been run during the period of this report. The complete data (as presented in previous reports) is available on request.

Explanation of Headings

Table I

Well ID

EGSP# when possible. Others as follows:

Brown - Belmont County, Ohio
Dawson - Richland County, Ohio
Egner - Richland County, Ohio
Romig - Richland County, Ohio
Warn - Chatauqua County, New York

Density Bulk

Density measured using toluene as displacing fluid

Isotherm Slope

Volume of gas sorbed into rock (STP) per unit volume rock per torr pressure

BET Area

Volume of nitrogen (STP) calculated from BET equation required

G

Specific degasibility. Volume of gas (STP) released from a sq cm of rock surface per $(sec)^{\frac{1}{2}}$ per torr of discontinuous pressure drop.

Explanation of Headings (cont)

Table II

Well ID

Brown - Belmont County, Ohio
Dawson - Richland County, Ohio
Egner - Richland County, Ohio
Romig - Richland County, Ohio
Warn - Chatauqua County, New York

Diffusion Constant

Calculated from degassing data. Expressed in cm^2/sec.

Density, Helium

Density found using helium as the displacing fluid.

Net Methane Sorption

The amount of methane that must be in solution in kerogen, or adsorbed onto surfaces expressed in volume sorbed/volume rock/torr pressure.

Permeability

Expressed in darcies.

Apparent Porosity

Calculated in the standard manner from helium and methane isotherms. These numbers do not, however, reflect actual void spaces in the shale.

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 *E4	ISO SLOPE METHANE TORR^-1 *E4	BET AREA	G METHANE CM/TORR *E7	G NITROGEN CM/TORR *E7
BROWN:4400	2.735	0.211	2.132	4.4	2.68	47.44
BROWN:5541	2.661	0.580	2.724	5.0	1.66	106.02
BROWN:5561	2.611	0.314	1.678	2.2	0.72	6.30
BROWN:5586	2.623	0.573	2.109	2.7	1.10	13.29
CH-11940:3481.5	2.500	******	2.180	*****	*******	*******
CH-11940:3636.4	2.678	0.195	1.570	*****	*******	*******
CH-11940:3778.9	2.504	0.551	4.009	*****	*******	*******
CH-11940:3787.9	2.554	0.137	1.579	*****	*******	*******
DAWSON:676	2.370	0.461	10.327	4.0	8.76	61.24
DAWSON:686	2.684	0.039	0.896	3.2	0.01	69.31
EGNER:340	2.605	1.204	6.477	12.5	0.31	188.49
EGNER:345	2.656	1.289	6.150	11.2	0.29	155.78
EGNER:510	2.560	2.638	10.580	5.8	11.44	113.73
EGNER:520	2.424	0.685	8.297	6.7	9.61	150.39
IL#1-EGSP:3010	2.568	0.862	4.834	*****	0.16	*******
IL#1-EGSP:3038	2.346	1.322	7.504	*****	1.16	*******
IL#1-EGSP:3052	2.480	0.659	3.093	2.2	0.94	8.95
IL#1-EGSP:3070	2.410	1.426	5.124	*****	0.89	*******
IL#1-EGSP:3094	2.379	0.936	4.938	*****	1.09	*******
IL#1-EGSP:3106	2.628	0.434	0.503	2.5	0.02	0.01
IL#2-EGSP:321.3	2.520	1.684	7.678	16.7	0.08	111.74
IL#2-EGSP:418.33	2.560	1.432	4.715	18.6	0.12	185.78
IL#2-EGSP:465.65	2.483	1.175	5.838	11.6	0.24	588.52
IL#2-EGSP:513.1	2.502	0.939	6.361	*****	0.34	*******
IL#3-EGSP:926.5	2.592	0.908	5.011	13.3	0.06	92.96
IL#3-EGSP:976.2	2.560	******	4.498	12.2	0.06	85.06
IL#3-EGSP:1026	2.539	1.446	8.839	18.4	0.16	170.93

Table I

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 *E4	ISO SLOPE METHANE TORR^-1 *E4	BET AREA	G METHANE CM/TORR *E7	G NITROGEN CM/TORR *E7
IL#3-EGSP:1076.0	2.524	1.400	7.189	13.8	0.17	164.37
IL#3-EGSP:1126	2.788	1.158	3.631	7.7	0.10	92.96
NY#1-EGSP:375	2.882	0.384	3.658	7.7	0.24	136.99
NY#1-EGSP:425	2.690	0.733	2.588	5.2	0.12	65.60
NY#1-EGSP:475	2.748	0.391	2.063	5.2	0.17	63.80
NY#1-EGSP:988.25-988.47	2.405	2.343	4.108	3.1	2.53	39.91
NY#1-EGSP:1427	2.731	0.306	0.607	2.1	0.03	0.68
NY#1-EGSP:1628	2.688	1.063	2.823	4.0	0.66	*******
NY#1-EGSP:1678	2.728	1.148	3.253	5.2	0.83	85.06
NY#1-EGSP:1778	2.685	0.884	2.912	3.6	2.79	53.30
NY#1-EGSP:1829.21-1829.50	0.833	9.416	10.019	1.4	0.53	15.57
NY#1-EGSP:1891	2.735	1.099	3.565	5.5	1.80	77.31
NY#1-EGSP:1941	2.743	0.683	2.015	4.3	0.63	45.84
NY#1-EGSP:1990	2.681	1.537	3.658	5.0	0.57	57.45
NY#1-EGSP:2040	2.695	0.742	2.208	3.8	0.32	40.75
NY#1-EGSP:2092	2.674	1.031	2.218	3.8	0.92	24.12
NY#1-EGSP:2192	2.637	1.399	3.953	4.9	1.81	70.41
NY#1-EGSP:2245	2.731	0.764	2.765	4.0	1.81	67.55
NY#1-EGSP:2295	2.651	0.783	2.035	3.4	0.89	39.47
NY#1-EGSP:2345	2.742	1.024	2.937	4.7	0.99	67.17
NY#1-EGSP:2491	2.752	0.587	1.967	4.1	1.15	48.72
NY#1-EGSP:2541	4.082	******	******	*****	*******	*******
NY#1-EGSP:2541.20-2541.43	2.596	1.412	******	2.4	0.74	7.44
NY#1-EGSP:2591	2.647	0.899	2.864	3.4	2.59	47.96
NY#1-EGSP:2641.18-2641.45	2.468	1.931	3.517	3.4	1.77	55.99
NY#1-EGSP:2783	2.702	0.470	2.707	3.9	2.82	61.23
NY#1-EGSP:2893	2.388	1.672	5.589	2.3	0.90	19.41
NY#1-EGSP:2733.42-2733.66	2.186	2.846	4.002	1.4	1.37	0.19
CH#2-EGSP:3544	2.694	0.020	0.930	*****	*******	*******
ROMIG:570	2.682	0.540	2.465	11.9	0.13	263.26

Table I (cont)

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 #E4	ISO SLOPE METHANE TORR^-1 #E4	BET AREA	G METHANE CM/TORR #E7	G NITROGEN CM/TORR #E7
ROMIG:571	2.748	0.936	4.662	8.5	0.50	197.42
ROMIG:684	2.400	0.959	10.111	26.5	100.24	2383.86
ROMIG:704	2.777	######	10.934	5.5	15.22	112.47
WARN:1517	2.673	0.785	2.706	5.2	0.58	106.05
WARN:2630	2.517	0.051	1.099	2.2	0.66	13.29
WARN:2660	2.419	0.941	3.098	2.1	0.89	11.09
WARN:2675	2.677	0.294	1.729	3.7	2.72	73.55
WU#5-EGSP:2723	2.488	0.383	2.066	1.9	0.59	0.30
WU#5-EGSP:2823	2.704	0.837	3.209	5.7	2.02	81.37
WU#5-EGSP:2935	2.471	0.547	3.426	1.7	0.97	0.78
WU#5-EGSP:3030	2.429	0.253	2.105	1.2	1.26	1.05
WU#5-EGSP:3035	2.658	0.855	3.144	4.7	3.17	70.64
WU#5-EGSP:3135	2.661	1.357	4.200	7.0	2.05	145.14
WU#5-EGSP:3235	2.676	0.443	3.580	4.2	4.38	88.46
WU#5-EGSP:3305	2.648	0.704	2.564	0.6	0.94	110.72
WU#5-EGSP:3335	2.428	0.568	2.120	1.4	0.49	1.02
WU#5-EGSP:3355	2.359	0.381	4.508	1.2	0.90	0.86
WU#5-EGSP:6142	2.612	0.965	3.427	2.8	1.87	31.22
WU#6-MERC-1X:7215	2.592	0.916	3.205	3.7	1.77	54.78
WU#6-MERC-1X:7267	2.671	0.494	8.015	7.5	4.95	85.92
WU#6-MERC-1X:7316	2.639	1.033	6.233	6.2	3.93	77.72
WU#6-MERC-1X:7369	2.572	0.951	16.118	13.0	13.46	142.04
WU#6-MERC-1X:7421	2.522	0.647	29.439	15.5	19.53	86.72
WU#6-MERC-1X:7474	2.509	1.040	10.815	13.3	4.53	123.10
WU#7-EGSP:6242	2.672	0.868	4.560	3.4	2.83	27.37
WU#7-EGSP:6342	2.706	1.277	3.474	4.6	1.64	79.29
WU#7-EGSP:6464	2.609	1.187	2.883	3.4	1.34	53.93
WU#7-EGSP:6566	2.617	1.027	3.774	3.7	3.19	45.00

Table I (cont)

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 *E4	ISO SLOPE METHANE TORR^-1 *E4	BET AREA	G METHANE CM/TORR *E7	G NITROGEN CM/TORR *E7
EGSP-WV#7:6516	2.765	0.046	1.002	3.2	0.70	51.89
EGSP-WV#7:6621	2.497	0.943	10.761	8.5	9.04	139.83
20336:2449	2.424	0.374	1.853	1.6	0.70	0.53
20336:2459	2.454	0.648	2.268	1.6	0.82	0.74
20336:2539	2.657	1.161	4.105	7.7	0.89	147.15
20336:2579	2.644	0.590	4.606	9.0	1.92	158.08
20336:2629	2.660	1.132	4.004	5.3	3120.00	*******
20336:2873	2.642	0.752	2.554	3.1	1.22	25.98
20336:3029	2.492	0.285	1.366	1.9	0.57	0.64
20336:3129	2.648	0.703	2.461	5.6	0.37	145.09
20336:3139	2.642	1.330	3.232	5.8	0.13	142.11
20336:3349	2.554	0.569	3.029	*****	1.84	*******
20338:4921	2.566	0.514	6.334	5.7	4.24	44.82
20338:4971	2.695	0.453	3.486	6.1	3.29	*******
20338:5221	2.692	0.557	1.804	*****	0.38	*******
20338:5451	2.542	0.563	18.634	14.6	8.89	62.00
20403:2756.3	2.765	0.372	2.485	4.2	1.37	37.99
20403:2836.2	2.721	0.309	3.707	5.6	4.48	67.74
20403:2846.1	2.658	1.824	3.154	3.3	0.69	39.98
20403:2866.3	2.699	0.612	3.733	5.4	3.61	64.25
20403:2876.1	2.698	0.337	3.303	*****	4.02	64.04
20403:2876.3	2.740	0.352	4.133	6.1	5.40	65.33
20403:2886.1	2.668	0.629	3.301	3.6	1.75	*******
20403:2896.1	2.683	0.365	0.974	2.3	0.57	5.19
20403:2906.1	2.708	0.377	2.681	2.8	1.36	28.62
20403:2916.1	2.690	0.060	1.093	2.8	0.30	18.01
20403:2916.3	2.697	0.528	2.092	3.4	1.84	28.40
20403:2926.1	2.737	0.325	2.941	8.8	2.00	37.25
20403:2936.1	2.708	******	2.911	3.2	1.97	15.58
20403:2946.1	2.744	0.412	2.649	3.0	2.25	23.65

Table I (cont)

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 *E4	ISO SLOPE METHANE TORR^-1 *E4	BET AREA	G METHANE CM/TORR *E7	G NITROGEN CM/TORR *E7
20403:2946.3	2.732	0.839	3.432	4.2	2.54	38.76
20403:2976.1	2.679	0.814	3.656	20.5	3.27	94.43
20403:2996.1	2.624	0.138	1.727	1.4	0.68	3.30
20403:3006.1	2.666	******	1.633	0.8	2.32	59.88
20403:3016.1	2.745	******	0.776	15.0	0.86	70.72
20403:3016.3	2.620	0.932	2.659	3.7	2.08	37.31
20403:3026.1	2.669	0.096	1.197	0.3	0.73	2.10
20403:3026.3	2.654	0.618	2.196	2.0	0.83	5.92
20403:3036.1	2.744	0.669	2.615	2.5	13.60	244.00
20403:3046.1	2.726	0.369	2.564	2.9	1.73	*******
20403:3046.3	2.670	0.334	2.521	4.3	2.78	35.85
20403:3056.1	2.742	0.241	2.541	3.8	2.64	25.43
20403:3066.1	2.674	0.579	2.470	2.9	1.95	28.62
20403:3066.3	2.582	0.840	2.966	2.3	1.46	14.60
20403:3076.1	2.678	0.496	1.854	2.8	1.76	27.53
20403:3086.1	2.703	0.733	2.964	2.8	1.50	14.34
20403:3116.3	2.597	0.815	3.579	2.4	1.36	11.93
20403:3126.3	2.588	1.372	4.416	6.0	4.01	46.19
20403:3186.3	2.647	0.326	1.246	2.1	0.42	2.06
20403:3201.3	3.178	******	1.837	6.0	5.65	67.11
20403:3211.3	2.681	0.724	3.220	3.4	1.87	23.92
20403:3241.3	2.704	0.232	3.643	31.3	3.35	170.96
20403:3251.3	2.648	0.408	2.738	3.7	2.55	39.89
20403:3291.3	2.716	1.023	3.769	6.8	3.60	62.51
20403:3301.3	2.750	0.622	3.740	5.9	3.45	49.17
20403:3311.3	2.646	0.583	1.543	1.7	0.39	2.09
20403:3321.3	2.653	0.174	1.196	14.7	0.63	14.46
20403:3376.3	2.631	1.234	3.362	3.6	2.39	29.70
20403:3436.1	2.390	1.369	4.717	1.7	0.71	4.61
20403:3476.3	2.570	0.531	1.206	1.7	0.30	2.30
20403:3506.3	2.628	0.863	2.092	3.3	2.28	55.39
20403:3526.3	2.494	0.995	2.210	2.2	0.31	1.37
20403:3546.3	2.583	0.318	1.608	1.8	0.41	1.49

Table I (cont)

WELL ID	DENSITY BULK G/CM^3	ISO SLOPE HELIUM TORR^-1 *E4	ISO SLOPE METHANE TORR^-1 *E4	BET AREA	G METHANE CM/TORR *E7	G NITROGEN CM/TORR *E7
20403:3556.3	2.677	0.863	2.852	4.8	2.16	86.12
20403:3616.3	2.684	0.775	1.832	2.4	1.17	16.87
20403:3656.3	2.670	0.693	2.415	5.0	0.14	120.54
20403:3666.3	2.714	0.554	2.380	5.3	0.16	119.67
20403:3676.3	2.670	0.980	2.780	4.6	1.07	*******
20403:3686.3	2.650	0.420	2.340	6.5	1.42	*******
20403:3756.1	2.330	0.659	0.857	1.9	1.41	0.29
20403:3786.1	2.767	1.188	3.349	5.8	0.12	132.37
20403:3796.3	2.672	0.617	2.858	6.0	0.10	130.23
20403:3816.3	2.870	0.222	1.930	5.9	0.16	144.59
20403:3876.3	2.715	0.490	2.060	5.4	0.23	134.83
20403:3946.1	2.512	1.098	2.320	2.0	0.67	6.93
20403:3976.3	2.506	0.212	0.791	2.2	0.26	1.48

Table I (cont)

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
BROWN:4400	49.70	2.78	1.921	8.262	1.6	16.2
BROWN:5541	11.62	2.78	2.144	2.469	4.4	20.7
BROWN:5561	5.79	2.67	1.364	0.758	2.4	12.8
BROWN:5586	8.54	2.74	1.536	1.405	4.4	16.0
CH-11940:3481.5	*******	****	2.180	********	*****	16.6
CH-11940:3636.4	*******	2.72	1.375	********	1.5	11.9
CH-11940:3778.9	*******	2.61	3.458	********	4.2	30.5
CH-11940:3787.9	*******	2.58	1.443	********	1.0	12.0
DAWSON:676	22.63	2.46	9.865	18.219	3.5	78.5
DAWSON:686	0.01	2.69	0.857	0.000	0.3	6.8
EGNER:340	0.07	2.87	5.274	0.037	9.1	49.2
EGNER:345	0.07	2.94	4.861	0.033	9.8	46.7
EGNER:510	36.72	3.20	7.942	30.291	20.0	80.4
EGNER:520	42.18	2.56	7.612	27.288	5.2	63.1
IL#1-EGSP:3010	0.03	2.75	3.972	0.013	6.5	36.7
IL#1-EGSP:3038	0.76	2.61	6.183	0.442	10.0	57.0
IL#1-EGSP:3052	2.87	2.61	2.434	0.693	5.0	23.5
IL#1-EGSP:3070	0.95	2.70	3.697	0.378	10.8	38.9
IL#1-EGSP:3094	1.53	2.56	4.002	0.589	7.1	37.5
IL#1-EGSP:3106	0.06	2.72	0.069	0.002	3.3	3.8
IL#2-EGSP:321.3	0.00	2.89	5.994	0.002	12.8	58.4
IL#2-EGSP:418.33	0.02	2.87	3.283	0.007	10.9	35.8
IL#2-EGSP:465.65	0.05	2.73	4.663	0.025	8.9	44.4
IL#2-EGSP:513.1	0.09	2.69	5.423	0.044	7.1	48.3
IL#3-EGSP:926.5	0.00	2.78	4.103	0.002	6.9	38.1
IL#3-EGSP:976.2	0.01	****	4.498	0.002	*****	34.2
IL#3-EGSP:1026	0.01	2.85	7.392	0.007	11.0	67.2

Table II

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
IL#3-EGSP:1076.0	0.02	2.82	5.789	0.010	10.6	54.6
IL#3-EGSP:1126	0.02	3.06	2.473	0.007	8.8	27.6
NY#1-EGSP:375	0.14	2.97	3.658	0.039	2.9	27.8
NY#1-EGSP:425	0.07	2.85	2.587	0.014	5.6	19.7
NY#1-EGSP:475	0.22	2.83	2.063	0.035	3.0	15.7
NY#1-EGSP:988.25-988.47	11.96	2.93	4.106	3.830	17.8	31.2
NY#1-EGSP:1427	0.08	2.80	0.606	0.004	2.3	4.6
NY#1-EGSP:1628	1.73	2.92	2.823	0.381	8.1	21.5
NY#1-EGSP:1678	2.04	2.99	3.252	0.516	8.7	24.7
NY#1-EGSP:1778	28.78	2.88	2.910	6.534	6.7	22.1
NY#1-EGSP:1829.21-1829.50	0.09	2.93	10.019	0.069	71.6	76.1
NY#1-EGSP:1891	7.99	2.98	3.563	2.222	8.4	27.1
NY#1-EGSP:1941	3.07	2.89	2.014	0.482	5.2	15.3
NY#1-EGSP:1990	0.76	3.04	3.658	0.217	11.7	27.8
NY#1-EGSP:2040	0.67	2.86	2.207	0.115	5.6	16.8
NY#1-EGSP:2092	5.36	2.90	2.217	0.928	7.8	16.9
NY#1-EGSP:2192	6.60	2.95	3.952	2.036	10.6	30.0
NY#1-EGSP:2245	13.53	2.90	2.764	2.917	5.8	21.0
NY#1-EGSP:2295	6.05	2.82	2.035	0.960	5.9	15.5
NY#1-EGSP:2345	3.56	2.97	2.936	0.816	7.8	22.3
NY#1-EGSP:2491	10.69	2.88	1.966	1.640	4.5	15.0
NY#1-EGSP:2541	*******	****	******	********	*****	*****
NY#1-EGSP:2541.20-2541.43	*******	2.91	******	********	10.7	*****
NY#1-EGSP:2591	25.74	2.84	2.861	5.748	6.8	21.8
NY#1-EGSP:2641.18-2641.45	7.94	2.89	3.516	2.176	14.7	26.7
NY#1-EGSP:2783	34.06	2.80	2.704	7.189	3.6	20.6
NY#1-EGSP:2893	0.82	2.74	5.589	0.359	12.7	42.5
NY#1-EGSP:273342-2733.66	3.70	2.79	4.001	1.155	21.6	30.4
OH#2-EGSP:3544	*******	2.70	0.910	********	0.2	7.1
ROMIG:570	0.09	2.80	1.926	0.018	4.1	18.7

Table II (cont)

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
ROMIG:571	0.36	2.96	3.727	0.129	7.1	35.4
ROMIG:684	3087.93	2.59	9.152	2434.340	7.3	76.8
ROMIG:704	60.85	****	10.934	51.876	*****	83.1
WARN:1517	1.47	2.84	1.921	0.309	6.0	20.6
WARN:2630	11.38	2.53	1.048	0.975	0.4	8.4
WARN:2660	2.56	2.61	2.157	0.619	7.2	23.5
WARN:2675	77.48	2.74	1.436	10.448	2.2	13.1
WV#5-EGSP:2723	2.60	2.56	1.684	0.419	2.9	15.7
WV#5-EGSP:2823	12.45	2.89	2.372	3.114	6.4	24.4
WV#5-EGSP:2935	2.51	2.58	2.879	0.672	4.2	26.0
WV#5-EGSP:3030	11.17	2.48	1.852	1.834	1.9	16.0
WV#5-EGSP:3035	32.04	2.84	2.289	7.854	6.5	23.9
WV#5-EGSP:3135	7.50	2.97	2.843	2.457	10.3	31.9
WV#5-EGSP:3235	46.94	2.77	3.137	13.103	3.4	27.2
WV#5-EGSP:3305	4.26	2.80	1.860	0.851	5.3	19.5
WV#5-EGSP:3335	1.66	2.54	1.552	0.274	4.3	16.1
WV#5-EGSP:3355	1.26	2.43	4.127	0.444	2.9	34.3
WV#5-EGSP:6142	9.39	2.82	3.425	2.508	7.3	26.0
WV#6-MERC-1X:7215	9.63	2.79	2.289	2.407	7.0	24.4
WV#6-MERC-1X:7267	12.00	2.78	7.522	7.501	3.8	60.9
WV#6-MERC-1X:7316	12.50	2.86	5.199	6.076	7.9	47.4
WV#6-MERC-1X:7369	21.91	2.77	15.166	27.539	7.2	122.5
WV#6-MERC-1X:7421	13.82	2.65	28.792	31.731	4.9	223.7
WV#6-MERC-1X:7474	5.51	2.72	9.775	4.644	7.9	82.2
WV#7-EGSP:6242	12.11	2.86	4.558	4.307	6.6	34.7
WV#7-EGSP:6342	7.01	3.00	3.472	1.898	9.7	26.4
WV#7-EGSP:6464	6.81	2.87	2.882	1.531	9.0	21.9
WV#7-EGSP:6566	22.44	2.84	3.771	6.603	7.8	28.7

Table II (cont)

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
EGSP-WU#7:6516	15.20	2.77	1.002	1.188	0.3	7.6
EGSP-WU#7:6621	22.18	2.69	10.751	18.610	7.2	81.8
20336:2449	4.51	2.49	1.480	0.651	2.8	14.1
20336:2459	4.13	2.58	1.619	0.731	4.9	17.2
20336:2539	1.49	2.91	2.944	0.476	8.8	31.2
20336:2579	5.44	2.77	4.015	1.952	4.5	35.0
20336:2629	19.08	2.91	2.872	5.955	8.6	30.4
20336:2873	7.17	2.80	1.802	1.427	5.7	19.4
20336:3029	5.39	2.55	1.081	0.573	2.2	10.4
20336:3129	0.69	2.80	1.759	0.133	5.3	18.7
20336:3139	0.05	2.94	1.902	0.014	10.1	24.6
20336:3349	11.60	2.67	2.460	2.740	4.3	23.0
20338:4921	14.07	2.67	5.820	6.949	3.9	48.1
20338:4971	28.04	2.79	3.033	7.621	3.4	26.5
20338:5221	1.38	2.81	1.247	0.194	4.2	13.7
20338:5451	7.15	2.66	18.071	10.394	4.3	141.6
20403:2756.3	9.52	2.85	2.483	1.844	2.8	18.9
20403:2836.2	45.79	2.79	3.398	13.238	2.3	28.2
20403:2846.1	1.49	3.09	1.330	0.366	13.9	24.0
20403:2866.3	29.34	2.83	3.120	8.539	4.7	28.4
20403:2876.1	46.47	2.77	2.966	11.967	2.6	25.1
20403:2876.3	53.55	2.82	3.781	17.254	2.7	31.4
20403:2886.1	8.83	2.80	2.673	2.273	4.8	25.1
20403:2896.1	10.83	2.76	0.609	0.822	2.8	7.4
20403:2906.1	8.08	2.79	2.304	1.689	2.9	20.4
20403:2916.1	2.35	2.70	1.033	0.200	0.5	8.3
20403:2916.3	24.40	2.81	1.564	3.980	4.0	15.9
20403:2926.1	14.47	2.81	2.616	3.318	2.5	22.4
20403:2936.1	14.46	****	2.911	3.281	*****	22.1
20403:2946.1	22.75	2.83	2.237	4.700	3.1	20.1

Table II (cont)

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
20403:2946.3	17.22	2.92	2.593	4.607	6.4	26.1
20403:2976.1	25.17	2.86	2.842	7.175	6.2	27.8
20403:2996.1	4.93	2.65	1.590	0.664	1.0	13.1
20403:3006.1	63.42	****	1.633	8.060	*****	12.4
20403:3016.1	38.42	****	0.776	2.324	*****	5.9
20403:3016.3	19.29	2.82	1.727	3.998	7.1	20.2
20403:3026 1	11.73	2.69	1.102	1.095	0.7	9.1
20403:3026.3	4.50	2.78	1.578	0.770	4.7	16.7
20403:3036.1	84.97	2.89	1.946	173.300	5.1	19.9
20403:3046.1	14.35	2.80	2.195	2.869	2.8	19.5
20403:3046.3	38.09	2.74	2.187	7.486	2.5	19.2
20403:3056.1	33.97	2.79	2.300	6.730	1.8	19.3
20403:3066.1	19.51	2.80	1.890	3.758	4.4	18.8
20403:3066.3	7.63	2.76	2.126	1.765	6.4	22.5
20403:3076.1	28.45	2.78	1.359	4.113	3.8	14.1
20403:3086.1	8.04	2.86	2.231	1.858	5.6	22.5
20403:3116.3	4.54	2.77	2.764	1.266	6.2	27.2
20403:3126.3	25.93	2.89	3.044	8.928	10.4	33.6
20403:3186.3	3.51	2.71	0.920	0.341	2.5	9.5
20403:3201.3	296.77	****	1.837	42.517	*****	14.0
20403:3211.3	10.61	2.84	2.496	2.664	5.5	24.5
20403:3241.3	26.59	2.75	3.412	7.554	1.8	27.7
20403:3251.3	27.20	2.73	2.330	5.807	3.1	20.8
20403:3291.3	28.60	2.94	2.746	8.403	7.8	28.6
20403:3301.3	26.74	2.89	3.737	7.799	4.7	28.4
20403:3311.3	1.99	2.77	0.960	0.240	4.4	11.7
20403:3321.3	8.81	2.69	1.022	0.822	1.3	9.1
20403:3376.3	15.88	2.90	3.359	4.163	9.4	25.5
20403:3436.1	0.71	2.67	4.717	0.259	10.4	35.9
20403:3476.3	1.92	2.68	0.674	0.180	4.0	9.2
20403:3506.3	37.27	2.81	1.229	6.077	6.6	15.9
20403:3526.3	0.63	2.70	2.210	0.108	7.6	16.8
20403:3546.3	2.08	2.65	1.607	0.260	2.4	12.2

Table II (cont)

WELL ID	DIF CONST METHANE CM^2/S *E7	DENSITY HELIUM G/CM^3	NET CH4 SORPTION TORR^-1 *E4	PERM DARCIES *E9	APP POROSITY HELIUM %	APP POROSITY METHANE %
20403:3556.3	18.03	2.87	1.989	4.010	6.6	21.7
20403:3616.3	12.87	2.85	1.057	1.838	5.9	13.9
20403:3656.3	0.10	2.82	1.722	0.019	5.3	18.4
20403:3666.3	0.14	2.83	1.826	0.027	4.2	18.1
20403:3676.3	4.69	2.88	1.800	1.017	7.4	21.1
20403:3686.3	11.57	2.74	1.920	2.111	3.2	17.8
20403:3756.1	0.80	2.45	8.856	0.550	5.0	67.3
20403:3786.1	0.04	3.04	3.349	0.011	9.0	25.5
20403:3796.3	0.04	2.80	2.241	0.009	4.7	21.7
20403:3816.3	0.20	2.92	1.708	0.031	1.7	14.7
20403:3876.3	0.39	2.82	1.570	0.063	3.7	15.7
20403:3946.1	2.64	2.74	1.222	0.477	8.3	17.6
20403:3976.3	3.37	2.55	0.578	0.208	1.6	6.0

Table II (cont)

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Appendix E

WELL PRODUCTION IN TIGHT SHALES: DIFFUSION-FLOW IN THE RADIAL CASE

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WELL PRODUCTION IN TIGHT SHALES: DIFFUSION-FLOW IN THE RADIAL CASE

Abstract

Well production is examined in the case where in both degasibility effects through the rock matrix and flow effects through a horizontal fracture system to the well bore must be considered. The productivity vs. time curves are flatter than for other cases including the vertical fracture case and the short open fracture case. Some implications are discussed.

Introduction

A model was recently introduced (1) that calculates well productivity as a function of time that takes into account both the processes of flow of gas into a fracture from the rock matrix as well as its subsequent flow along the fracture to the well bore. The model assumed a single vertical fracture of constant thickness and defined height. One end of the fracture was terminated by the well bore; the other termination was at infinity. Thus linear diffusive flow through the rock matrix was coupled with Poiseuille flow of the gas through the fracture. The resulting solution indicated that

$$1) \quad \frac{dM_T}{dt} = At^{-1/4}$$

or

$$2) \quad M_T = \frac{4}{3} At^{3/4}$$

where M_T = cumulative well production,

t = time,

A = a constant containing the specific degasibility, G, the rock pressure, p_2, etc.

These results were compared with an open fracture case (wherein resistance through the fracture could be neglected) and a "constricted fracture case."

The purpose of this paper is to consider the case of radial flow taking into account both fracture flow and matrix flow in a manner similar to that of the linear case. We shall consider the case of a single horizontal fracture of uniform width intersected at right angles by the well bore. The fracture will be assumed to be of uniform width, h, and of great enough extent in each direction so that "end" effects are not detectable. At time zero the pressure in the well bore is assumed to drop from rock pressure, p_2, to a new constant value, p_0, as production begins. As a result of flow through the fracture, a radial pressure

gradient will be set up which will determine a pressure profile within the fracture. This flow is maintained by diffusive flow through the fracture faces into the fracture. Flow changes with time because as the concentration of gas within the rock decreases the pressure gradient decreases correspondingly. This in turn decreases the flow into the fracture which causes a decreased pressure gradient along the fracture and hence a decrease in production with time.

Theoretical

The volume flux of gas at any given point within the fracture is given, as before (1), as

$$3) \quad Q_v(r) = \frac{h^3}{12\eta} \frac{\partial P}{\partial r}$$

This can be immediately integrated around the radius to give a total flow (in moles) of

$$4) \quad \left.\frac{dM_T}{dt}\right|_r = \frac{\pi r p h^3}{6\eta RT} \frac{\partial p}{\partial r}$$

at radius r. As before we take the flux into the fracture as

$$5) \quad J_n = G(p_2 - P)t^{-\frac{1}{2}}$$

where J_n is the contribution to flow per unit area of fracture face. Defining

$$6) \quad P = \frac{p}{p_2}$$

$$7) \quad u = \left[\frac{24G\eta RT}{h^3 p_2 t^{\frac{1}{2}}}\right]^{\frac{1}{2}} r$$

we obtain (setting the divergence of flow equal to the diffusive flux)

$$8) \quad \frac{\partial}{\partial u}\left(P u \frac{\partial P}{\partial u}\right) = (1 - P)\, u$$

for the pressure profile of the gas in the fracture as a function of radius.

The total flow is given by

$$9)\quad \left.\frac{dM_T}{dt}\right|_{r_0} = \frac{h^3 \pi p_2^2}{6\eta RT} F_0$$

$$F_{r_0} = \left[Pu\frac{\partial P}{\partial u}\right]_{r_0}$$

where the evaluation is made at r_0 = the well bore radius.

Equation 8) integrates directly to give

$$10)\quad F_{u+h} = F_u + A$$

$$A = \int_u^{u+h} u(1 - P)\, du$$

$$F_u = \left[PP'u\right]_u$$

$$F_{u+h} = \left[PP'u\right]_{u+h}$$

Noting that $PP' = \frac{1}{2}\frac{dP^2}{du}$

$$11)\quad \tfrac{1}{2}\frac{dP^2}{du} = \frac{F_u}{u+h} + A$$

or by integrating

$$12)\quad \tfrac{1}{2}P^2 = \tfrac{1}{2}P_u^2 + F_u \ln(1+x) + \int\frac{A}{u+h}\, dh$$

$$x = \frac{h}{u}$$

The solution of this latter equation permits evaluation of the pressure at any radius given the value of P and the reduced flow F at some other radius. The function A is most easily solved for small values of h corresponding to small changes in radii. Specifically

$$13)\quad A \cong u_0(1 - P_0)h + (1 - P_0 - u_0P_0')\frac{h^2}{2}$$

$$14)\quad \int \frac{A}{u_0 + h} = u_0^2(1 - P_0)\, L(1;x) + \frac{u_0^2}{2}\,(1 - P_0 - u_0 P_0')\, L(2;x)$$

where

$$15)\quad L(n;x) = \int_0^x \frac{x''}{1 + x}\, dx \cong \sum_{i=1}^{\infty} \frac{(-)^{i+1} x^{n+i}}{n + i}$$

and

$$x = \frac{h}{u_0}$$

Results

Figure I shows a plot of production rate vs. time for the following assumptions. The calculations were made assuming a .01 cm wide fracture, a specific degasibility of 4×10^{-7} cm^3 gas (STP)/cm^2 rock/torr, a rock pressure of 500 psi and that the viscosity of methane is 102.6×10^{-6} poise, and that the well bore radius was 10 cm. A primary feature of the productivity curve obtained (Fig. I) is its flatness.

A second feature is the relatively large rate of flow associated with the single fracture. In this regard it should be noted that the flow rate is a sensitive function of the assumed fracture width; an error of a factor of two makes almost an order of magnitude difference in flow. As a second point it should be noted that a radial (i.e., horizontal) fracture is much more effective per unit length of intersection with the well bore than a vertical fracture. Comparing our result here with the linear case of identical fracture width, it becomes apparent that the .63 meters of radial fracture-well bore intersection involved in this calculation produces 10 times more gas than 40 meters of the vertical fracture-well bore intersection. The qualitative reason for this is that the geometry of the radial fracture moves the pressure gradient toward the well bore. Since flow is associated with the gradient at the bore-fracture intersection the radial

fracture should be more efficient per unit length of bore intersection. (This conclusion will need to be reexamined to determine the extent to which it holds in the case of finite fractures.)

The radial model closely fits the equation

$$\frac{dM_T}{dt} = At^b$$

$$A = 490.$$

$$b = -.026$$

This small value of b compares with -.5 for the "open fracture" model, -.25 for the infinite linear (vertical) fracture and 0.0 for the constricted exit model (1). It should be noted that for the four cases considered, the closer the exponent is to zero the more the pressure gradient along the fracture has been shifted toward the well bore.

Conclusion

As in previous cases the well productivity is a function of rock matrix parameters (i.e., specific degasibility), fracture parameters (i.e., fracture width, geometry and extent) and well bore parameters (rock pressure and wellhead pressure). Successful production can only (or best) occur when all three types of parameters have favorable values.

The calculations shown here for the radial fracture case are supportive of the notion that the production from wells with flattened productivity curves can be increased because these flattened curves correlate with high pressure gradients and hence constrictions near or at the well bore-fracture interface. For example propping of an (infinite) radial fracture could be particularly effective because of the high sensitivity of the flow rate to the fracture width combined with the relative importance of the area of the fracture near the bore. The only exception to this generalization is some modeling work a couple of years ago which attained

flattened curves by postulating a skin effect due to slickensiding or mineralization of the fracture surface(2). We have had plans to look at the degassing kinetics of natural fracture surfaces in order to ascertain whether a "skin" effect is in fact a realistic possibility or not. Regardless of the outcome of this postulated "exception," it seems inescapable to avoid the conclusion that many, if not all, flattened production curves are produced by conditions that can be corrected or at least improved by application of appropriate technology such as propping.

We are continuing work on the various implications and generalizations of these calculations.

Bibliography

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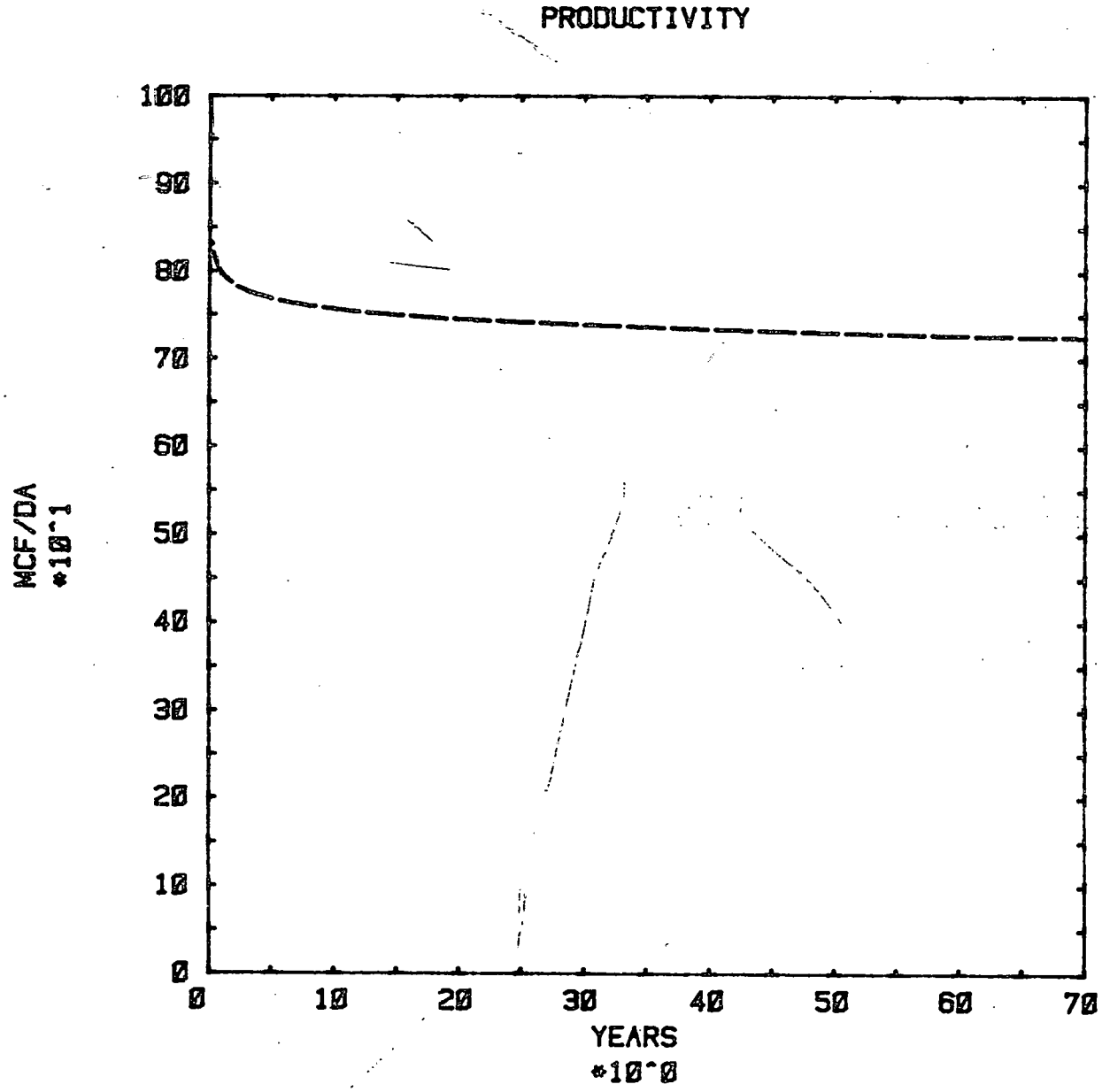
PRODUCTIVITY
MCF/DA
*10^1
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
YEARS
*10^0

FIG # 1

ORO-5197-14
Appendix F

INFRARED AND X-RAY STUDIES

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INFRARED AND X-RAY STUDIES

A systematic study has been initiated on the infrared spectral properties of a group of 14 selected shale samples displaying both average and extreme values of the physical parameters arising from the Juniata EGSP measurements (isotherms, degasibilities, etc.). Primary emphasis is being placed on the wavelength region from 11-23 microns, readily accessible using KBr optics. Samples are prepared as KBr pellets using shale crushed and sieved to pass 400 mesh (38 μ) at a weight concentration in the range of 0.5-1%. The standard NaCl region (3-14 μ) is also being scanned, though to date it appears less promising in that few differences are apparent from sample to sample. In the KBr region some variable features have been identified, primarily as weak absorption bands or shoulders, but it is premature to attempt to assess their significance.

The samples selected for IR study will also, in coming weeks, be extensively investigated using powder X-ray diffraction techniques, and it is further planned to utilize them for more sophisticated temperature and pressure variation studies so that reasonably complete physicochemical profiles can be constructed in an attempt to isolate new parameters that can be used to predict gas production potential.