

**ENHANCED RECOVERY OF IN SITU  
METHANE BY CARBON-DIOXIDE INJECTION:  
AN EXPERIMENTAL FEASIBILITY STUDY**

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May 1982

Work Performed Under Contract No.: DE-FG21-80MC14262

For  
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ABSTRACT

A set of experiments is described in which carbon dioxide is injected into large cores of methane-and water-saturated bituminous coal, at elevated pressures. CO<sub>2</sub> at pressures of up to 800 psig is used to simulate the enhanced recovery of in-situ methane from coal beds. Carbon-dioxide injection increases the recovery of methane by a factor of 2-3 times that achieved in simple desorption by pressure drawdown and atmospheric diffusion. In general, higher CO<sub>2</sub> pressures achieve greater methane recovery. The presence of even small amounts of nitrogen in the injection gas, greatly reduces the methane recovered. CO<sub>2</sub> at pressures of 500-800 psig are shown to be capable of completely de-methanating integral coal samples. This fact was also confirmed by tests run on crushed cores. The consumption of CO<sub>2</sub> by permanent adsorption is quite high vis-a-vis the methane recovered and may preclude its use as an enhanced-recovery energy process. Its primary function would appear to be as a means of safely de-methanating coal beds prior to mining.

INTRODUCTION

The present paper represents an extension of the work by Fulton, et. al<sup>1</sup> to higher CO<sub>2</sub> pressures. A rather complete literature review is presented in this previous work<sup>1</sup> and will not be repeated here.

This paper describes a series of laboratory tests run on Pittsburgh Seam bituminous coal from West Virginia. Large coal cores were injected with methane to various equilibrium pressures and saturated with water. The methane was then vented and allowed to desorb at atmospheric pressure. This procedure is termed "natural production". Carbon-dioxide

was injected until a pre-determined equilibrium pressure was reached. The pressure was then released either rapidly or slowly until atmospheric production was negligible. The gas quality and quantity was analysed and the CO<sub>2</sub> adsorbed determined by material balance.

Variations on this basic procedure included the exclusion of the natural production cycle; the speed of CO<sub>2</sub> pressure drawdown; the number of CO<sub>2</sub> cycles which constitute the simulated recovery process; the use of N<sub>2</sub>/CO<sub>2</sub> mixtures as the injection gas; variations in injection pressures from 200-800 psig; subsequent exposure of crushed samples to CO<sub>2</sub>; and the determination of the total in-place methane by successive injections of CO<sub>2</sub> at 800 psig after the process cycles and regardless of the CO<sub>2</sub> pressure employed in the latter.

#### EXPERIMENTAL PROCEDURE

The experimental procedures and equipment descriptions are essentially the same as those described in Reference 1. Briefly, the same size coal samples were employed (3 1/2-inch diameter) and the pressure vessels were replaced with high-pressure stainless steel cylinders with "O" ring seals. A new gas chromatograph was employed with the collector system remaining essentially unchanged (see Figure A-2).

Appendix A includes six schematic diagrams depicting sample preparation, experimental set-up, and recovery simulation.

The coal was stored under water with a bactericide added, until cored. The cores were then dried @ 70°C under vacuum for 30-70 days (see Figure A-1). The cores were then subjected to methane adsorption until an equilibrium pressure was established at 200 psig (800 psig in the case of sample 22). The cores were then permitted to imbibe water treated

with a bactericide for several days. The immersed cores were then subjected to a methane pressure equal to the adsorption pressure to achieve maximum water saturation (see Figure A-3).

The excess water was then drained from the vessels and the porosity computed from the volume of water remaining and the assumption of 100 percent saturation of the coal fractures and matrix pores by the water.

The coal was then allowed to desorb methane at atmospheric pressure until the methane produced was negligible. This lasted from 5-15 days and was proportional to the adsorption pressure (see Figure A-4). The natural production cycle was not included in runs 14-16.

Carbon dioxide ( $\text{CO}_2/\text{N}_2$  in the case of run no. 20) was then injected until some specified equilibrium pressure was established. These pressures are listed in Table 1 and ranged from 200-800 psig. The vessels were then vented either rapidly or slowly (runs 21, 23 and 24) to atmospheric pressure and production permitted to continue until methane production was negligible. Such a competitive adsorption/desorption process constituted one "process" cycle.

A complete enhanced recovery process consisted of three such cycles for rapid pressure drawdown to atmospheric pressure (30-90 minutes). In the case of slower pressure drawdowns to atmospheric pressure (~ 1400 cc total gas per 8 hour period), a single cycle constituted the enhanced process. Subsequent atmospheric production for either case ranged from 2-4 days (see Figure A-5).

All runs, regardless of the "process" pressure were then subjected to multiple  $\text{CO}_2$  injections at 800 psig until methane recovery was negligible. This required from 1 to 4 cycles as shown in Table 1 and Figures 2, 5, and 6. This provided the total in-place methane value for the

sample which was considerably in excess of that added by laboratory adsorption. This excess methane was simply the residual in-situ methane which was not removed from the cores during preparation.

The 800-psig CO<sub>2</sub> injections effectively remove all of the in-place methane. This is confirmed by the tests run on samples 18 and 19 after crushing (see Table 6) which are described below.

Finally a dual material balance check was provided by that on the supply reservoir and that on the sample vessel. Also, all vessel void space was accounted for in the mass balances.

All tests were performed at between 60 & 70°F.

#### TOTAL METHANE-IN-PLACE

The 12 samples tested show total methane-in-place values of 138-193 SCF/Ton of coal for the 10 samples in which methane was adsorbed at 200 psig (see Table 1). Sample 22 which adsorbed methane at 800 psig yielded a higher total in-place-methane value of 222 SCF/Ton of coal. The latter value is clearly a result of the large amount of methane adsorbed at 800 psig, 158 SCF/Ton compared to corresponding values of 65-147 SCF/Ton for the other samples.

It should be recalled that the methane adsorption values of Table 1 were computed for the methane remaining in the cores, after the adsorption pressure was vented to atmospheric pressure.

The total in-place methane values appear to be quite reasonable for Pittsburgh-Seam coals and, are considerably higher than those reported by Fulton, et. al.<sup>1</sup> which is to be expected inasmuch as these earlier experiments were limited to pressures of less than 200 psig.

Figures 1 and 2 show the effect of 800 psig CO<sub>2</sub> cycles run subsequent to the process-pressure cycles. The amount of additional methane recovered is inversely proportional to the process CO<sub>2</sub> pressure. Sample 14 at a process CO<sub>2</sub> pressure of 200 psig for 3 cycles (Figure 1) desorbs 150 percent more methane when exposed to 4 cycles of CO<sub>2</sub> injected at 800 psig (Figure 2). Smaller but significant increases are similarly displayed by samples 15 and 16 for CO<sub>2</sub> process-pressures of 560 and 800 psig, respectively.

The total methane-in-place values do not correlate with the apparent porosities listed in Table 1.

#### POROSITY

Porosity values range from 2.76-8.5 percent of bulk volume and are listed in Table 1. At an average value of 4+ percent these values are somewhat in excess of the 2.5 percent values obtained by Reznik, et. al.<sup>2</sup> for Pittsburgh type coal from Pricetown, West Virginia. They are quite close to values obtained for Pocohontas coals<sup>3</sup> which are more friable than Pittsburgh coals.

The discrepancy between the values obtained in Reference 2 and the present work is probably the result of the better experimental procedure employed by Reznik, et. al.<sup>2</sup> in which water was imbibed into almost completely evacuated cores. Countering this effect is the probability of a more highly developed fracture system in the larger 3 1/2-inch diameter cores of the present paper compared to the 1 1/2-inch diameter cores employed in References 2 and 3.

The values, in any case, appear to be reasonable and the assumption of 100 percent water saturation is consequently justified. Thus, the gas

desorption rates would be minimized<sup>1</sup> and the cores may be representative of the coal around a well bore. Significant amounts of carbon dioxide would also be dissolved in the water.

#### METHANE RECOVERY

Table 2 and Figures 3-6 reveal the relatively low and constant methane recoveries achieved by natural production (labeled "N" on the Figures) at atmospheric pressure. This type of process is clearly diffusion controlled and yields about 30 percent of the total methane-in-place. Sample 20, Figure 6, yields the lowest value at about 20 percent while sample 22, in which methane was adsorbed at 800 psig, yields the highest value at 45 percent.

Figure 1 shows the significant increase in methane recovery as the CO<sub>2</sub> pressure is increased. In these 3 runs, 14-16, the recovery process consisted of 3 CO<sub>2</sub> cyclic injections at the end of which recoveries of approximately 40, 82, and 92 percent were achieved for CO<sub>2</sub> pressures of 200, 560, and 800 psig, respectively.

Figure 3 shows that for CO<sub>2</sub> pressures of 300, 400, and 560 psig, the recovery was almost identical at about 80 percent (see Table 2). An additional 10 percent of the methane-in-place was recovered using CO<sub>2</sub> at 800 psig in run number 18. All four runs included a natural desorption step.

Figure 4 shows the large methane recovery which can be achieved by a single CO<sub>2</sub> injection cycle when the production rate is maintained low. Including natural desorption, the recovery is about the same, for CO<sub>2</sub> at 200 psig, as that when the process consists of 3 CO<sub>2</sub> cycles. At 800 psig CO<sub>2</sub> pressure, 75 percent of the methane-in-place of sample 21 is

recovered after only a single  $\text{CO}_2$  injection cycle following natural desorption. Sample 24 which was run in a similar fashion, but at a  $\text{CO}_2$  pressure of 560 psig, displayed a methane recovery of 68 percent, only slightly lower than that achieved by  $\text{CO}_2$  at 800 psig from sample 21.

Figure 5 compares 4 samples run at  $\text{CO}_2$  pressures of 800 psig. Differences in the runs are: The elimination of natural desorption for run 16,  $\text{CH}_4$  adsorption at 800 psig for run 22, rapid  $\text{CO}_2$  pressure drawdown for run 18, and slow  $\text{CO}_2$  pressure drawdown for run 21. All 800 psig  $\text{CO}_2$  cycles are included. Performance is similar for all runs, being characterized by high recoveries. Sample 22 displays the best performance and may argue against the low recoveries at  $\text{CO}_2$  pressures of 200 psig being interpreted as a result of that pressure being identical with the usual methane adsorption pressure.

#### NITROGEN/CARBON DIOXIDE MIXTURES

Figure 6 and Table 3 show the results of using mixtures of  $\text{N}_2$  and  $\text{CO}_2$  as the injection gas. The  $\text{CO}_2$  partial pressures ranged from 60 to 800 psig for a constant, total injection pressure of 800 psig. Nine injection cycles following natural desorption were required to recover all of the in-place methane. Three cycles with  $\text{CO}_2$  @ 60 psig resulted in only doubling the already low recovery due to natural desorption. The fourth cycle at a  $\text{CO}_2$  partial pressure of 200 psig resulted in about the same recovery as that for a total pressure of 200 psig. Further, the recovery at a  $\text{CO}_2$  partial pressure of 560 psig resulted in significantly lower recovery than a total  $\text{CO}_2$  pressure cycle of the same value. The last 4 cycles were 100 percent  $\text{CO}_2$  and resulted in doubling the production.

Material balance indicated that none of the  $N_2$  was adsorbed by the coal when in the presence of  $CO_2$ . It would appear that mixtures of  $N_2$  and  $CO_2$ , over a wide concentration range, greatly reduce the recovery of methane. This result is in agreement with that observed in  $CO_2$  water-flooding of petroleum reservoirs<sup>4</sup>.

#### METHANE RECOVERY FROM CRUSHED COAL

After all apparent methane had been recovered from samples 18 and 19, these cores were crushed to cumulative size distributions tabulated in Table 6. Crushed coal from sample 18 was subjected to nitrogen at 30 psig and shut in for 72 hours. The production gas contained only 0.1 percent methane (see Figure A-6).

Crushed coal from sample 19 was subjected to a fourth  $CO_2$  injection cycle at 800 psig. This yielded only 1.68 SCF/Ton of additional methane or 1.16 percent of the total methane-in-place value as computed prior to crushing. We conclude that multiple  $CO_2$  cycles at 800 psig (near the critical point at 60-70°F) completely strip all of the in-situ methane from coal (see Figure A-6).

#### CARBON DIOXIDE ADSORBED

Table 5 shows the amount of  $CO_2$  permanently adsorbed on the coal for the various tests. The results are scattered but clearly reveal a negative result with regard to energy efficiency. Disregarding the optimistic results of sample 15, about 9 SCF of  $CO_2$  per SCF of  $CH_4$  is required to recover all of the methane by rapid  $CO_2$  pressure drawdown. Slower drawdown of the production gas pressure reduces this to about 6 SCF of  $CO_2$  per SCF of  $CH_4$ .

The CO<sub>2</sub> lost increases with the CO<sub>2</sub> injection pressure. Thus the more CH<sub>4</sub> recovered the greater is the loss of CO<sub>2</sub>. The only run which yields a roughly even trade-off between CH<sub>4</sub> recovered and CO<sub>2</sub> adsorbed is the low pressure, slow production run of sample 23. However, this process would still leave 60 percent of the in-situ methane unrecovered.

#### COMPOSITION OF PRODUCED GAS

Table 4 shows the low quality of the product gas produced. For cycle 1, the methane content of the produced gases is greater at lower CO<sub>2</sub> pressures but never exceeds 20 percent by volume. Subsequent cycles produce gases of very low methane content. In most runs, CO<sub>2</sub> comprises 90-99 percent of the product gas. No attempt was made to recycle this gas.

#### CONCLUSIONS

1. The production of methane from coal beds by natural desorption produces about 30 percent of the total in-place methane. This value should increase slightly with beds of greater depth. This process is diffusion controlled.

2. Carbon dioxide at pressure between 500 and 800 psig is capable of completely desorbing all of the in-situ methane from coal beds by cyclic injection. The process is primarily controlled by fluid dynamics, Darcian or fully laminar. The latter production period, which may be diffusion controlled, recovers an insignificant amount of methane for any cycle.

3. The large quantities of carbon dioxide which are permanently adsorbed on the coal probably preclude its employment as an enhanced recovery process.

4. Cyclic carbon-dioxide injections at high pressure with recycling of the product gas may represent a safe way to de-methanate a coal seam prior to mining.

#### PRESENTATIONS AND PAPERS

The following presentations and/or papers resulted from this work:

1. Shah, N. B.: "An Experimental Simulation of Enhanced Recovery of In-Situ Methane from Bituminous Coal by Carbon Dioxide Injection", M. S. Thesis, University of Pittsburgh, Pittsburgh, 1981.
2. Barron, W.: "SPE Student Paper Contest", Pittsburgh, April, 1981 (3rd place).
3. Foley, W. L.: "SPE Student Paper Contest", Morgantown, W. Va., April 1982 (3rd place).
4. Reznik, A. A., Singh, P. K., and Foley, W. L.: "An Analysis of the Effect of Carbon Dioxide Injection on the Recovery of In-Situ Methane from Bituminous Coal: An Experimental Simulation" SPE/DOE paper 10822, Proceedings of the SPE/DOE Unconventional Gas Recovery Symposium, Pittsburgh, (May 16-18, 1982) pp. 275-278.
5. Singh, P. K.: "An Analysis of the Effect of Carbon Dioxide Injection on the Recovery of In-Situ Methane from Bituminous Coal: An Experimental Simulation", M.S. Thesis, University of Pittsburgh, Pittsburgh, 1982.

#### ACKNOWLEDGEMENTS

This work was primarily funded by the Morgantown Energy Technology Center of the United States Department of Energy, under Contract No. DE-FG21-80 MC 14262.

REFERENCES

1. Fulton, P. F., Parente, C. A., Rogers, B. A., Shah, N. B., and Reznik, A. A.: "A Laboratory Investigation of Enhanced Recovery of Methane from Coal Beds by Carbon Dioxide Injection", paper SPE/DOE 8930, Proceedings of the First Annual Symposium on Unconventional Gas Recovery, Pittsburgh, (May 18-21, 1980) 65-72.
2. Reznik, Alan A., Lien, C. L., and Fulton, P. F.: "Permeability Characteristics of Coal", Proceedings of the Fourth Annual Underground Coal Conversion Symposium, (printed June, 1978) 435-452 (Available from NTIS).
3. Dabbous, M. K., Reznik, A. A., Taben, J. J., and Fulton, P. F.: "The Permeability of Coal to Gas and Water", Soc. Pet. Eng. J. (December, 1974) 563-572 and Trans. AIME, 257, 556-565.
4. Graue, Dennis J., and Zana, E. T.: "Study of a Possible CO<sub>2</sub> Flood in Rangely Field", J. Pet. Tech. (July, 1981) 1312-1318.

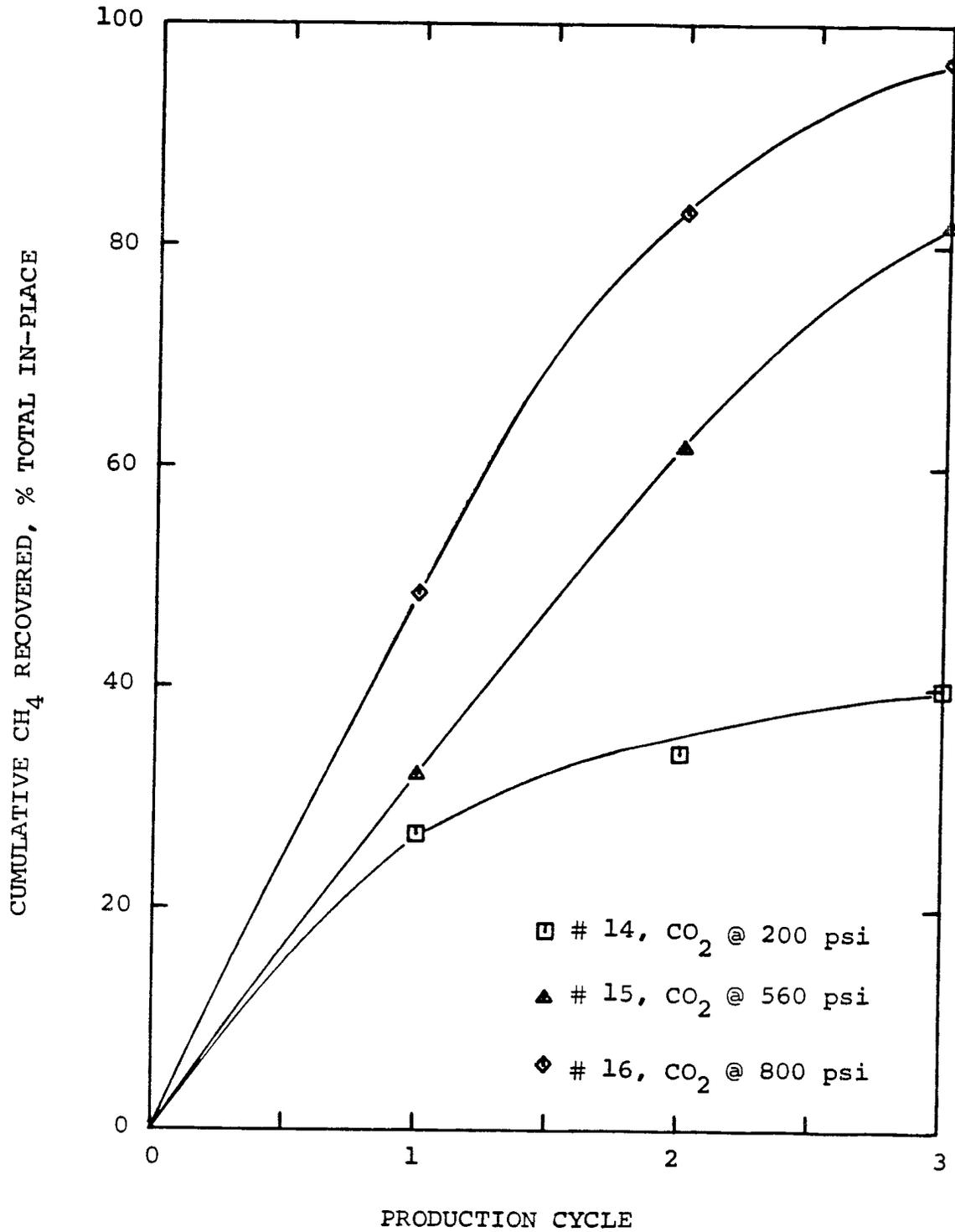
Fig. 1 - Effect of CO<sub>2</sub> pressure on methane recovery

Fig. 2 - Determination of total methane in-place

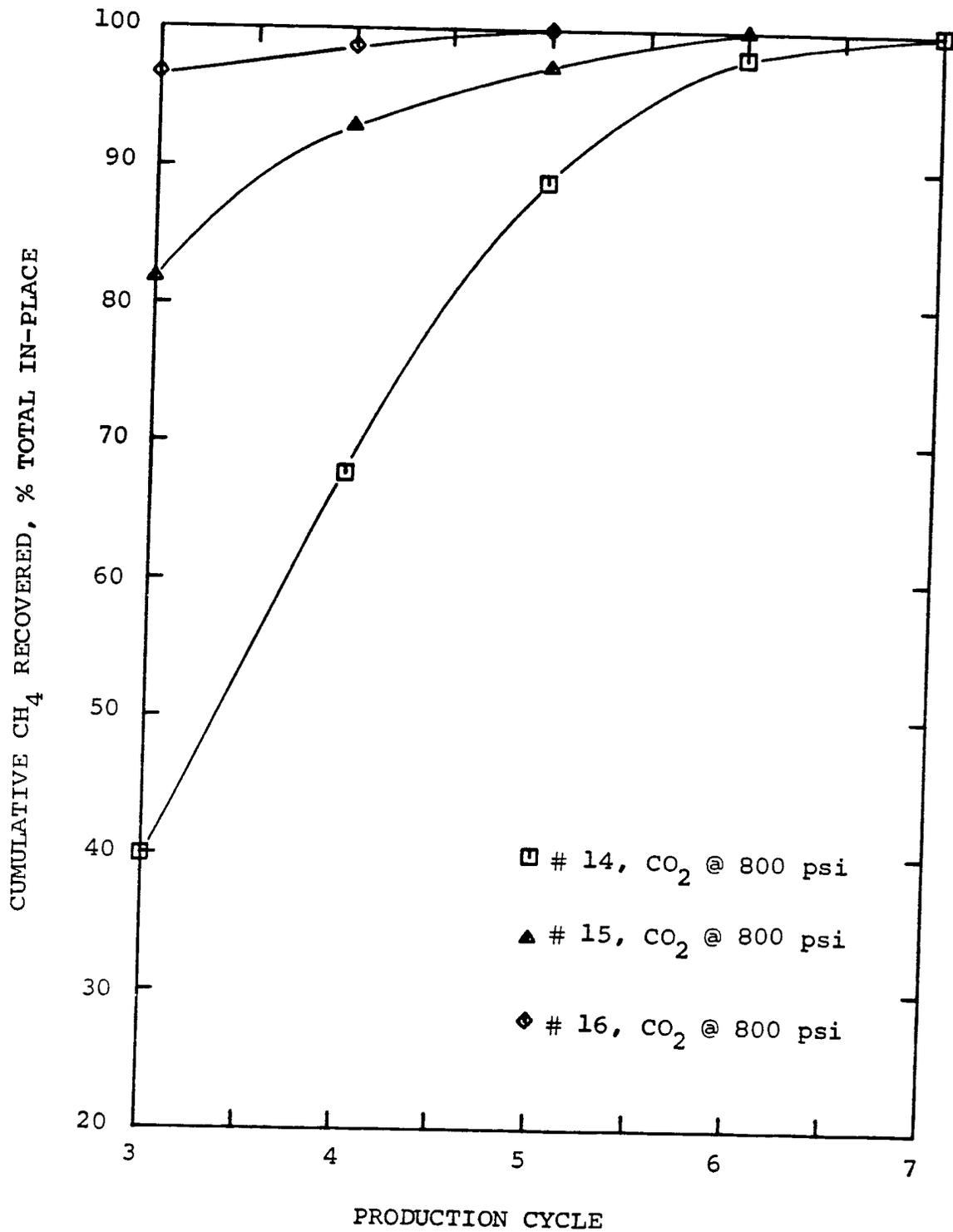


Fig. 3 - Methane recovery by natural and enhanced recovery

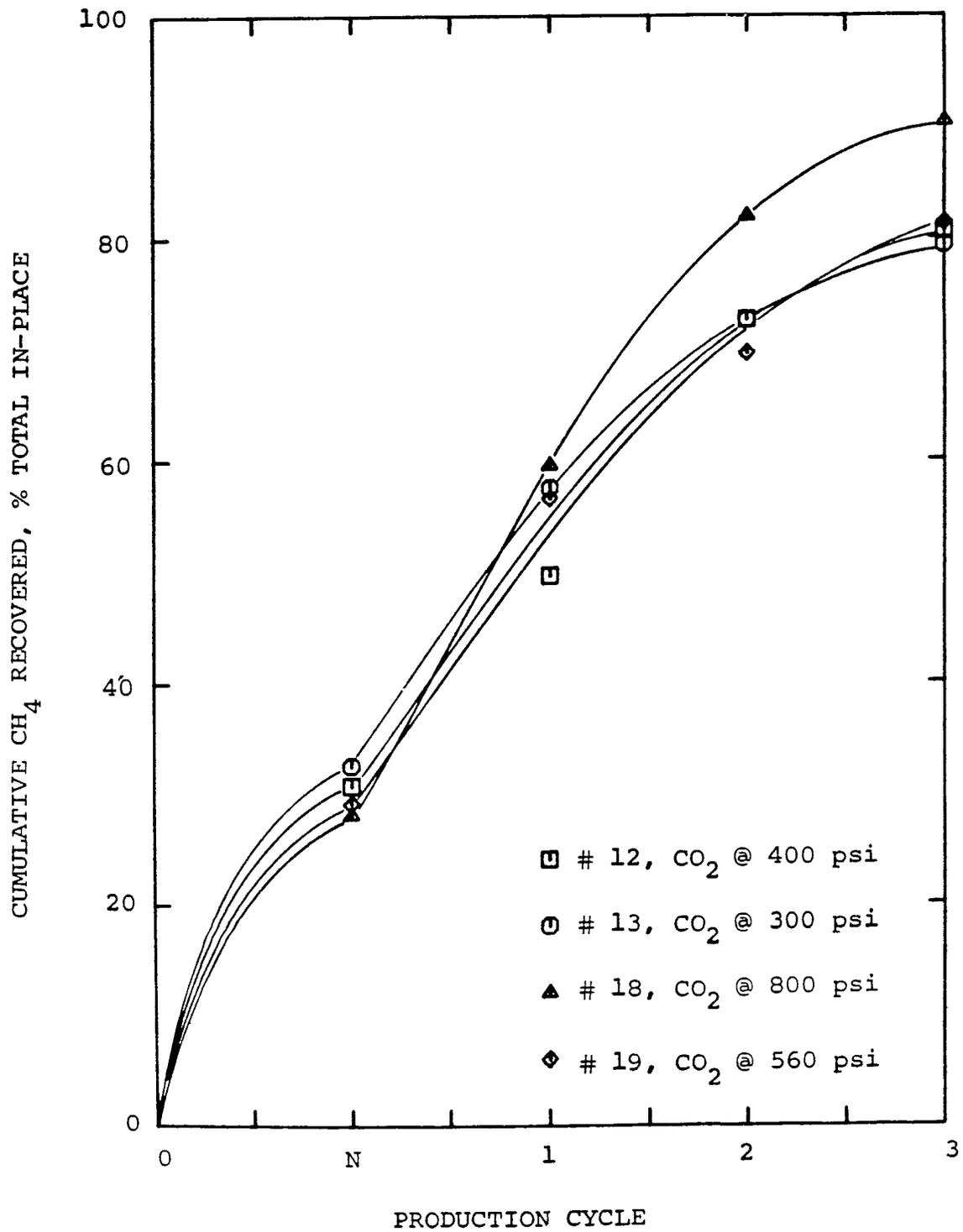


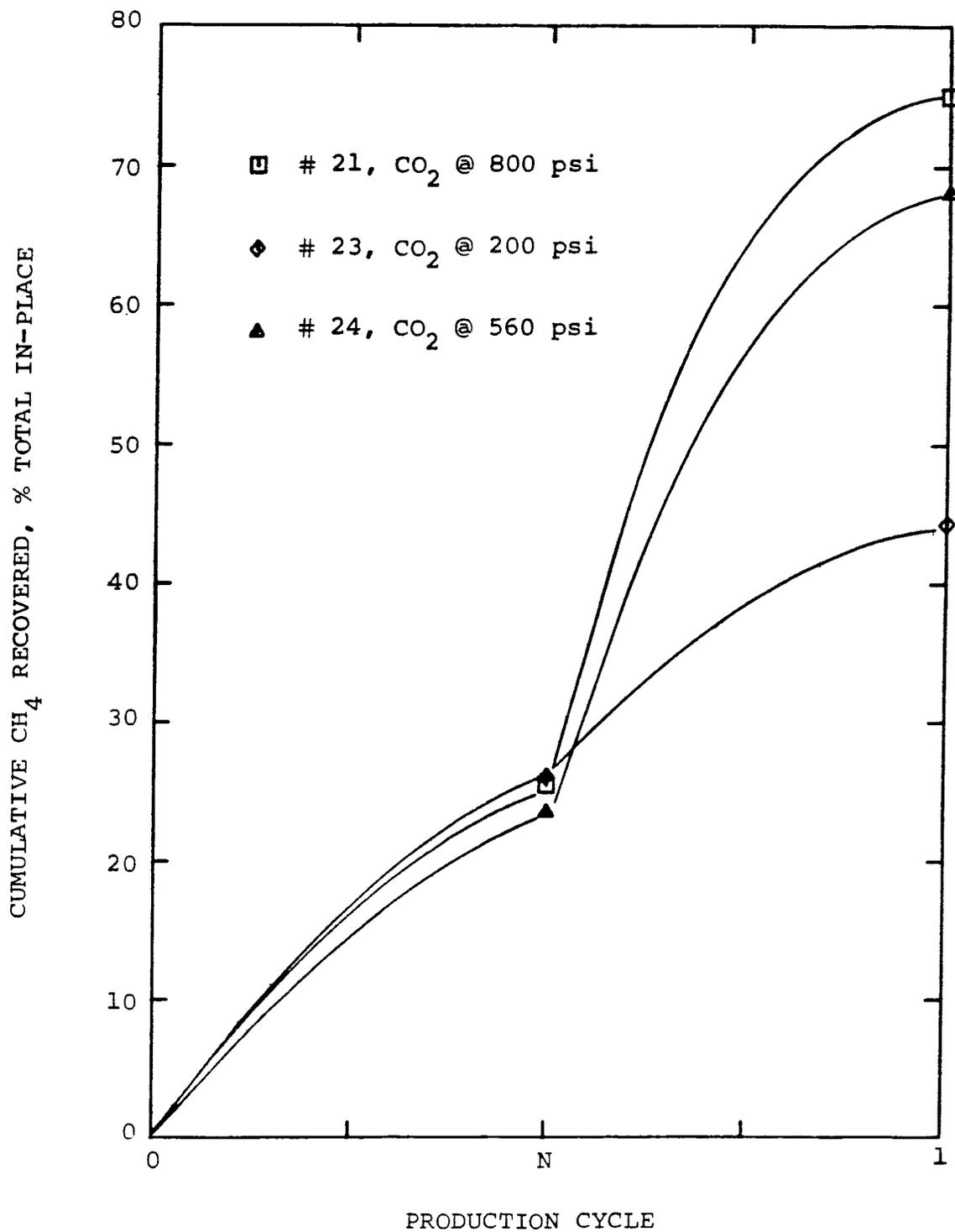
Fig. 4 - Effect of CO<sub>2</sub> pressure on slow production cycle

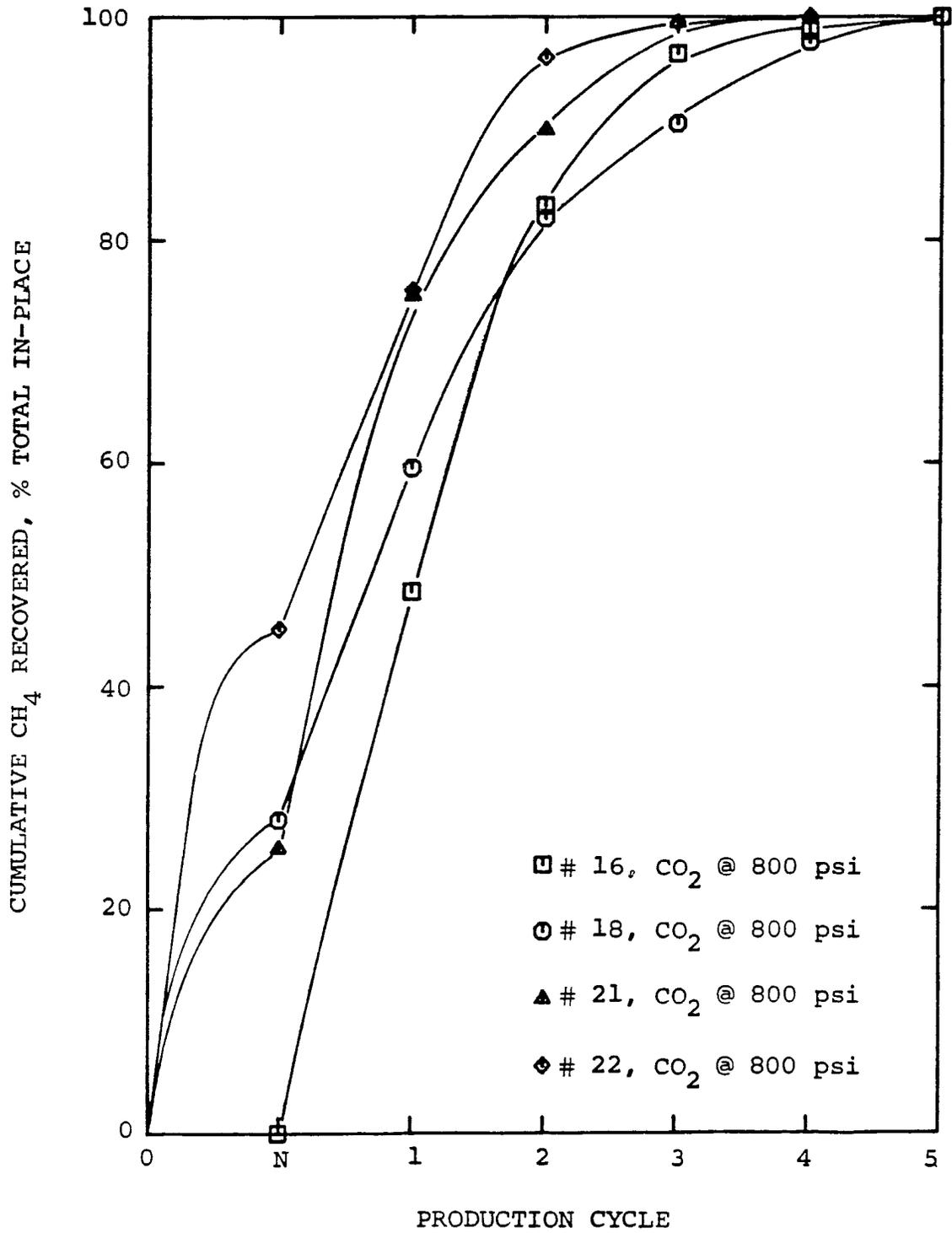
Fig. 5 - Comparison of 800-psig CO<sub>2</sub> tests

Fig. 6 - Effect of nitrogen concentration on methane recovery

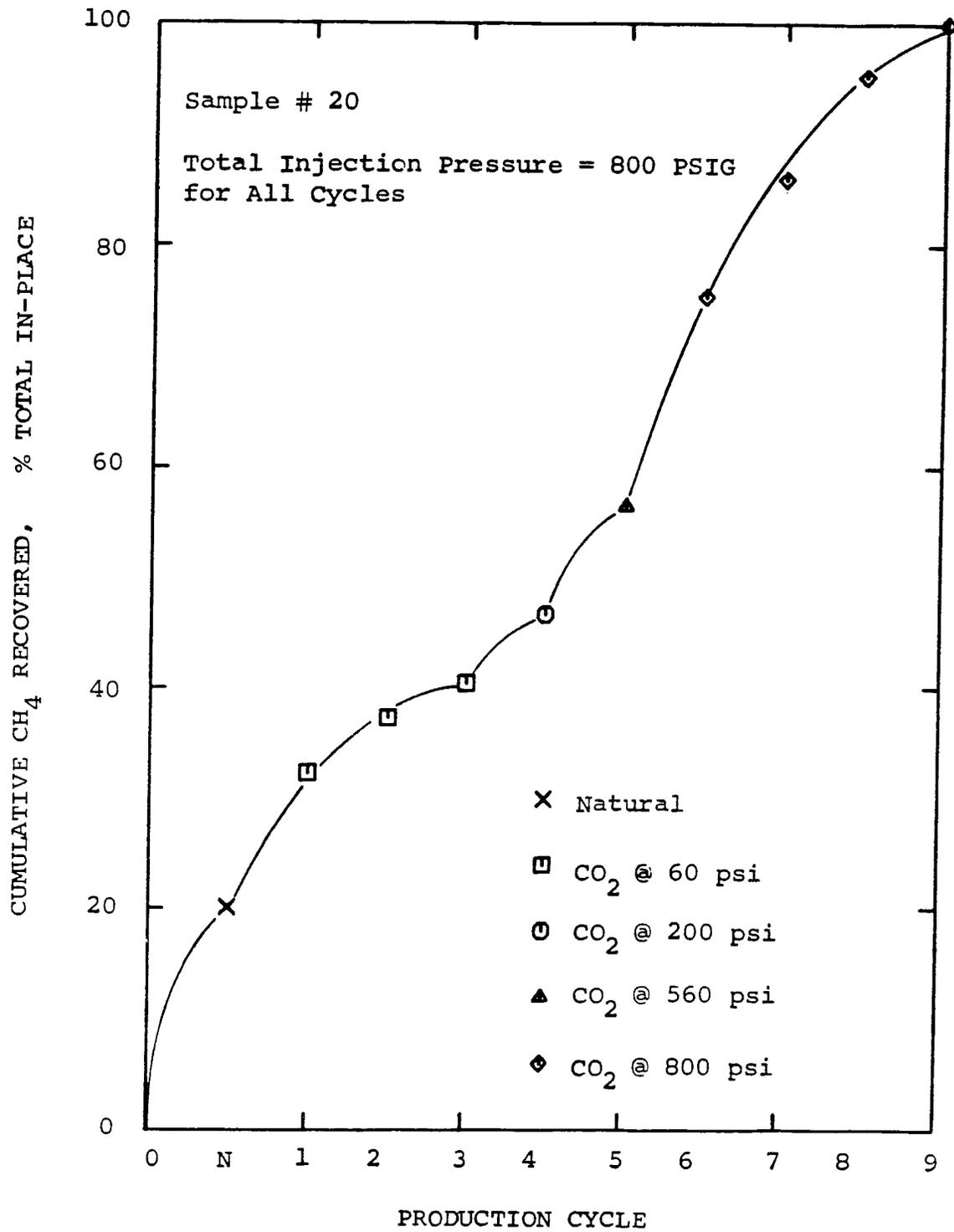


TABLE 1  
SAMPLE PROPERTIES AND TEST PARAMETERS

Sample & Run No.	12	13	14	15	16	18	19	20	21	22	23	24
Apparent porosity, % of bulk volume	4.20	4.80	2.76	5.14	3.77	5.80	8.50	4.20	5.35	3.98	4.74	4.46
Total CH <sub>4</sub> in-place, SCF/TON	165	165	138	151	150	156	143	154	193	222	161	178
CH <sub>4</sub> adsorbed, SCF/TON	143	142	67.0	71.1	65.7	127	105	110	90.4	158	147	154
CH <sub>4</sub> adsorption pressure PSIG	200	200	200	200	200	200	200	200	200	800	200	200
CH <sub>4</sub> produced by natural desorption	yes	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes
CO <sub>2</sub> pressure for enhanced recovery simulation, PSIG	400	300	200	560	800	800	560	Variable (See Table 3)	800, for cycle 1, only	800	200, for cycle 1, only	560, for cycle 1, only
Additional CO <sub>2</sub> Cycles @ 800 PSIG required to determine total in-place CH <sub>4</sub>	2	2	4	3	2	2	3	"	3, after cycle 1	1	4, after cycle 1	3, after cycle 1
Relative speed of CO <sub>2</sub> pressure drawdown	Rapid	Slow	Rapid	Slow	Slow							
Subsequent crushing and testing	no	no	no	no	no	yes	yes	no	no	no	no	no

TABLE 2  
METHANE PRODUCTION BY NATURAL DESORPTION AND CARBON-DIOXIDE INJECTION

Sample & run no.	12	13	14	15	16	18	19	20	21	22	23	24
CH <sub>4</sub> produced by natural desorption, SCF/TON	50.7	53.5	not run	not run	not run	43.8	41.6	31.0	49.2	100	42.0	42.0
(% of total in-place CH <sub>4</sub> )	(30.7)	(32.5)				(28.1)	(29.1)	(20.1)	(25.5)	(45.1)	(26.1)	(23.6)
No. of CO <sub>2</sub> cycles employed to simulate enhanced recovery process	3	3	3	3	3	3	3	variable (see Table 3)	1	3	1	1
Cumulative CH <sub>4</sub> produced by process simulation (not incl. natural desorption), SCF/TON	82.4	77.0	55.1	124	145	97.4	74.4	"	95.4	120	29.4	79.6
(% of total in-place CH <sub>4</sub> )	(49.9)	(46.8)	(39.9)	(81.8)	(96.7)	(62.3)	(52.2)		(49.5)	(54.3)	(18.3)	(44.6)
	400	300	200	560	800	800	560		800	800	200	560
	PSIG	PSIG	PSIG	PSIG	PSIG	PSIG	PSIG		PSIG	PSIG	PSIG	PSIG
Cumulative CH <sub>4</sub> produced by natural desorption and process simulated CO <sub>2</sub> injection, SCF/TON	133	131	55.1	124	145	141	116	"	145	220	71.4	122
(% of total in-place CH <sub>4</sub> )	(80.6)	(79.3)	(39.9)	(81.8)	(96.7)	(90.4)	(81.3)		(75.0)	(99.4)	(44.4)	(68.2)

TABLE 3  
EFFECT OF NITROGEN PARTIAL PRESSURE ON ENHANCED METHANE RECOVERY:  
SAMPLE AND RUN NO. 20

Cycle No.	1	2	3	4	5	6	7	8	9
	Natural								
Total injection pressure (N <sub>2</sub> + CO <sub>2</sub> ) PSIG	0	800	800	800	800	800	800	800	800
CO <sub>2</sub> partial pressure PSIG	0	60	60	200	560	800	800	800	800
Cumulative CH <sub>4</sub> produced, SCF/TON (% total in-place CH <sub>4</sub> )	30.1 (20.1)	49.8 (32.3)	57.5 (37.3)	62.3 (40.5)	72.0 (46.7)	87.0 (56.5)	116 (75.4)	133 (86.0)	147 (95.2)
CO <sub>2</sub> adsorbed/cycle SCF/TON	0	19.4	13.8	12.4	55.1	204	233	165	114
Produced Gas composition									
% CH <sub>4</sub>	100	4.30	1.69	1.05	1.95	2.41	3.07	1.65	1.28
% CO <sub>2</sub>	0	4.25	5.31	5.46	24.32	67.26	95.93	97.14	97.74
% N <sub>2</sub>	0	91.45	93.0	93.49	73.73	30.33	1.0	1.21	0.98

TABLE 4  
COMPOSITION OF PRODUCED GAS PER CYCLE

Cycle no.	Component % of total	Sample and Run No. (not incl. no. 20 (see Table 3))											
		12	13	14	15	16	18	19	21	22	23	24	
1	CH <sub>4</sub>	5.2	11.1	19.6	6.0	5.8	4.3	5.7	11.3	7.0	15.6	12.9	
	CO <sub>2</sub>	94.0	87.9	75.7	91.1	92.0	94.6	90.5	88.0	92.3	83.6	86.4	
	N <sub>2</sub>	0.8	1.0	4.7	2.9	2.2	1.1	3.8	0.7	0.7	0.8	0.7	
2	CH <sub>4</sub>	8.4	8.2	6.0	4.3	3.9	2.4	1.8	4.2	3.5	2.7	2.8	
	CO <sub>2</sub>	91.1	90.3	92.5	95.0	95.5	96.7	96.9	95.2	96.0	96.7	96.7	
	N <sub>2</sub>	0.5	1.5	1.5	0.7	0.6	0.9	1.3	0.6	0.6	0.6	0.5	
3	CH <sub>4</sub>	1.6	2.5	6.2	2.6	1.3	0.9	2.3	1.8	0.5	1.6	1.0	
	CO <sub>2</sub>	97.4	96.7	92.3	96.8	98.1	98.3	97.1	97.7	99.0	97.8	98.5	
	N <sub>2</sub>	1.0	0.8	1.5	0.6	0.6	0.8	0.6	0.5	0.5	0.6	0.5	
4	CH <sub>4</sub>	1.3	1.3	3.0	0.9	0.2	0.7	0.8	0.1	0.1	1.6	0.8	
	CO <sub>2</sub>	97.3	97.3	95.3	98.5	99.2	98.7	98.1	99.4	99.5	97.9	98.8	
	N <sub>2</sub>	1.4	1.4	1.7	0.6	0.6	0.6	1.1	0.5	0.4	0.5	0.4	
5	CH <sub>4</sub>	0.2	0.2	2.5	0.4	0.1	0.1	0.6					
	CO <sub>2</sub>	99.2	98.2	96.9	99.0	99.4	98.9	98.0					
	N <sub>2</sub>	0.6	0.6	0.6	0.6	0.5	1.0	1.4					
6	CH <sub>4</sub>			1.0	0.3			0.4					
	CO <sub>2</sub>			98.4	99.2			98.5					
	N <sub>2</sub>			0.6	0.5			1.1					
7	CH <sub>4</sub>			0.2									
	CO <sub>2</sub>			99.2									
	N <sub>2</sub>			0.6									
Cycles simulating enhanced recovery process		1-3	1-3	1-3	1-3	1-3	1-3	1-3	1	1-3	1	1	
Additional cycles @ 800 PSIG to determine in-place CH <sub>4</sub>		4-5	4-5	4-7	4-6	4-5	4-5	4-6	2-4	4	2-4	2-4	

TABLE 5  
 CARBON DIOXIDE ADSORBED AS A FUNCTION OF METHANE RECOVERED  
 (SEE TABLE 3 FOR NO. 20)

Sample and run no.	12	13	14	15	16	18	19	21	22	23	24
SCF CO <sub>2</sub> adsorbed per SCF CH <sub>4</sub> produced for cycle 1	7.9	4.9	2.0	2.2	2.9	9.4	9.6	3.2	3.0	2.6	2.4
SCF CO <sub>2</sub> adsorbed per SCF CH <sub>4</sub> produced for natural + cycle 1	2.8	2.1	2.0	2.2	2.9	5.0	4.7	2.1	1.2	1.1	1.6
SCF CO <sub>2</sub> adsorbed per SCF CH <sub>4</sub> produced for all CO <sub>2</sub> cycles simulating enhanced recovery process & natural	5.5	4.4	4.2	1.4	5.7	9.3	6.2	2.1	3.0	1.1	1.6
SCF CO <sub>2</sub> adsorbed per SCF CH <sub>4</sub> produced to obtain ~100% CH <sub>4</sub> recovery (incl. natural)	9.7	8.7	8.6	3.7	7.1	11.8	8.3	7.4	4.4	5.1	5.6

(1 CO<sub>2</sub> cycle only)

(1 CO<sub>2</sub> cycle only)

(1 CO<sub>2</sub> cycle only)

(1 CO<sub>2</sub> cycle only)

TABLE 6  
PARTICLE-SIZE DISTRIBUTION OF CRUSHED COAL CORES

Sample & run no. 18	
Apparent Diameter (mm), less than:	Fraction of Total Weight
0.1	0.0372
0.335	0.0724
1	0.2518
4	0.4344
6	0.5036
12	0.6119
20	0.6597
30	0.7239
40	0.8835
70	1.0000

Sample & run no. 19	
Apparent diameter (mm), less than:	Fraction of total weight
0.1	0.0907
0.335	0.1714
0.565	0.4580
0.855	0.7209
10	0.7605
15	0.7937
20	0.8349
25	0.8929
45	1.0000

APPENDIX A

EXPERIMENTAL PROCEDURE AND SIMULATION SCHEMATICS

FIGURES (A - 1) to (A - 6)

Figure A-1

PREPARATION OF SAMPLE

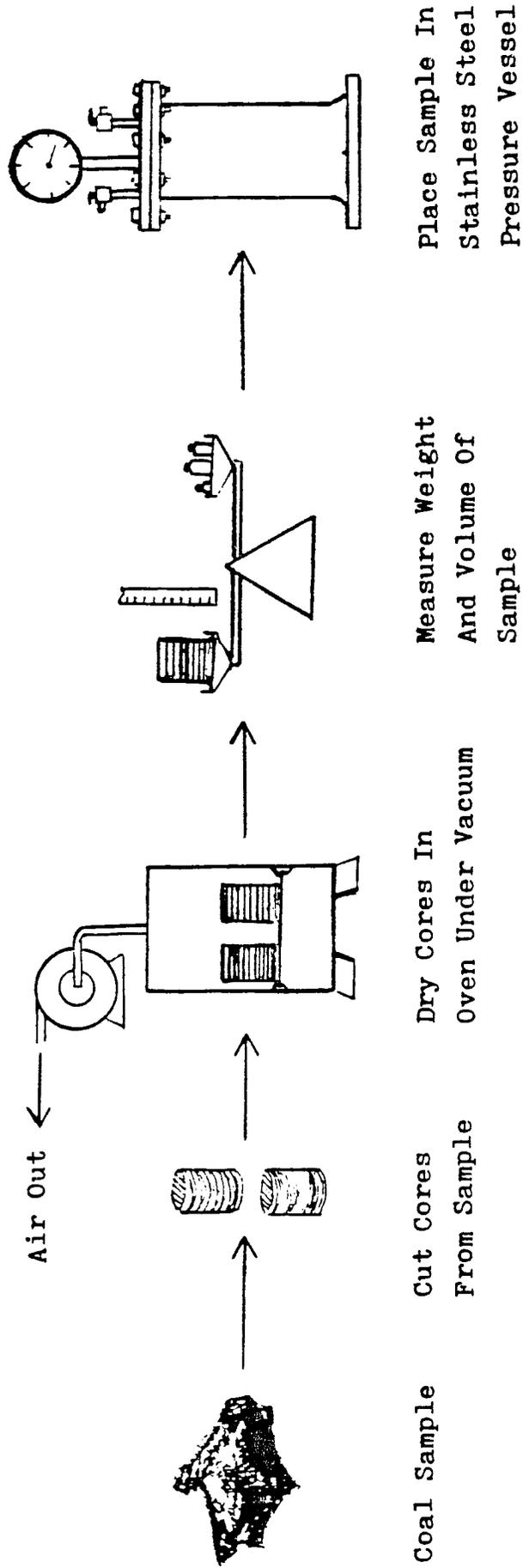
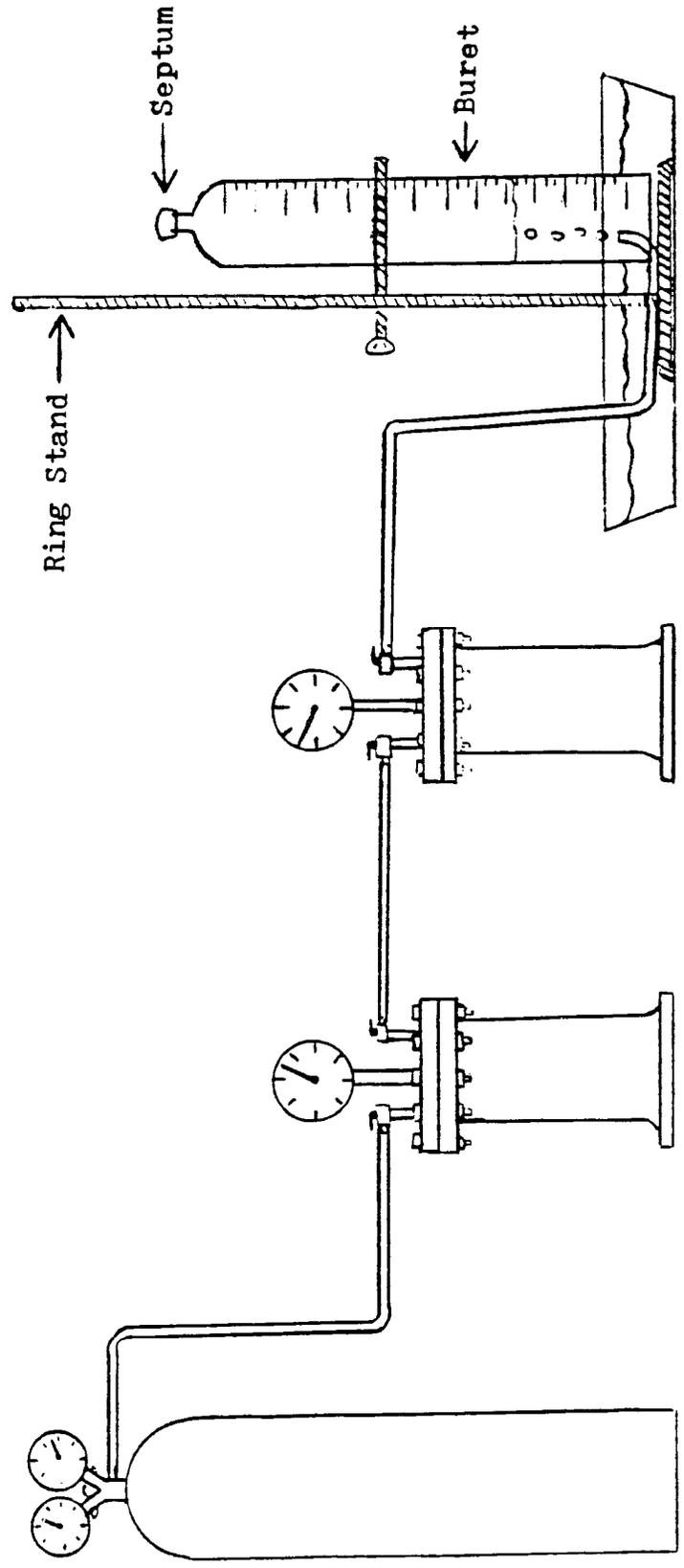


Figure A-2

GAS INJECTION AND COLLECTION SET-UP



Gas Tank CH <sub>4</sub> , CO <sub>2</sub> , Or N <sub>2</sub>	Gas Reservoir ( Known P, V, T )	Sample Placed In Stainless Steel Pressure Vessel	Gas Collection System
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Figure A-3

CH<sub>4</sub> AND WATER SATURATION OF SAMPLE

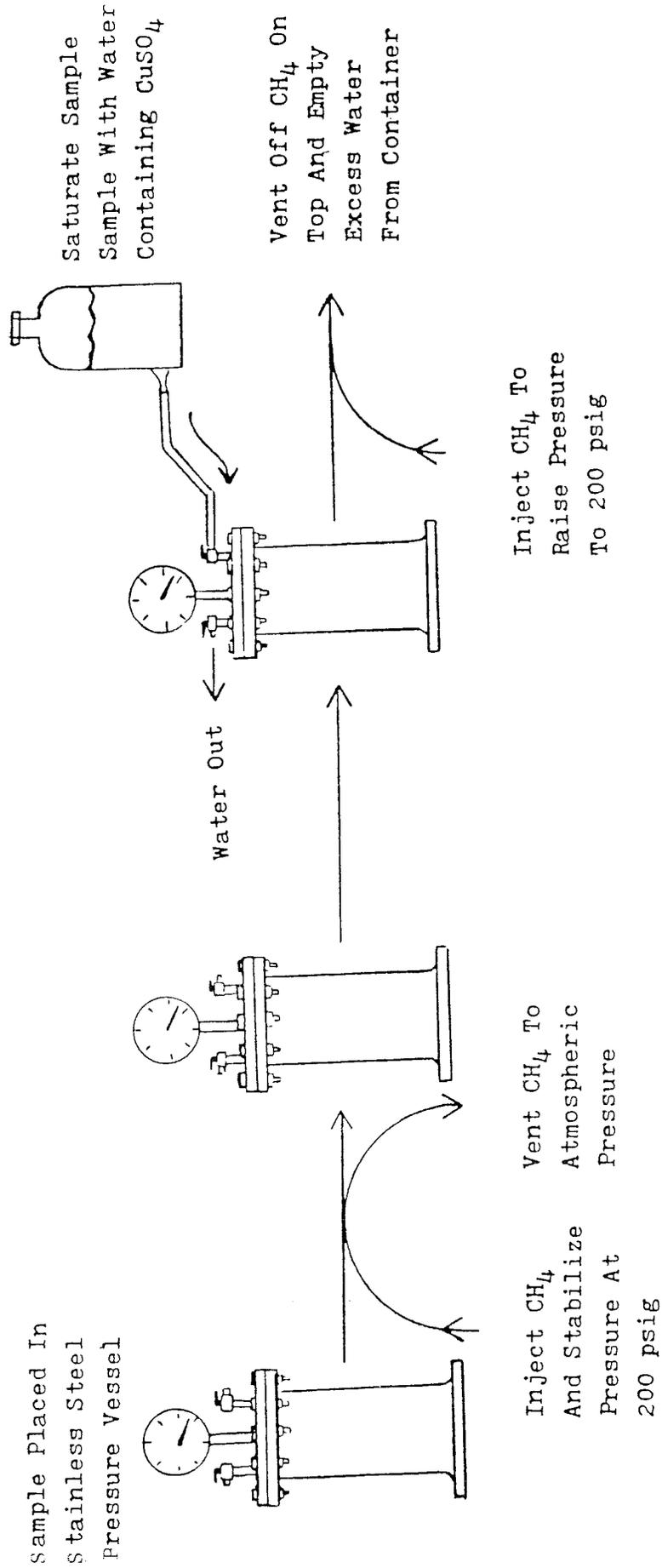


Figure A-4

NATURAL PRODUCTION

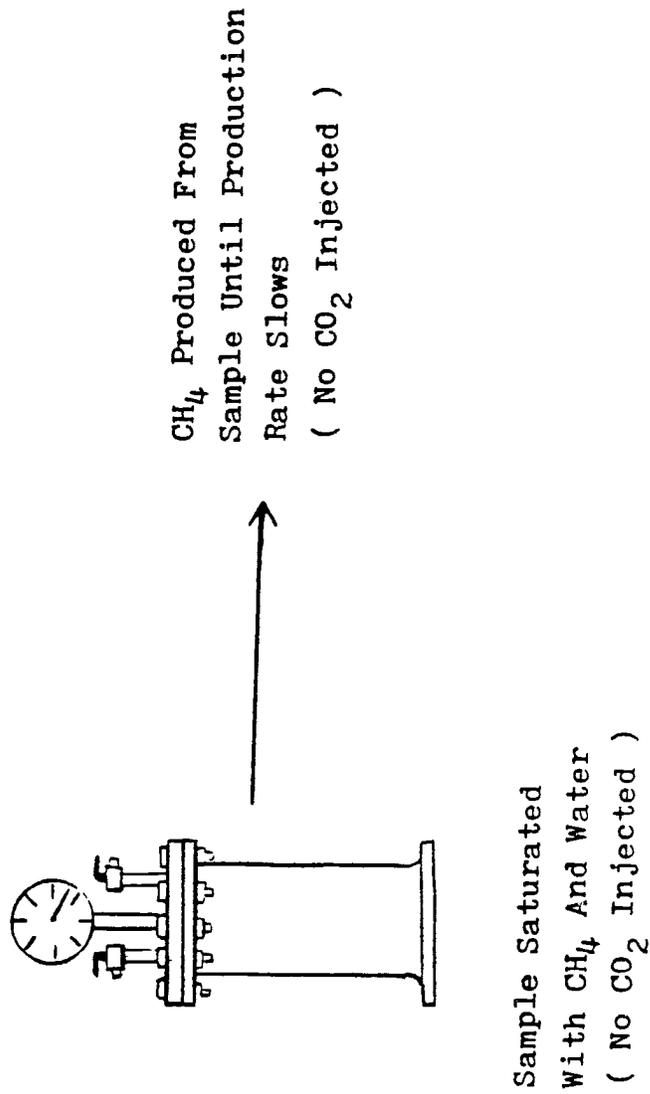
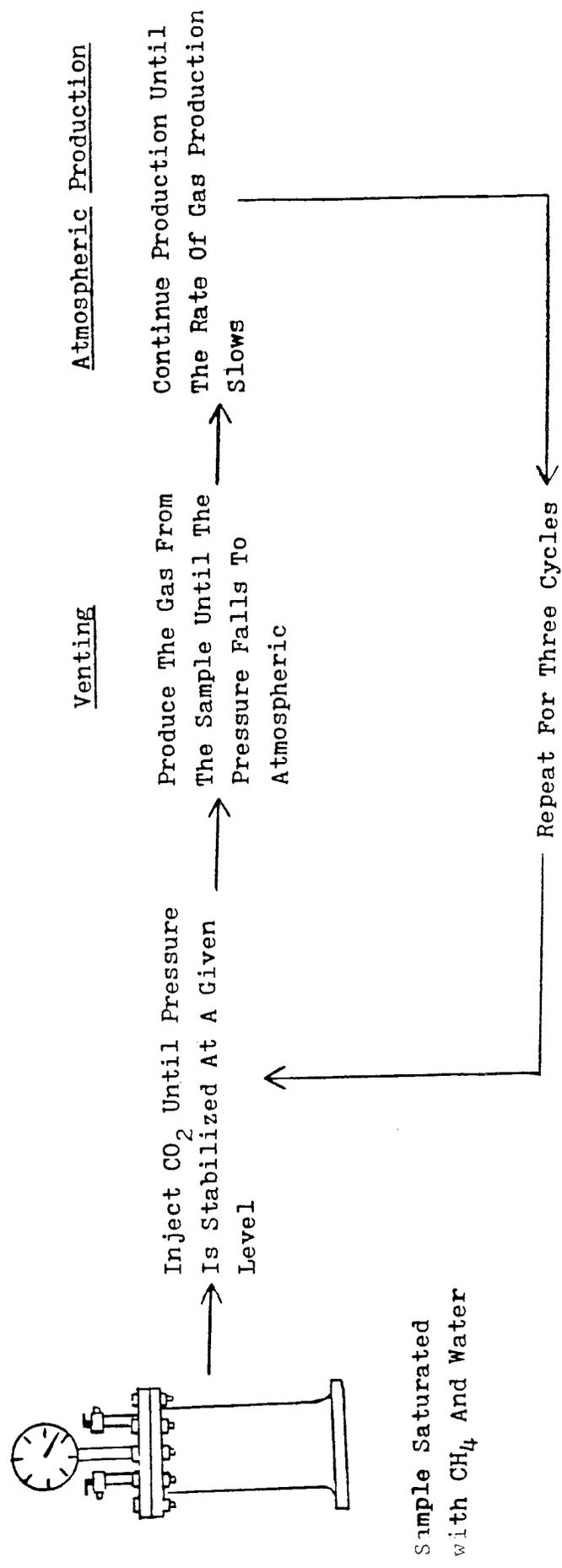


Figure A-5

ENHANCED PRODUCTION CYCLE



\* More Cycles Are Repeated At 800 psig To Estimate The Total Recoverable CH<sub>4</sub> Present In System

COAL SAMPLES CRUSHED

Figure A-6

