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UNDERGROUND COAL GASIFICATION USING OXYGEN AND STEAM *

D. R. Stephens, C. B. Thorsness and R. W. Hill

Abstract

Twenty-one field Underground Coal Gasification (UCG) tests have been carried out in the USA since 1973, along with related theoretical, laboratory and environmental programs. The product gas quality obtained from these field tests is comparable to that of surface gasification, using either air or steam and oxygen. Cost estimates are very favorable. The UCG process is found to be quite stable: experiments run continuously.

Key features of the successful U.S. program include: careful site selection, steam-oxygen gasification, extensive use of in-situ instrumentation, and theoretical modeling. Plans for commercial implementation of the technology are under development by four groups in the USA, all using steam/oxygen injection.

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Introduction

There are three basic reasons for the recent emergence of Underground Coal Gasification (UCG) as a leading synfuels candidate: (1) favorable projected economics, (2) ability to use coal seams that are unattractive for mining, and (3) modest environmental impact.

Figure 1 illustrates the UCG process and points out its important advantages. The process is similar to conventional coal gasification except that the coal is gasified in place underground, with steam and oxygen injected to support the reactions. The product is a medium-heating-value gas which can be converted into a wide variety of fuels in surface facilities. The fuels that can be produced include gasoline, methanol, oxo chemicals, pipeline quality gas, or medium-heating-value gas that can serve as an industrial heating fuel or for generating electricity.

In order for the UCG process to work, there must be a connecting channel within the coal seam between process wells to permit adequate gas flow. Such a channel normally does not exist in nature but must be prepared.

One method of preparing a channel is by reverse combustion. The coal is ignited at the bottom of the production well, while air is forced into the injection well, flowing to the production well through natural fractures in the coal. The burn front is drawn by conduction toward the source of oxygen, burning a narrow channel in the direction countercurrent to the flow of air--hence the name reverse combustion.

Another effective way to connect the injection and production wells is witn a horizontal hole drilled in the coal seam (Fig. 2). Such a hole can be drilled from the surface by the technique of directional drilling.

After the wells are connected, the coal at the bottom of the injection well is ignited (Fig. 2a). Air or a mixture of oxygen and steam is injected to support gasification, and the fire travels slowly through the coal bed toward the production well on a broad front, consuming the coal and producing valuable gaseous products. These products--primarily carbon dioxide, carbon monoxide, hydrogen, and methane--are continuously collected at the production well.

An alternative, new technique, shown in Fig. 2b, is called the controlled retraction injection point, or CRIP method.

As a UCG cavity initially develops, the product-gas heating value, chemistry, and thermal efficiency are all excellent. When the burn reaches the roof, heat losses begin, with a corresponding decline in gasification indicators and in economics. The amount of decline is acceptable at sites with strong dry roof material, but is less acceptable at sites with a wet weak overburden. The CRIP method was developed to minimize these heat losses.[1] The concept requires a drilled hole for linkage as shown in Fig. 2b. A liner, inserted through the casing of the injection well until its tip reaches a position near the intersection point with the production well, carries the injectant, either air or oxygen/steam. As the burn cavity grows larger, it eventually intersects the roof of the seam and roof collapse begins. At some point the heat lost to the roof material begins to significantly degrade the gas quality. When this happens the injection point is retracted in the upstream direction by burning off a section of the injection liner with the igniter. The coal opposite the burned zone ignites and a new cavity starts to grow. Since the high temperature zone is once again entirely within the coal, the heating value of the product gas will rise back to its original value. The

CRIP concept involves a repetition of this process over and over again, drawing the burn step by step, in a controlled manner, upstream from the original injection point.

It is important to locate the connecting channel between the wells near the bottom of the seam. Low rank coals such as subbituminous and lignite shrink and fall apart on heating, so the coal immediately above the gasification zone falls to the bottom, creating an underground packed bed of coal. Thus the burn consumes the bottom as well as the top of the coal bed, utilizing almost all the coal.

A combination of convective and dispersive effects in the thermally evolving system causes lateral movement of oxygen and/or thermal energy out to a considerable distance from the ignition point, which accounts for the experimentally observed wide gasification zone (60 to 100 ft wide in low rank coal with 100-ft spacing between injection and production wells). A commercial UCG operation would employ a large number (perhaps 100) of injection-production well pairs like the pairs in Fig. 1-2, operating simultaneously in a system. Each well pair would consume about 100 tons of coal per day, producing some 5 million standard cubic feet (scf) per day of medium-heating-value gas.

Uncontrolled burns can be prevented by utilizing only those coal seams which lie below the natural water table. Since stopping the injection allows water to invade the reaction zone and extinguish the fire. A certain amount of underground water is desirable for the steam-char reaction. However, most UCG sites contain more water than is wanted, and control of water influx is a problem.

Although Figs. 1-2 show gasification of a flat-lying coal beds, similar principles apply also to steeply dipping beds. Such beds are difficult to mine by conventional techniques but appear to be accessible by the UCG process.

Cost Estimates

Cost estimates (in 1982$) for some products made using UCG include:[2,3]

Medium Btu gas	$4.35/10^6 Btu
Pipeline quality gas	$6.25/10^6 Btu
Methanol	$0.50/gal
Gasoline	$1.35/gal

These costs are "plant gate prices" and do not include transportation, excise taxes, or retail profit. The projected costs of medium-heating-value and pipeline gas and of methanol compare favorably with costs of the same products from existing sources, while that of gasoline exceeds the present market.

Site Selection and Characterization

The suitability of a coal deposit for UCG depends upon a number of factors, including market potential, ownership, institutional factors, and environmental/socioeconomic aspects.[4] Only the coal type, depth, thickness, and geology/hydrology is considered here.

Low rank coals such as subbituminous and lignite are preferred over bituminous coal because they shrink upon heating, whereas bituminous swells, and are also usually thinner seams.

The Soviet, British, and early U.S. experiments in UCG encountered severe problems when attempting to gasify coal seams 2 m thick or less.[5] Heat losses are considerable with such thin seams, leading to low thermal efficiency and poor product-gas quality.

Minimum depths of 60 m for a seam 2 m thick and 90-120 m for a seam 6-9 m thick appear reasonable to avoid surface subsidence during gasification. The maximum depth is limited by economics.

A coal seam overlain by a strong, dry roof rock with some tendency to plastic failure seems desirable to minimize heat losses and escape of gas to the overburden. Moreover, the coal seam should not be a major aquifer, nor should major aquifers be found above the coal for at least twice the stable cavity height. One wishes to minimize excessive water influx into the gasifier, whether from the coal itself or from aquifers above it which may connect into the reaction zone due to collapse of the intervening strata after a gasification cavity has been formed.

Site selection and characterization involve making measurements of the above parameters. Holes are drilled and logged, cores of the coal and overburden are taken for physical and chemical measurement, and hydrology and permeability tests are carried out in the coal seam and overburden. Some surface techniques also appear to be useful in delineating the coal and certain structural features.[6]

U. S. Program Status

The U.S. government resumed its sponsoring of UCG field testing in 1973. Since that time 21 UCG tests have been carried out, 16 of which were funded by the federal government. Test results are summarized in Tables 1 and 2. Results from these tests are consistent. Site selection plays a major role. Sites with relatively dry, strong overburden and at least moderately thick coal produce favorable results. Examples include the Hanna, Rawlins and Centralia tests. Sites with thin coal or containing wet, weak overburden produce less favorable results, as at Hoe Creek or the Texas tests.

The encouraging technical successes of these tests and of related environmental, theoretical, and laboratory programs have led to increased interest in UCG in the private sector.

Basic Resources Inc., a subsidiary of Texas Utilities, purchased the rights of the extensive soviet UCG technology in 1975 and, after conducting a number of tests in Texas lignite,[7,8] is in the planning and permitting phases of an electrical generating demonstration plant (7 MWe capacity). Gulf Oil[9] concluded two second successful tests in a steeply dipping coal bed near Rawlins, Wyoming. Gulf is presently considering plans for commercialization.

The Lawrence Livermore National Laboratory, in cooperation with two U.S. utilities, the Wasnington Water Power Co. and Pacific Power & Light, have completed two field tests near Centralia, Washington using the CRIP method.[10,11]

World Energy, Inc. has developed plans for a 25 MWe generating facility near Rawlins, Wyoming. Application has been made to the U.S. Synthetic Fuels Corporation.

Recent Field Results

Two steam-oxygen tests will be briefly described as recent examples of underground coal gasification technology in the USA.

A. Rawlins Test 2

The Rawlins tests were conducted by Gulf R&D Co. in a 22 ft. thick steeply dipping (63°) subbituminous coal bed near Rawlins, Wyoming. Rawlins was selected after careful screening of all available sites and then characterized in detail. Rawlins 1 was executed in 1979 and Rawlins 2, a much larger steam-oxygen test was successfully carried out in 1981.[9]

An isometric view of the test is shown in Fig. 3. Two injection wells were used, a vertical and a slant well. The production well was slanted along the dip of the coal.

The coal seam was ignited on August 23, 1981, and the slant injection and slant production wells linked by September 4. Steam-oxygen gasification began on September 6, with excellent results as shown in Fig. 4 and 5, and summarized in Table 3.[12,12a] Best results were obtained with the slant injection and production well mode, which ran until October 17. The slant production well was linked to the vertical injection well at that time and the vertical injection well was used during October 17-31. Both the vertical and the slant production wells then were used until the completion of the test on November 11, 1981.

Over 8500 tons of coal were gasified. The progress of the burn front was detected using thermocouple and high frequency electromagnetic diagnostics[13] (not shown in Fig. 3).

Major accomplishments for the Rawlins #2 test include:

(1) Very high product gas quality, primarily due to high methane and other hydrocarbons in the product.

(2) Confirmation of the suitability of the Rawlins site.

(3) Demonstrations of excellent results from a steeply dipping coal bed.

(4) Long-term operation with steam and oxygen.

B. CRIP Test

The Partial Seam CRIP test was carried out by the Lawrence Livermore National Laboratory in a 19 ft. thick subbituminous coal seam near Centralia, Washington.[11] An isometric view of the test is provided in Fig. 6. The injection well was drilled from an exposed coal face near the bottom of the seam. Two production wells were employed, a vertical well near the end of the injection well and an included production well, which slanted through the overburden down into the coal. The slant production well crossed near the injection well but did not connect to it, while the vertical well was mechanically connected to the injection well prior to the burn. Several instrumentation wells were emplaced.

The coal seam was ignited on October 16, 1983. Good product gas was obtained with steam-oxygen injection. Air was injected for brief periods when power outages occurred or when the steam boiler needed repairs.

The vertical production well was used until October 28, when we switched to the slant production well. We observed an improvement in product gas quality upon changing to the slant well, and the entire changeover went smoothly. On October 30 the controlled retraction maneuver was executed and a new cavity was successfully established.

We continued steam/oxygen gasification using the new cavity and the slant production well until November 14, 1983, when the experiment was shut down. Figure 7 shows the product gas heating value for the burn period, and Figure 8 shows some of the product gas chemistry. Interaction of the burn with the roof can be seen during days 6-12 (October 22-28) for the first cavity and during days 22-29 (November 7-14) for the second. The slant production well was used beginning on day 12 (October 28), and an increase in product gas quality can be seen. The CRIP maneuver was executed on day 14.

Approximately 500 tons of coal were gasified with the first cavity and 1000 tons during the second, for a total of 1500 tons. Good thermal responses were obtained in several instrumentation wells; well I-6 was near the initial injection point and responded first, followed by I-4. After the CRIP maneuver, well I-7 responded, followed by I-11 and I-8.

Figs. 9 and 10 show typical responses. The first thermal response at well I-6 was at the top of the coal seam for this location, while the burn near I-11 progressed from the drilled hole to the top.

Major results for the steam-oxygen injection periods are given in Table 4.

Our major conclusions from this underground coal gasification test are:

(1) The Centralia site is favorable for underground coal gasification (UCG).

(2) The small-scale Large Block tests, which we conducted two years ago at the same site, produced similar results as the much larger scale partial seam test. Therefore, we have shown that the small scale large block experiments have predictive capability for UCG.

(3) Use of a slant production well is advantageous for UCG.

(4) The controlled retraction injection point method (CRIP) was successfully tested, with an improvement in UCG performance.

Key Features of the United States Program

The keys to the success of the U.S. program include: careful site selection, of steam-oxygen gasification, extensive use of instrumentation, and modeling.

Since UCG is so site-specific, the economics of a project are extremely dependent upon the characteristics of the location. Site selection and characterization are employed to discriminate between potential project locations and to ensure that project economics will be favorable.

Steam-oxygen gasification has been employed in seven of the U.S.A. field tests, mostly since 1979. This technique allows conversion of the product gas into more valuable, more readily transported product. Thus a location remote from industrial markets can be utilized.

Fig. 11 and 12 compare product gas quality for Rawlins II and the CRIP test with that from two leading surface coal gasification processes, the Lurgi[14] and Texaco[15] processes. As can be seen, the product gas heating values are similar. The highest and the lowest values in Fig. 11 are both for UCG tests. The chemistry is not as similar but the values are comparable, as seen in Fig. 12. The highest methane content was for Rawlins II, while Texaco was very low. On the other hand, the Texaco process produced the greatest amount of CO and H_2, while the Rawlins test produced the least. The CRIP and Lurgi cases were intermediate.

Gash and Hunt[16] compared the average produced gas composition from UCG to that of the Lurgi-derived gas for Sasol, with the results shown in Table 5. Results from the Soviet UCG testing at Angren are also given. As can be seen, the results are similar, except for the lower methane and higher CO_2 for Angren.

The U.S. UCG program has benefited from the extensive use of in-situ instrumentation.[17] Successful diagnostics include use of thermocouples, downhole high-frequency electromagnetic measurements, borehole extensometers, material balances, and postburn coring or excavation. Material balances are not generally considered a diagnostic, but when used with a sweep model or prior knowledge of sweep geometry they provide surprisingly accurate resolution of the burn front.

Process modeling, either numerically or experimentally, serves at least two useful purposes: it provides a framework from which critical questions can be posed, and it can provide interim answers to a number of important questions, including product composition, temperatures, pressures, coal consumption and geometry, and roof collapse. These calculations have value only if they can be compared to actual field results. Thus, modeling and field diagnostics are interdependent; each has little value without the other.

The LLNL conducted a series of small-scale tests in 1981-1982 to obtain detailed field data to increase our understanding of UCG.

The excavation and mapping of these five burns[18] yielded a fairly clear picture of the early-time cavity geometry. A new multidimensional model has been reported which utilizes this new information and attempts to incorporate the major controlling phenomena, including motion of solids, into a complete process mode.[19] A preliminary version of the model was able to match details of the field test results, as shown in Table 6 and Fig. 13. The model is presently being modified to incorporate more details of the process chemistry and to treat burn zone interaction with the roof in more detail.

Conclusions

1. The technical feasibility of steam-oxygen underground coal gasification has been established by 21 U.S. field tests.
2. Cost estimates for UCG-derived products are very favorable.
3. Either flat or steep dipping bends can be gasified.
4. Product gas quality is comparable to that of surface gasification.
5. Keys to successful program include:
   - Careful site selection
   - Steam/oxygen gasification
   - In-situ instrumentation
   - Modeling
6. Commercial development is underway in the USA.

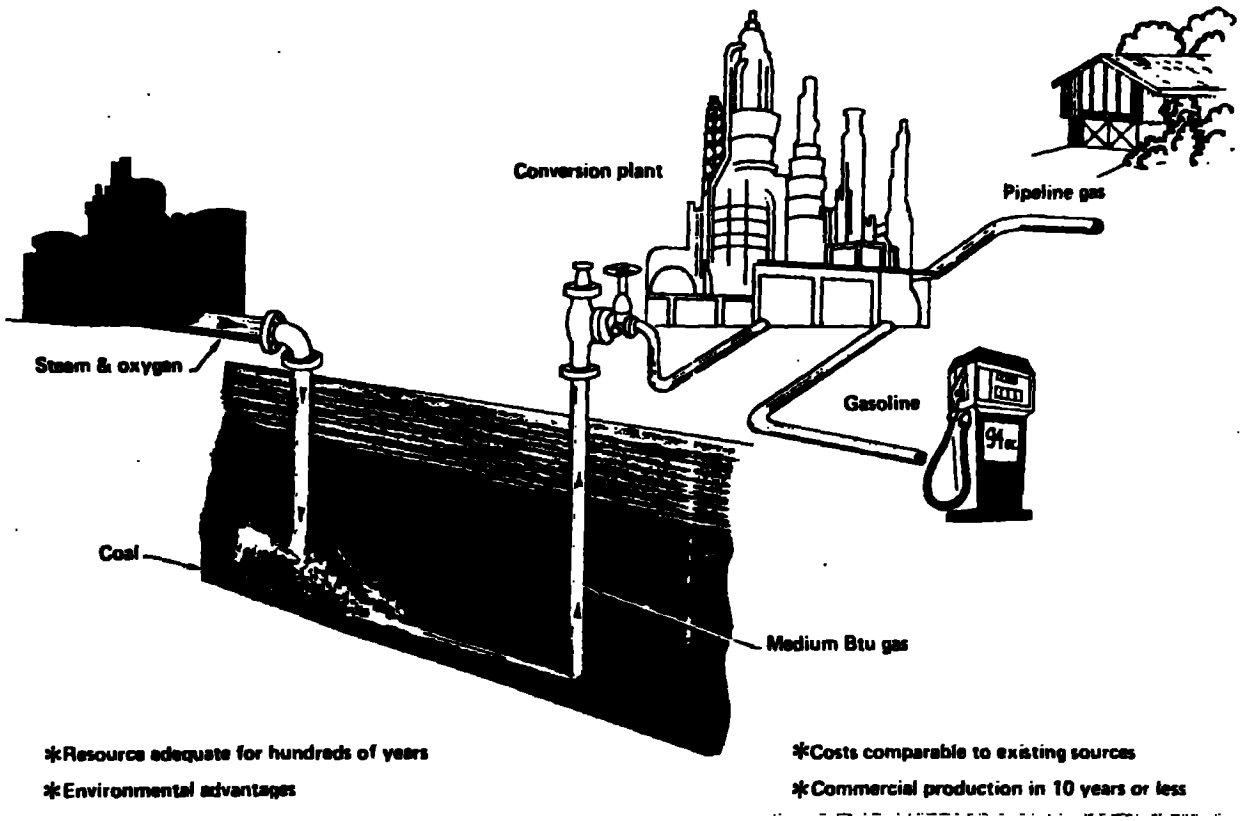
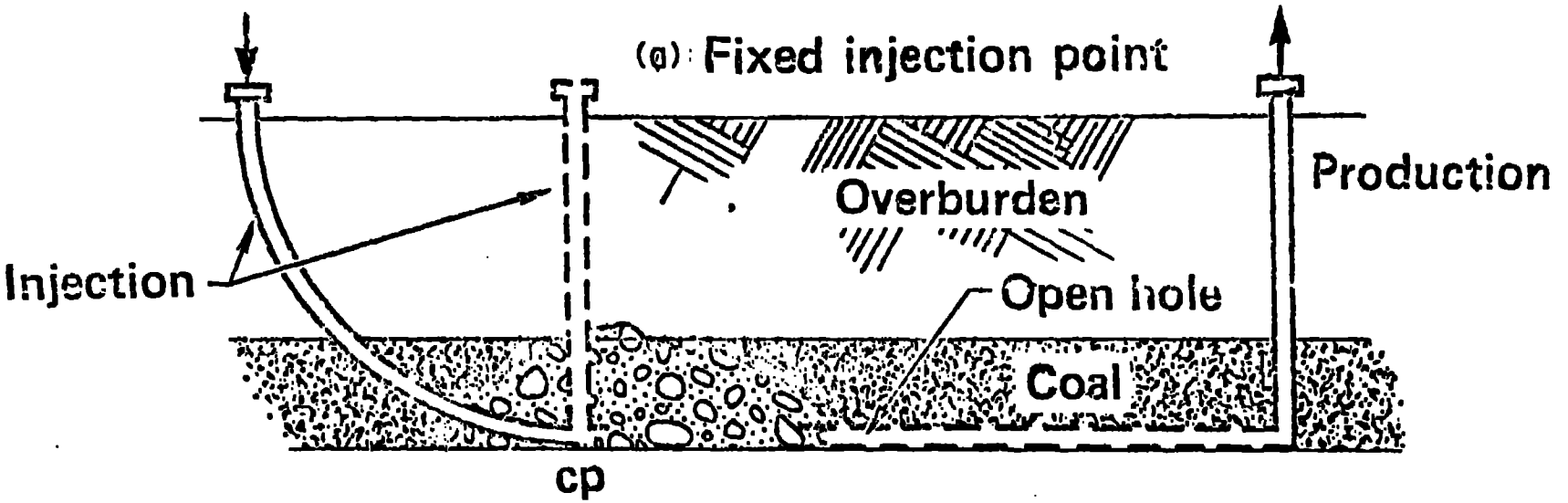


FIG 1. Underground Coal Gasification is a promising new source for clean energy.

FIG 2.

UCG using directional drilling



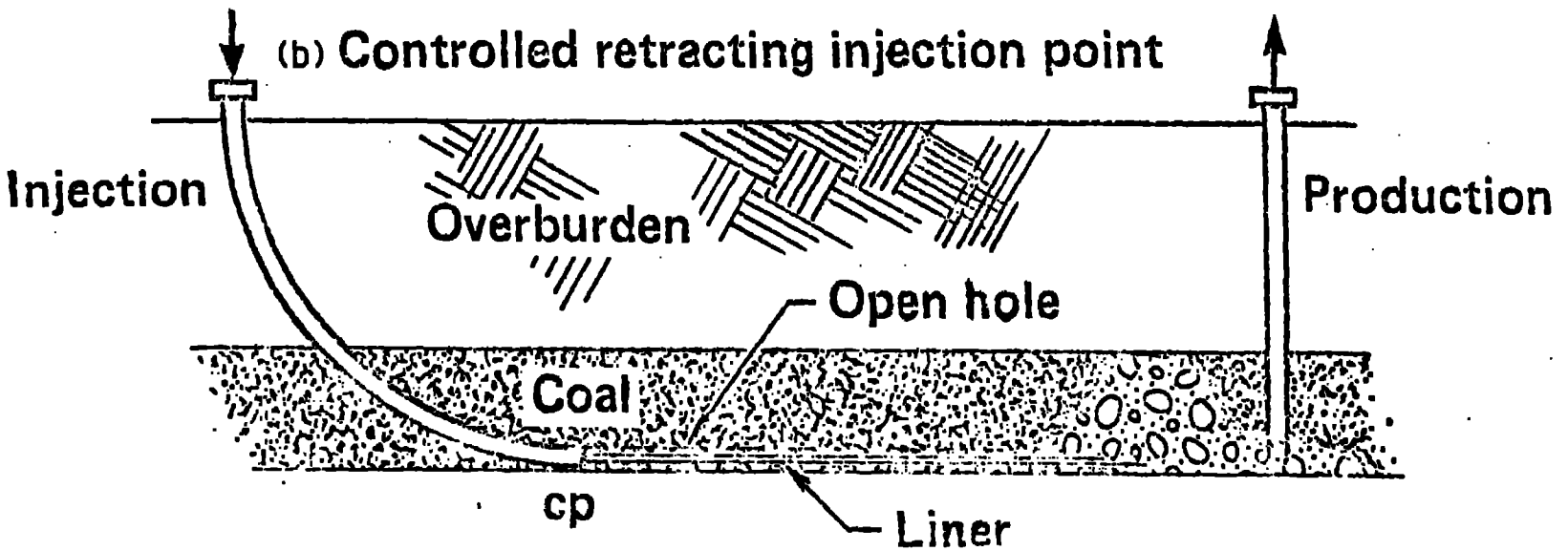


FIG. 3.

Isometric well configuration: Rawlins-2

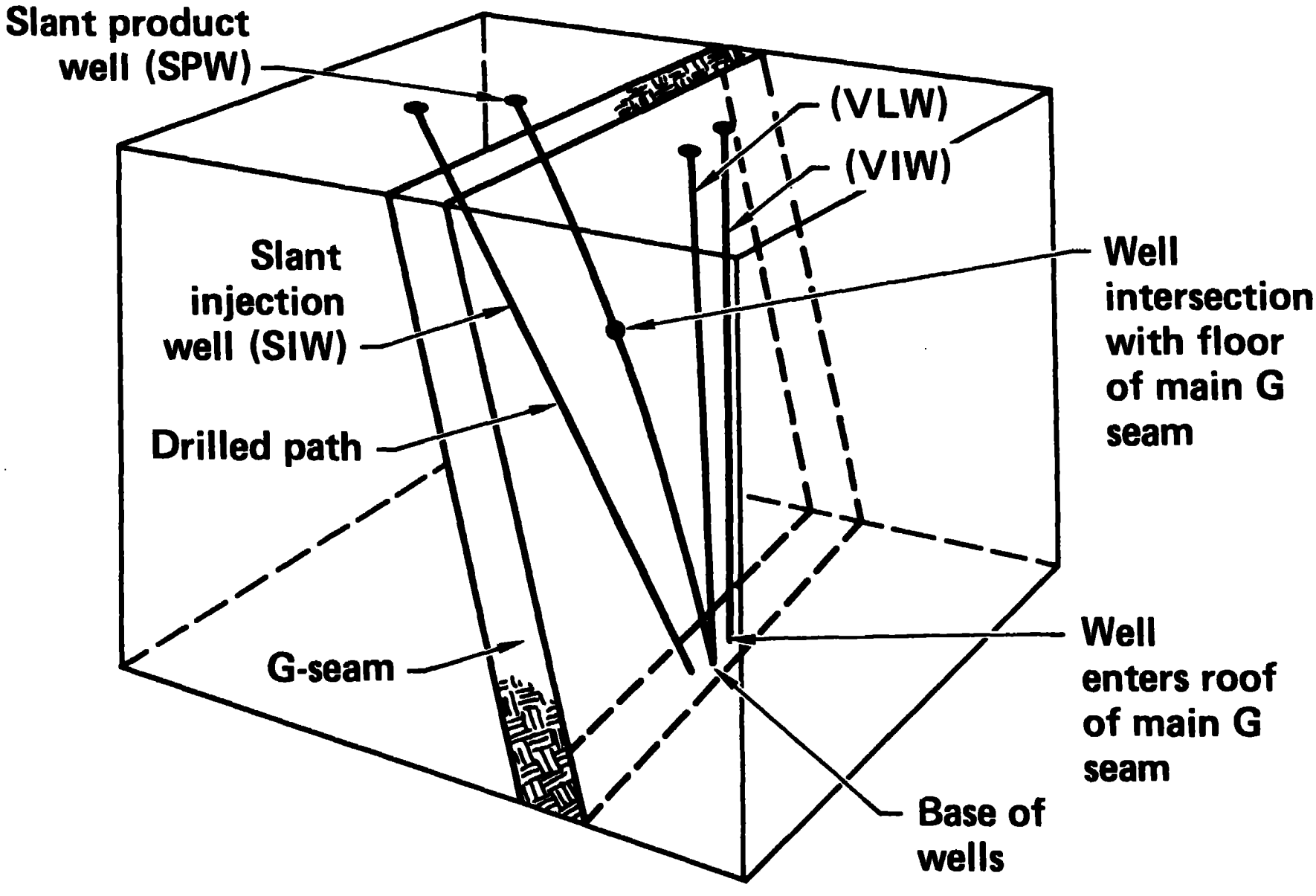


FIG. 4

PRODUCT GAS HEAT OF COMBUSTION

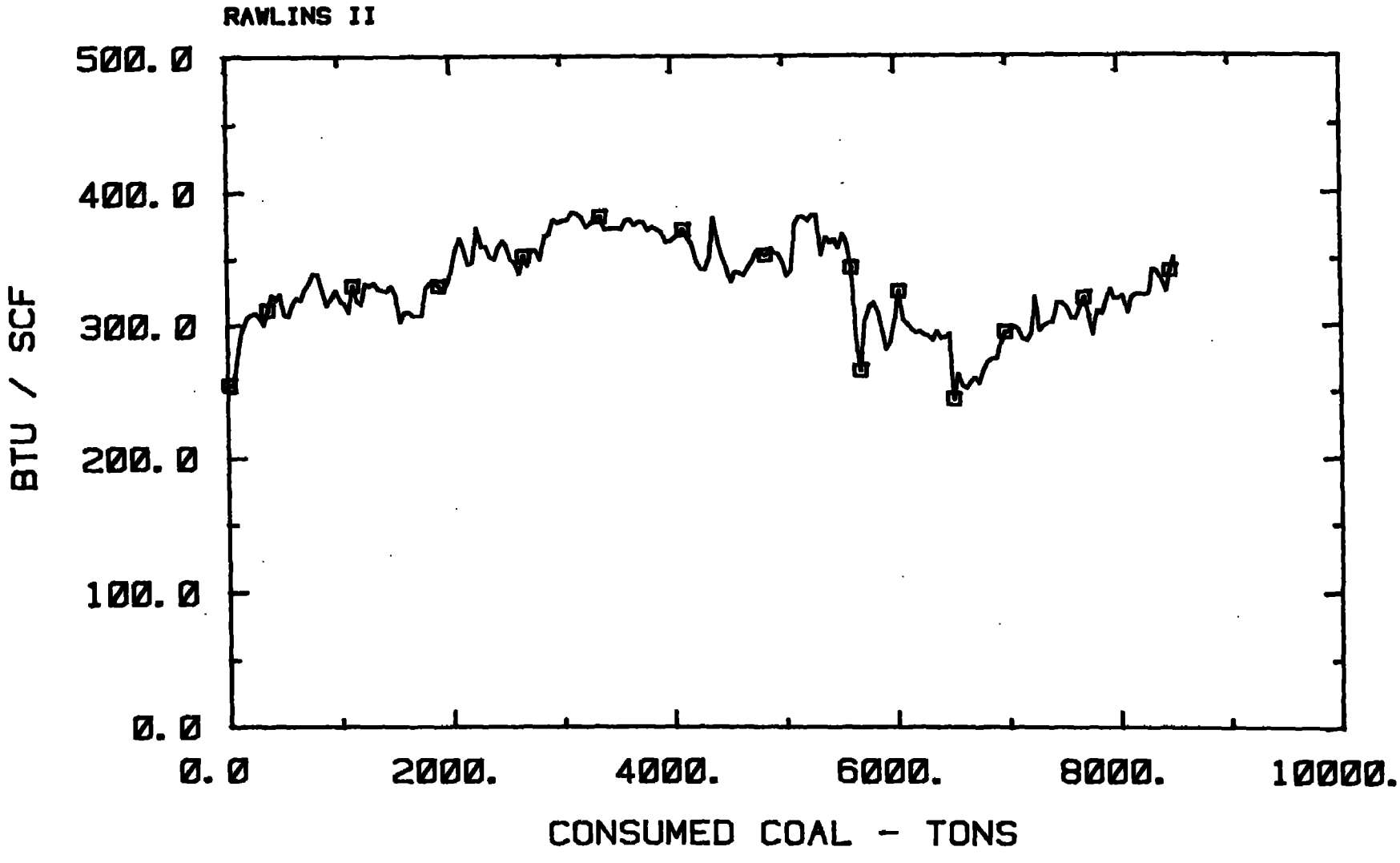


FIG. 5

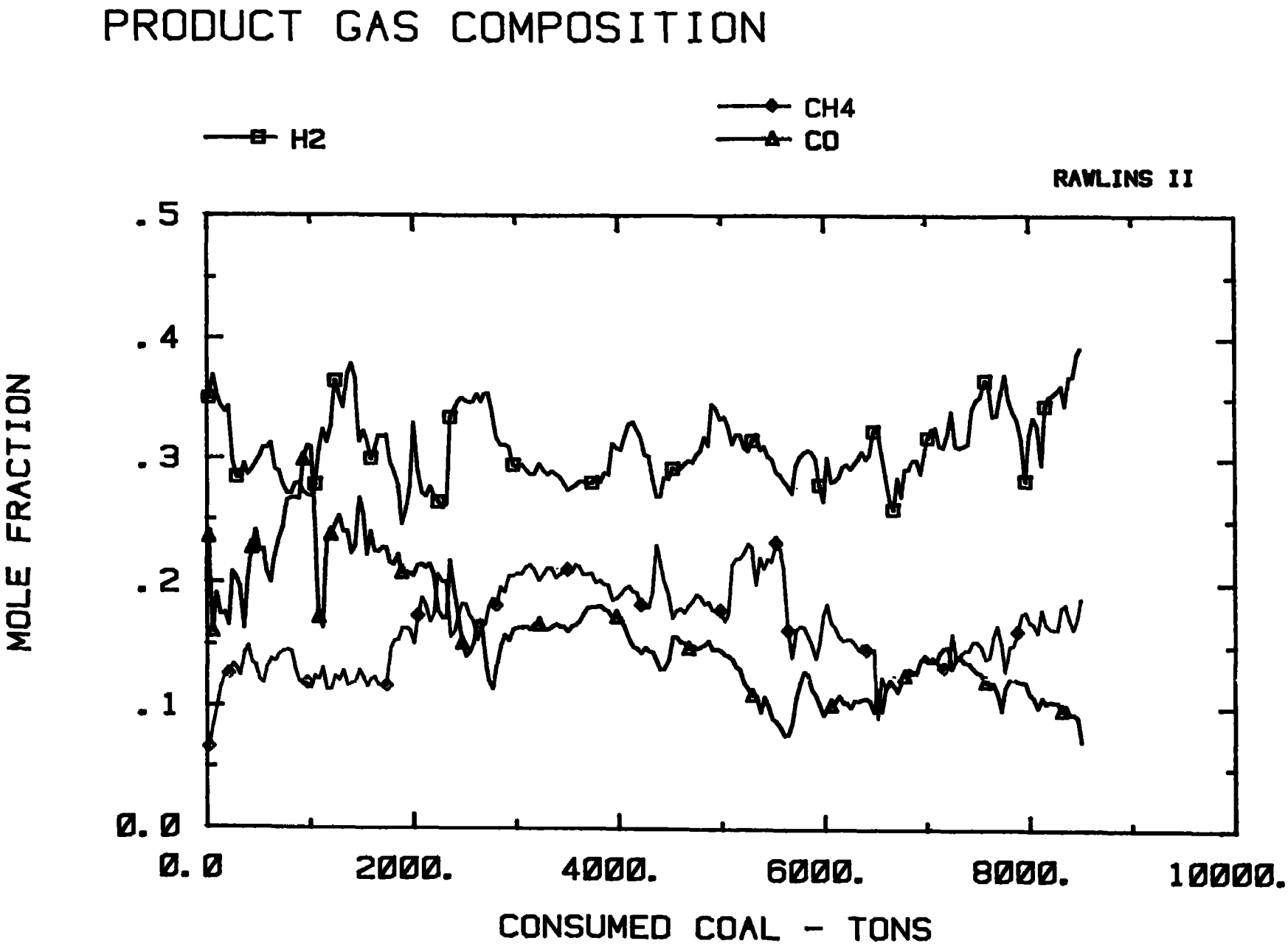

PRODUCT GAS COMPOSITION
H2
CH4
CO
RAWLINS II
MOLE FRACTION
.5
.4
.3
.2
.1
0.0
0.0
2000.
4000.
6000.
8000.
10000.
CONSUMED COAL - TONS

FIG. 6

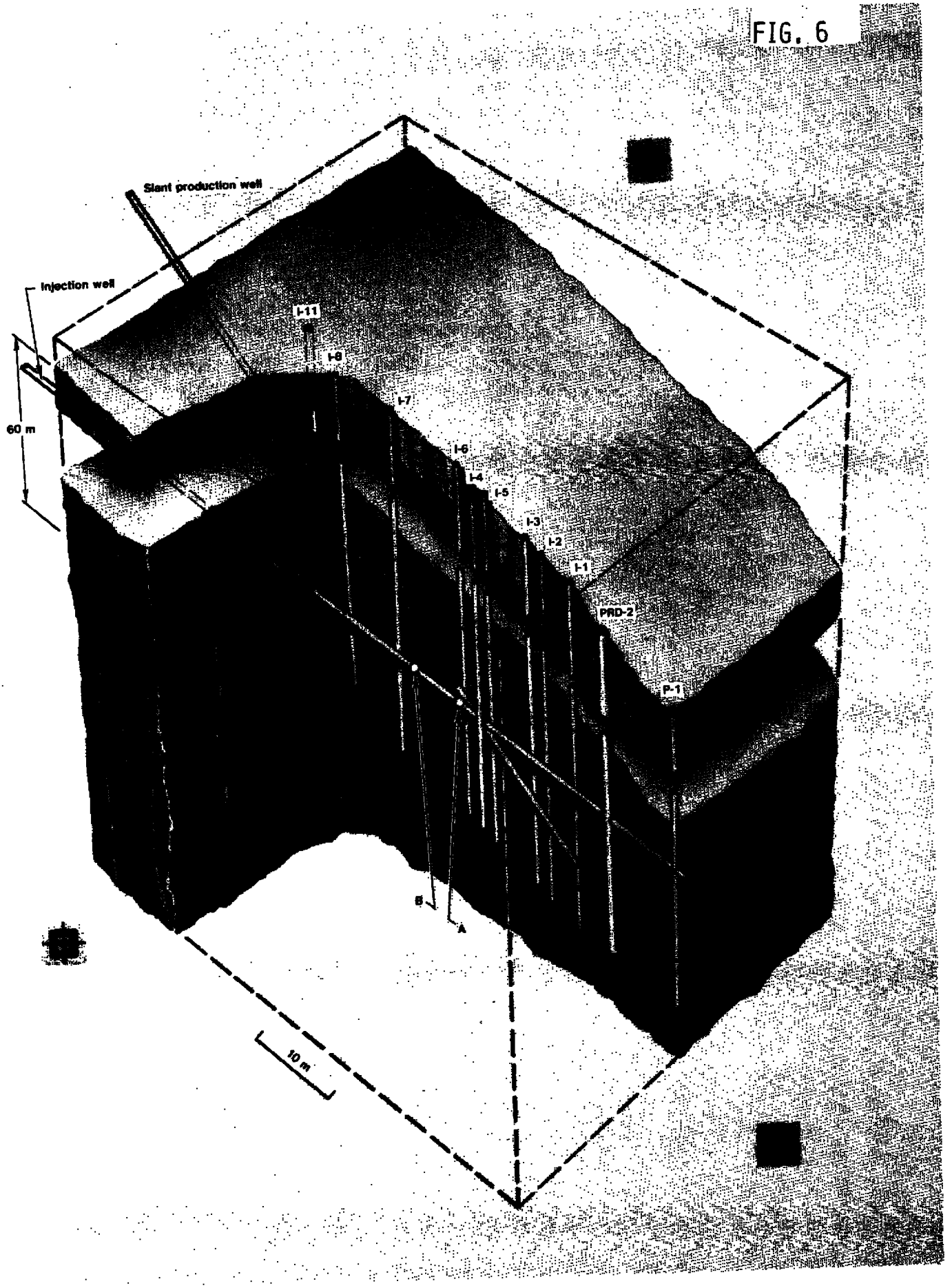

Slant production well
Injection well
60 m
I-11
I-8
I-7
I-6
I-4
I-5
I-3
I-2
I-1
PRD-2
P-1
B
A
10 m

FIG. 7

PRODUCT GAS HEAT OF COMBUSTION

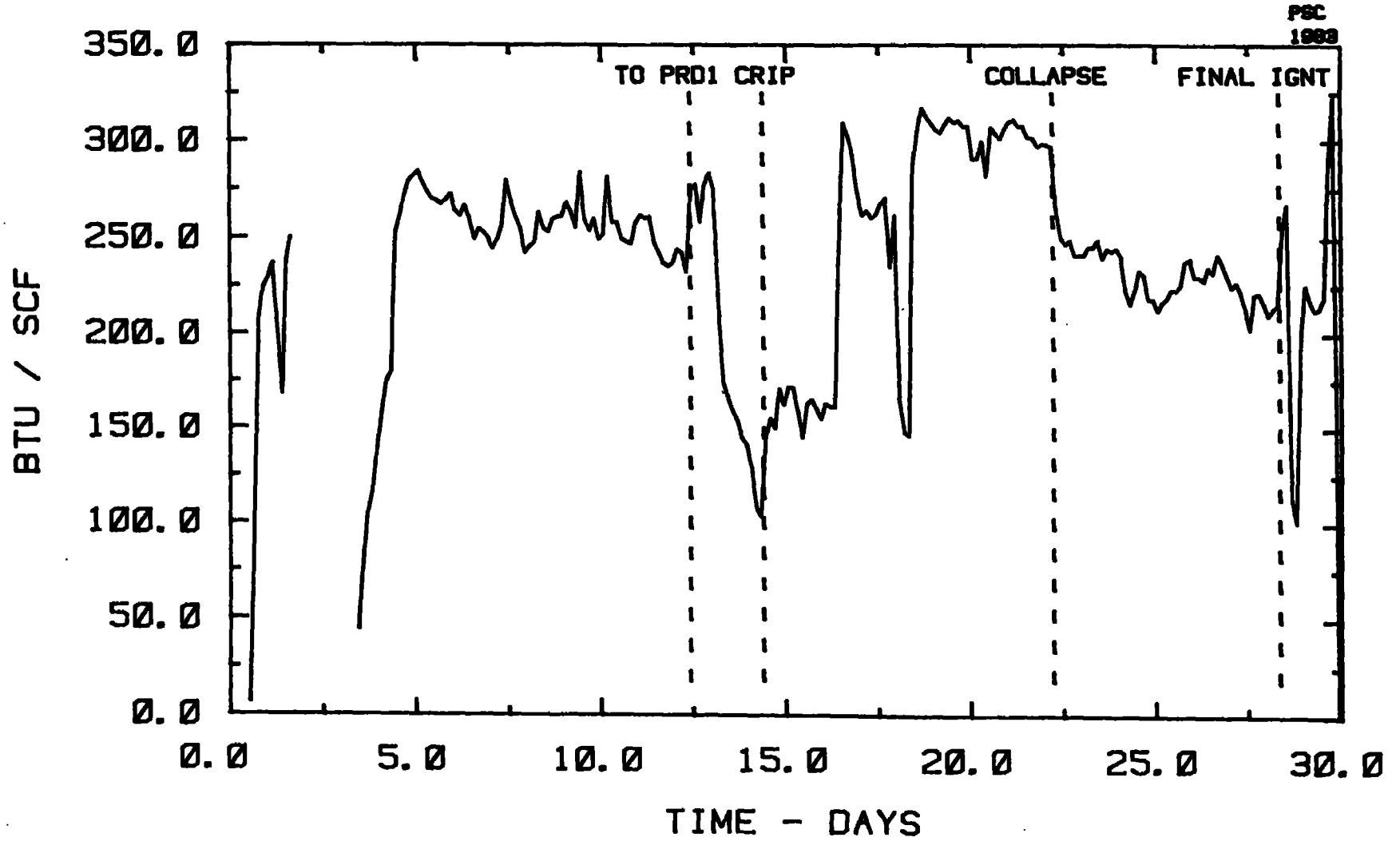


FIG. 8

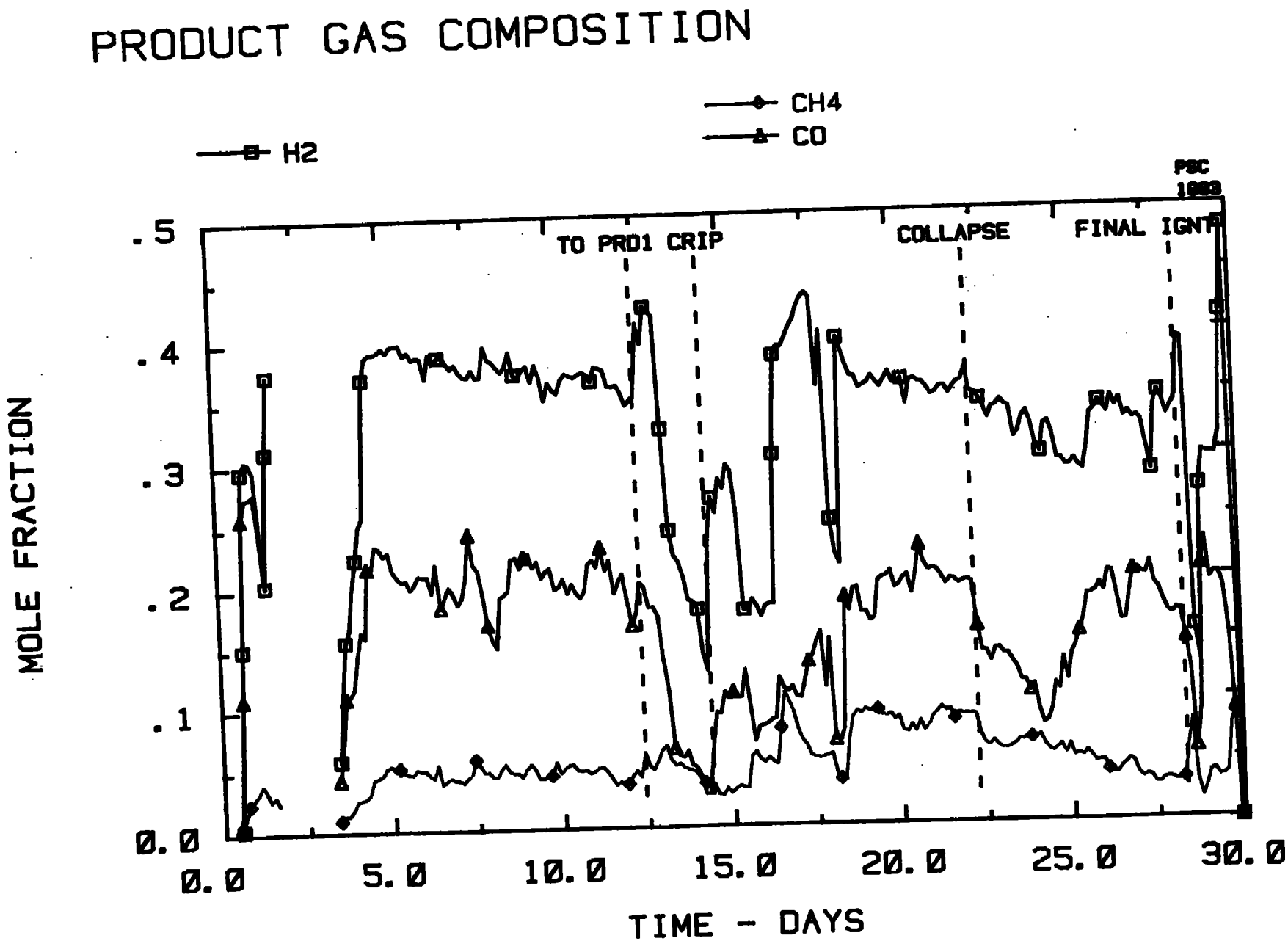

PRODUCT GAS COMPOSITION
CH4
CO
H2
TO PRD1 CRIP
COLLAPSE
FINAL IGNT
MOLE FRACTION
.5
.4
.3
.2
.1
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
TIME - DAYS

Figure Captions

Fig. 6 Layout of instrumentation, production, and injection wells for our partial-seam CRIP test at the WIDCO mine near Centralia, Washington. The burn was started at the point marked A and the gases were drawn off through vertical production well P-2. After a few days we switched over to the slant production well. When the quality of the production gases began top decline because of roof collapse, we pulled back the injection to point B and started a new burn, restoring gas quality.

Fig. 7 Product gas quality (heat of combustion) as a function of time for the entire test, including power outages and shut-downs for mechanical maintenance (plugged production line).

Fig. 8 Variation in the proportions of the three principal combustible components in the product gas. Gas composition is strongly dependent on reaction temperature. Heating value is strongly influenced by the amount of hydrocarbons (e.g., methane) present.

FIG. 9

TEMPERATURE CROSS-SECTIONS FOR WELL I6, CRIP TEST

(TIME IN DAYS)

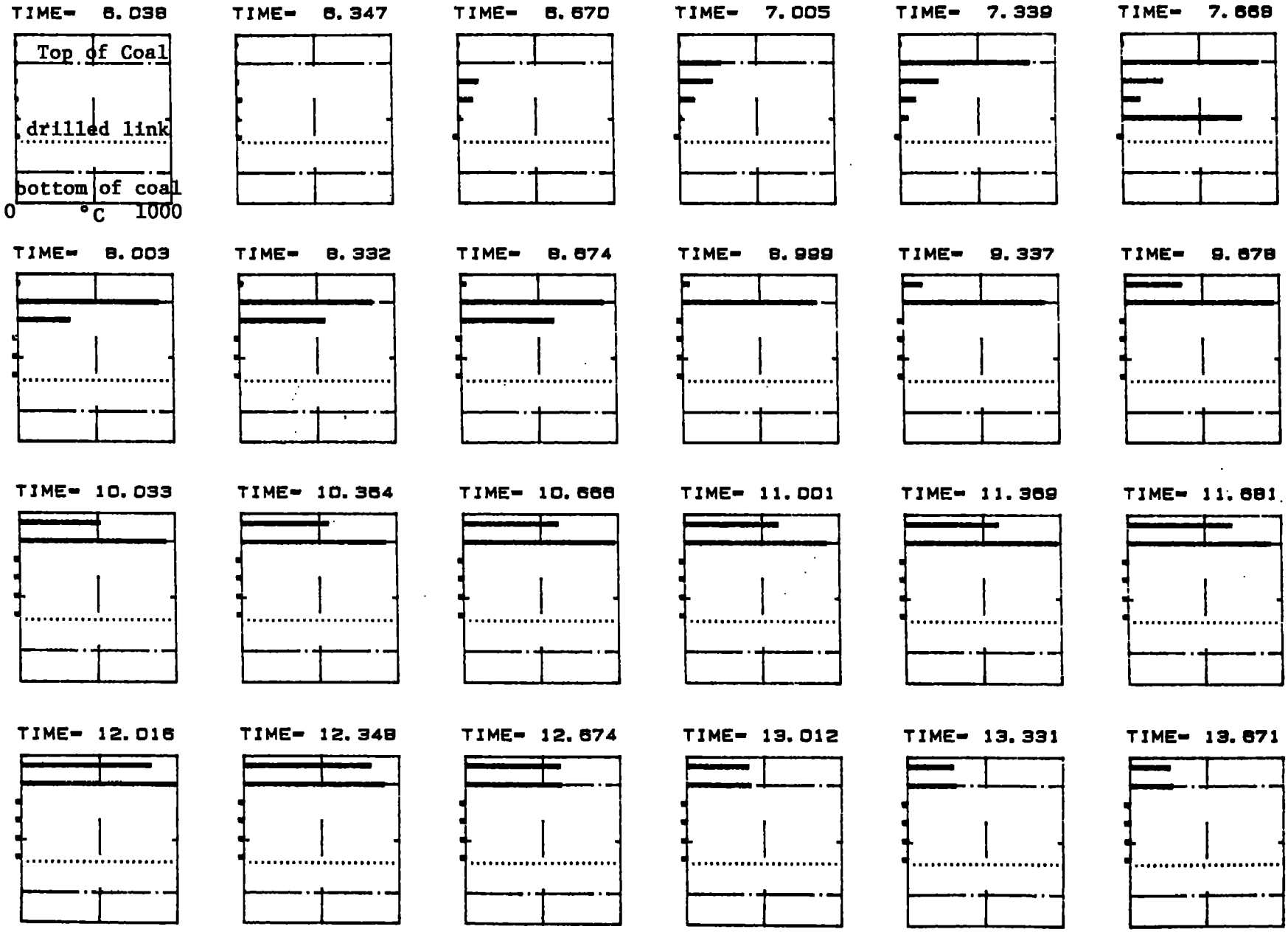
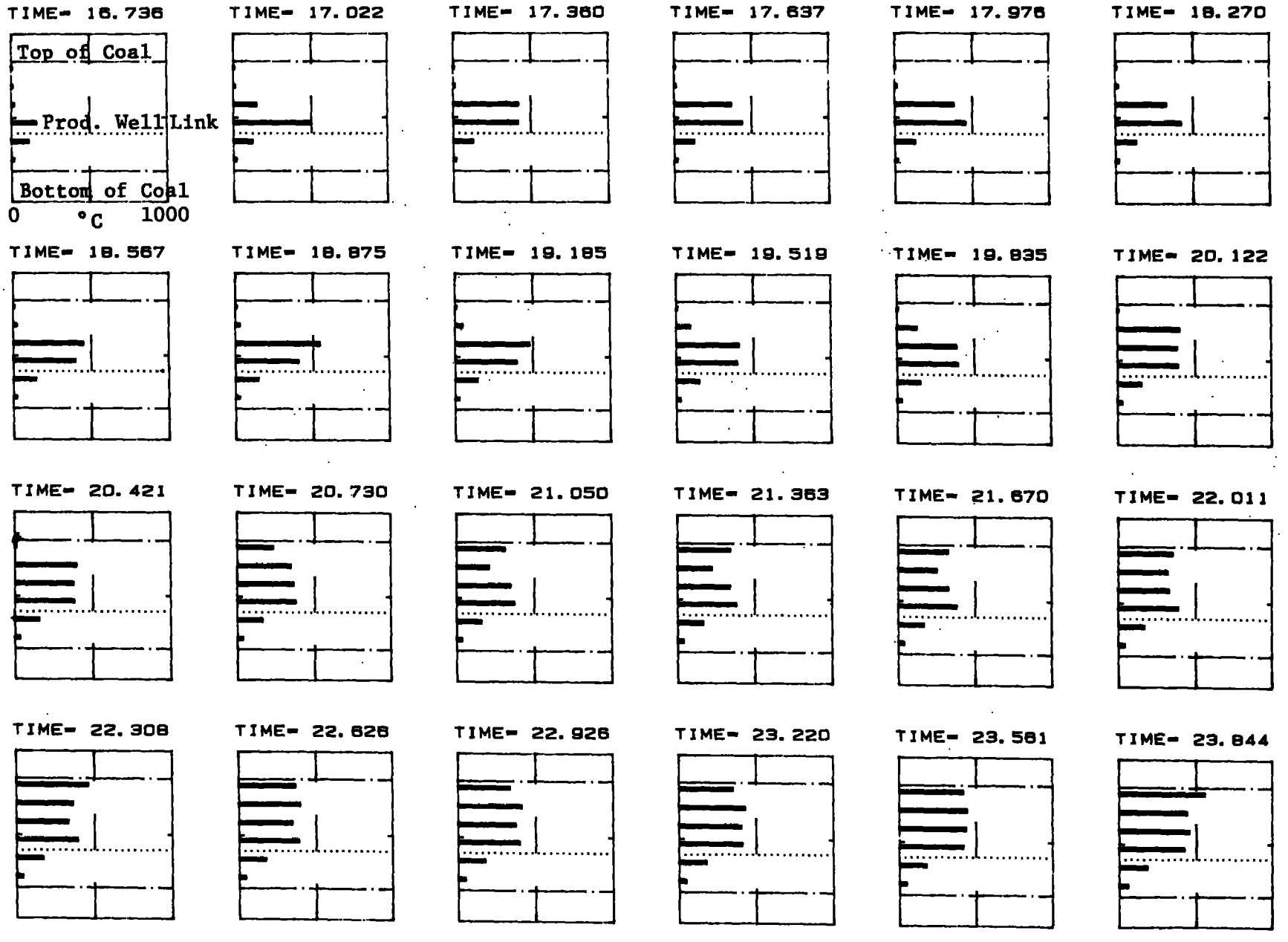


FIG. 10

TEMPERATURE CROSS-SECTIONS FOR WELL I 1 1, CRIP TEST
(TIME IN DAYS)



Underground coal gasification heating value compared to surface gasification

FIG. 11

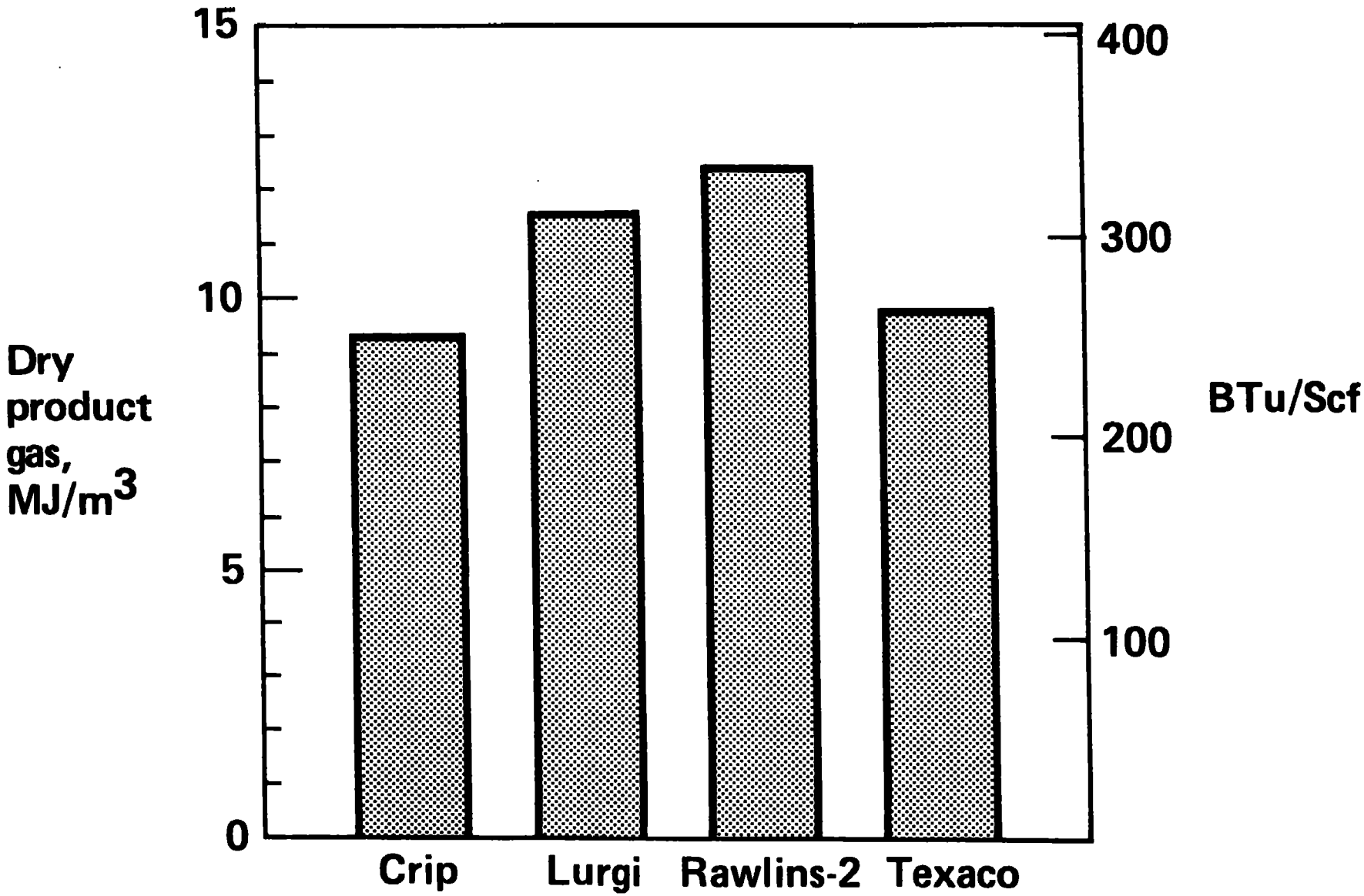


FIG. 12

Underground coal gasification product gas chemistry compared to surface gasification

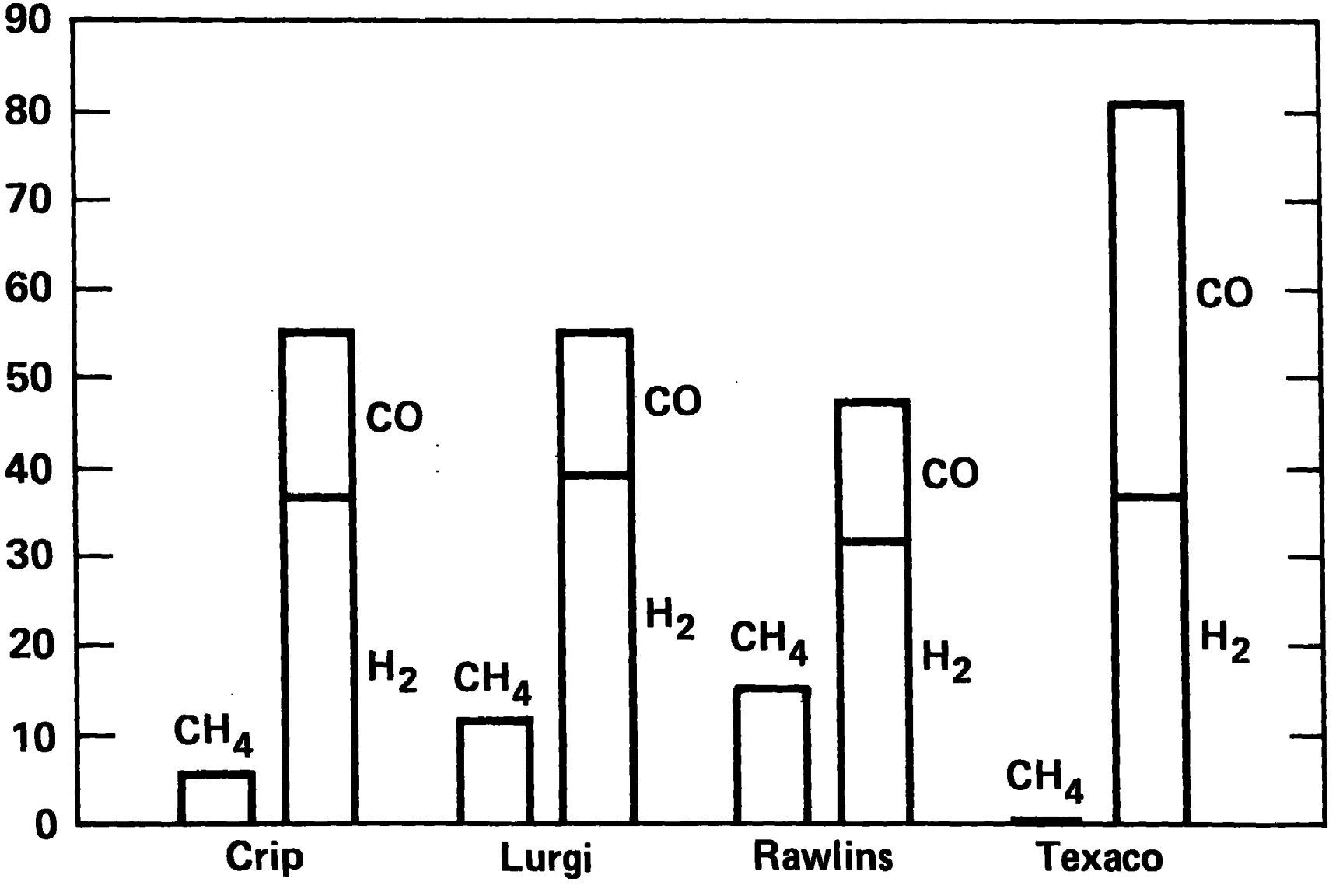


FIG. 13

COMPARISON OF LBK-1 CAVITY WITH MODEL
ELEVATION VIEW

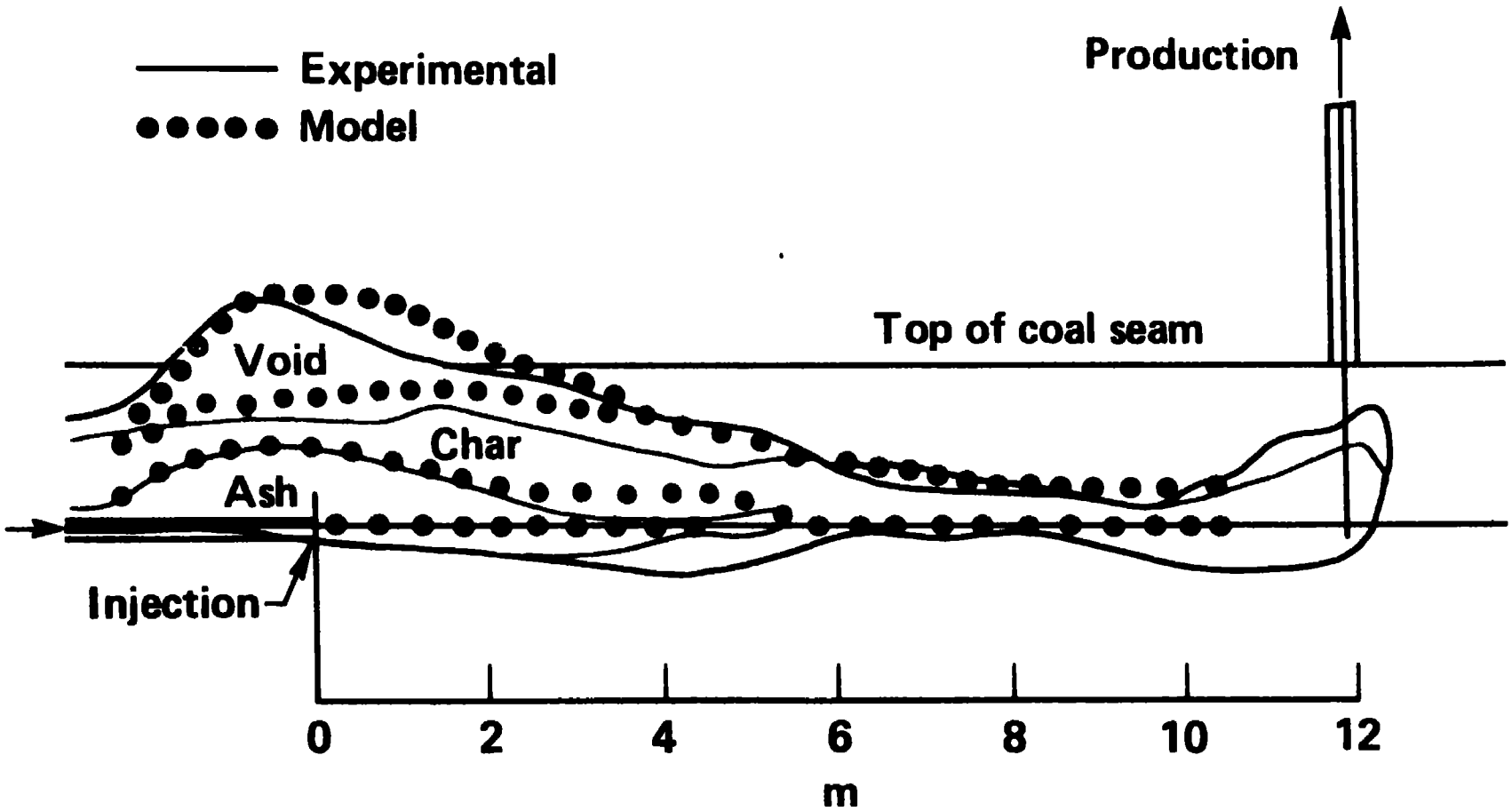


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Table 1. Summary of U.S. DOE-sponsored UCG field tests (forward gasification phase).

Test	Year	Duration (days)	Coal consumed (tons)	Gas quality (Btu/scf)	(MJ/m^3)	Cold Gas efficiency (%)
Laramie Energy Technology Center--Hanna, Wyoming, site						
I	1973-1974	168	2720	126	4.7	77
II-1A	1975	37	962	137	5.1	85
II-1B	1975	38	780	143	5.3	86
II-II	1976	26	2201	168	6.3	92
II-III	1976	39	3414	132	4.9	77
III	1977	38	2663	138	5.1	77
IV-A(a)	1978	7	294	109	4.1	78
IV-A(b)	1978	48	3184	102	3.8	73
IV-B(a)	1979	7	468	149	5.5	95
IV-B(b)	1979	16	663	122	4.5	83
Lawrence Livermore National Laboratory--Hoe Creek, Wyoming, site						
I	1976	11	123	101	3.8	82
II(air)	1977	13	286	108	4.0	80
II(O_2)	1977	2	47	263	9.8	88
II(air)	1977	43	1155	104	3.9	74
III(air)	1979	7	256	113	4.2	81
III(O_2)	1979	47	3251	212	7.9	73
(B) Centralia, Washington, site						
LBK(O_2)	1981-82	20	140	262-284	9.8-10.6	80
(air)				140	5.2	
CRIP(O_2)	1983	28	1500	248	9.2	74
Morgantown Energy Technology Center--Pricetown, West Virginia, site						
I	1979	17	234	149	5.5	97
Gulf Research and Development Co.--Rawlins, Wyoming, site						
I(air)	1979	30	1207	151	5.6	91
I(O_2)	1979	5	125	250	9.3	74
II(O_2)	1981	66	8550	330	12.3	88

Table 2. Privately sponsored UCG field tests in USA.

Test	Year	Duration (days)	Gas quality (Btu/scf)	MJ/m^3	Coal gasified (tons)	Cold gas thermal efficiency (%)
Basic Resources, Inc.						
Fairfield, TX	1976	26	126	4.7	--	--
Tennessee Colony, TX:						
Air injection	1978-79	197	81	3.0	4000-5000	--
Oxygen injection		10	230	8.6	212	--
ARCO Coal Co.						
Reno Junction, WY	1978	60	200	7.4	3600	94
Texas A&M University (with Industrial Consortium)						
College Station, TX	1977	1	35-114	1.3-4.2	2	--
Bastrop County, TX	1979	2	85	3.2	--	--
Bastrop County, TX	1980	--	35-150	1.3-5.6	--	--

Table 3

Rawlins 2 Burn Summary
Average Values During Steam-Oxygen
(September 7 - November 11, 1981)

Dry Product Gas Heating Value	330 Btu/scf 12.3 Mj/m^3
Coal Gasified	8550 tons
Dry Gas Composition (vol%)	
H_2	31.0%
CH_4	16.4
CO	15.8
CO_2	35.5
C_nH_m	0.8
H_2S	0.1
N_2	0.4
Product Gas mol Ratio H_2O/Dry Gas	0.32
Thermal Efficiency	88%

Table 4

Partial Seam CRIP Test Summary
Average Values During Steam-Oxygen Gasification
(October 16-November 14, 1983)

Dry Product Gas Heating Value	248 Btu/scf 9.2 Mj/m^3
Coal Gasified	1500 tons
Dry Gas Composition (vol%)	
H_2	36.1
CH_4	5.4
CO	18.5
CO_2	36.1
C_nH_m	1.0
H_2S	1.6
N_2& Ar	1.3
Product Gas mol Ratio H_2O/Dry Gas	1.3
Thermal Efficiency	74%

Table 5

UCG Produced Gas Composition Compared to Sasol, Dry, N_2-free Basis[16]

	Average UCG Gas (U.S. Tests)	Sasol	Angren (Soviet UCG)
	Vol%	Vol%	Vol%
Synthesis gas (H_2+CO)	60.4	60.8	59.5
CH_4	6.7	9.7	2.4
CO_2	32.9	29.3	38.1

Table 6. Comparison of model calculations with large block-1 test results.

	LBK-1 test	Model
Dry product gas:		
H_2	0.42	0.44
CH_4	0.035	0.026
CO	0.25	0.22
CO_2	0.28	0.30
Ratios to injected O_2		
Produced dry gas (mol/mol)	2.2	2.1
Heat of combustion (kJ/mol)	890.	820.
Cavity volumes (cubic meters)		
Void	8.	7.
Char rubble	19.	21.
Ash rubble	6.	6.
Total	33.	33.