INFLUENCE OF CHEMICAL FACTORS ON PRIMARY PROCESSING OF UTAH TAR SAND BITUMEN

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INTRODUCTION

Research of recovery and processing technology applicable to Utah tar sands is currently in progress. Development of this hydrocarbon resource has not yet occurred, principally because of high costs associated with present recovery methods. The processing of bitumens is also expected to be relatively more expensive than conventional petroleum processing because of the heavy nature and high heteroatom content of the bitumen. In processing of bitumen the primary conversion appears to be the most important step because of the possible high cost of hydrogen processing or loss in yields attendant with reducing the high molecular weight bitumen to synthetic crude. Methods and conditions of primary processing have a major effect on the composition of the products subsequently used as feedstocks for secondary processing. Secondary processing for production of fuels and other hydrocarbon products will probably utilize adaptation of processes developed for conventional petroleum.

The primary process most commonly used for upgrading of heavy oils, petroleum residuum or bitumen is some form of coking such as delayed or fluid coking. For these processes the range of operating variables which can be employed is rather limited and the product distribution and quality (composition) generated is primarily a function of the feedstock composition. Because the coking process is relatively inexpensive, industrial processes are often content with optimizing coking yields and then subsequently optimizing some secondary process more specifically aimed at altering the composition to produce a desired product. Such an approach is presently used with the Athabasca deposit where 15 to 20 weight percent of the feed is converted to a high sulfur coke and the liquid products are subjected to an expensive hydrotreating to obtain a synthetic crude oil amenable to conventional refining.

Recent work on the structure of Utah and Athabasca bitumens (1,2) has shown that Uinta Basin (Utah) bitumens possess a significantly different hydrocarbon and non-hydrocarbon structure than Athabasca bitumen. The higher molecular weight, higher viscosity, and lower volatility points toward a heavier material for the Uinta Basin bitumen, but the higher hydrogen content and API gravity, and the lower asphaltene content and carbon residue points toward a less aromatic bitumen. Interpretation of the structural analysis indicates that the Uinta Basin bitumen is comprised of relatively high molecular weight naphthenic hydrocarbons. The Athabasca bitumen is of lower molecular weight, but higher in aromatics. A comparison of compound type analysis suggests that Athabasca bitumen contains roughly twice the amount of aromatic carbon that Uinta Basin bitumen contains.

The differences apparent in the two groups of bitumens suggested that direct adaptation of process conditions used with Athabasca bitumen may not be the most desirable route for development of processes for Utah bitumens. Therefore, several alternatives for the primary conversion of bitumen have been examined, in addition to coking. Examination of alternate processing steps served two useful purposes. First, results of such a study helped identify processes particularly amenable to this unusual feedstock. Second, by paying particular attention to the structure of the feedstock and products more will be learned about conversion mechanisms and pathways influencing residual material processing.

In this paper results from coking, catalytic cracking, and hydropyrolysis of virgin Asphalt Ridge bitumen are compared. This study includes the effect of variables on yields and product composition. Product distribution and composition are compared

as a function of process variables and the conversion process employed. Detailed structural analysis is used in the evaluation of the respective processes. Implications of the product structure to thermal and catalytic conversion pathways are discussed.

EXPERIMENTAL

Analytical Methods

Physical properties and elemental analysis were obtained by conventional analytical techniques. All average molecular weights reported are those obtained by VPO in benzene. Average molecular weights determined in this fashion are expected to give values somewhat higher than the true average molecular weight because of solute-solute molecular associations (3). Liquid and gas densities were obtained by an electronic densitometer accurate to better than three significant figures.

Separation of products into compound type classes was accomplished by the dual silica-alumina column chromatographic technique (4) without prior separation of acids, bases, and neutral nitrogen compounds. Simulated distillation was accomplished by previously published procedures (1) utilizing as an internal standard a series of alkyl benzenes.

Coking

Batch coking experiments were conducted in a stainless steel reactor fitted with a Vycor glass liner. The reaction was brought to temperature by a preheated fluidized sand batch heater. Charge to the reactor was approximately 10 g. (See also references 5, 6). Pressure, when applied, was with helium, without sweep.

Catalytic Cracking

Two reactor configurations were used in order to assess various factors influencing catalytic cracking. (See also reference 8). One configuration was a semi-batch downflow reactor patterned after the CAT-A (7) test in which bitumen and catalyst are preheated before mixing. The other configuration was a batch type reactor in which feed and catalyst were intimately mixed prior to heating. This configuration minimized the diffusion limitations but required volatilization of products in a static atmosphere.

Hydropyrolysis

Reactor design for hydropyrolysis has been published by Ramakrishnan et. al. (9). The reactor tube was coiled 3/16 x 236 inch stainless steel tube which was held isothermally within $\pm 1^{o}C$ of the desired temperature. The interior surface was presulfided to minimize catlaytic effects.

RESULTS AND DISCUSSION

The approach taken in this work was to subject virgin bitumen to various processing steps and to then evaluate the results in terms of product yield and composition. Because the cost of recovery is expected to be high, it is critical that the processing steps maximize both yield and product quality. The ever increasing cost of hydrogen processing places an additional constraint on economics so optimum utilization of hydrogen is also a prime consideration.

The major primary processes which have been preliminarily examined are coking, catalytic cracking, hydropyrolysis, visbreaking and deasphalting. Catalytic hydrocracking and hydrotreating of virgin bitumen have not been examined in enough detail to make comment at this point. Visbreaking or deasphalting may play a role as pretreatment to the primary conversion process.

Characteristics of Asphalt Ridge bitumen are given in Table 1 and have been previously discussed in the literature (2,3,5,6).

Coking

Results of the coking (destructive distillation) of various deposits have been previously reported (5). These results showed that heteroatom content of the liquids followed the trends exhibited in the virgin bitumen. Total yields of liquids and gases were a function of hydrogen content; conversely the higher the aromatic content, the greater the coke yield. A secondary correlation was observed between increasing molecular weight and decreasing liquid and gas yield for a given hydrogen content.

Table 1

	C	H	N	S	O
Elemental Analysis	86.2	11.3	1.1	0.4	0.9

Average molecular weight (VPO-benzene)	713
Viscosity (Poise @ 77°F, cone-plate, .05 sec^{-1}	69,300
API gravity	12.5
Heating value (Btu/lb)	19,305
Asphaltenes (n-pentane)	11.8
Carbon residue (Rammsbottom)	9.1
% distillable below 535°C	40

The effect of temperature on process yields is given in Figure 1. The data represent ultimate yields from a series of isothermal runs. Note that near asymptotic values are reached by a temperature of 460°C. Elemental analysis and physical properties of liquids obtained at selected temperatures are given in Table 2.

Table 2

Characteristics of Pyrolysis Condensates
from Isothermal Cracking of Asphalt Ridge Bitumen (6)

	Temperature of Pyrolysis		
Property	380°C	415°C	460°C
Carbon	86.7	86.7	86.7
Hydrogen	12.1	12.3	12.2
Nitrogen	0.25	0.39	0.48
Sulfur	0.33	0.29	0.29
Oxygen	0.50	0.30	0.31
C/H Ratio	0.603	0.591	0.599
Density (20°C) g/cc	0.897	0.893	0.892
API gravity	25.9	26.7	26.9
Refractive index	1.4970	1.5010	1.4998
Molecular weight	261	296	321

The results shown in Table 2 reveal remarkably little difference in the average properties considering that the total condensate yields varied from 11% to 82% of the bitumen between 380°C and 460°C. Some difference is noted in the average molecular weight due to higher temperature of distillation of cracked products. Simulated distillation reveals that about 12% of the virgin bitumen would exhibit a TBP below 380°C; thus, a significant percentage of the 380°C products might be expected to be virgin material. For the 460°C condensate, no more than 27% of the condensate can be attributable to virgin compounds and to the extent that virgin material of this boiling range undergoes cracking the percentage contribution of virgin distillate would be reduced.

Although the properties of the condensates varied little over the temperature range examined, visual inspection of the residue/coke revealed that drastic chemical changes

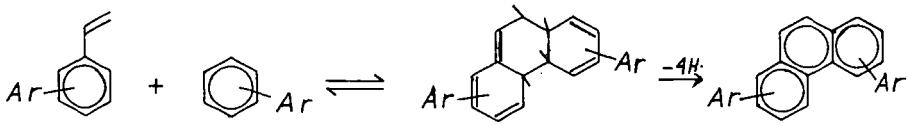
were being affected over the temperature range studied. At lower temperatures the residue was a viscous, soluble fluid, while at higher temperatures the residual material resembled a glassy char or coke. In an attempt to determine the temperature effect on the formation of this coke, presumably condensed aromatic species, the solubility of the residue in pyridine was measured. For this test to be meaningful, it was reasoned that dealkylation, dehydrogenation, or cyclization reactions would not likely result in the production of pyridine insoluble material, but that condensation or polymerization reactions producing higher ring aromatics would. The mechanisms leading to production of higher condensed aromatics are not well understood and will be referred to in this discussion simply as condensation reactions.

Results of pyridine solubility of residues are shown by the dotted line in Figure 3 and reveal that a dramatic change in pyridine solubility occurs between 425° and 435°C. Also plotted in Figure 3 is the percent yield of residue. This curve exhibits an inflection point some 22°C lower than the inflection point in the pyridine solubility curve. Scales on the vertical axis have been arbitrarily adjusted to allow some visual comparison of the various parameters measured. The data shows that volatiles formation and char formation are not simultaneous events and that the major reactions leading to volatiles and char formation occur at substantially different temperatures. Aromatics condensation apparently does not occur appreciably below 422°C even though over 70% of the bitumen has been produced as cracked products at this temperature. (See Table 8 for maximum possible contribution of virgin distillate).

In order to help confirm that pyridine solubility of the residue was a significant index for measuring aromatics condensation, a second parameter, H/C ratio, was measured. The results of this examination are also plotted in Figure 3 and reveal an inflection point quite near to the inflection point for pyridine solubility. This data showed that a linear correlation between H/C ratio and depth of cracking did not exist but that the reactions giving rise to the reduction in H/C ratio may possibly be the same as those resulting in pyridine insolubility. A correlation of pyridine solubility with H/C ratio reveals a linear relationship between 380° and 423°C, another linear relationship of different slope, between 433° and 460°C, with a non-linear transition region between 423° and 433°C. This correlation is shown in Figure 4 along with the corresponding temperature of cracking. The entire transition region actually occurs over a narrow temperature range of about 10°C.

Based on this information one can speculate about the general mechanism giving rise to the results. From 380° to 423°C primary cracking is limited to rupture of relatively weak σ bonds. The free radicals thus formed can participate in transfer or propogation reactions with aliphatic or naphthenic hydrocarbon systems. The decrease in pyridine solubility of the residue, which is accompanied by a dramatic decrease in H/C ratio, may be attributable to dehydrogenation of naphthenic ring systems, dealkylation reactions and volatilization of saturated hydrocarbons. Naphthenic ring systems may or may not be associated with aromatics but the inductive effects of aromatic rings, as exemplified by the compound tetralin, are known to promote hydrogen transfer.

Above 423°C additional reactions are introduced. These reaction mechanisms are not identified but they are characterized by several features observed in the results presented above. If fractional reduction in H/C ratio is used as a measure of the progress of reaction, an activation energy of about 70 Kcal/mole is calculated for the reaction occurring between 423° and 433°C. The calculations assumed zero order dependence on reactant concentration as assumptions of higher order produced an unreasonably high activation energy. The calculated activation energy is consistent with several possible polymerization and/or condensation reaction mechanisms. One possibility is that aromatic or benzyl hydrogens are abstracted in a free radical propagation step. The resulting phenyl or benzyl free radicals subsequently attack other aromatic rings to form biphenyl or diphenyl methane type linkages. The resulting molecules subsequently undergo further addition or ring closure depending on the alkyl substituents which might be present. An alternative reaction mechanism which might be considered is that of Diels-Alder type condensation of α-olefin aromatics acting as the diene and aromatics as the dienophile:



The reaction involves a partially hydrogenated intermediate which donates hydrogen in the process of volatiles formation.

In the region between 433° and 460°C the reduction in hydrogen content is attributable to several factors. One factor is the loss of aromatic C-H resulting from condensation of aromatics as discussed. Another factor is the significant increase in primary decomposition reactions such as dealkylation of aromatics. Analysis of products produced between 430° and 460°C show a definite trend toward increased paraffinic carbon compared to lower temperature products which were more naphthenic. Whereas transfer and free radical propagation reactions can occur at moderate temperatures, primary decomposition requires higher temperatures. Whichever the dominant mechanism, Figure 4 shows that the loss of hydrogen at higher temepratures has a much greater influence on decreasing the solubility of the residue than occurred at the low temperature end where considerable loss of hydrogen content had little effect on pyridine solubility.

There are several important implications of the proposed gross mechanism to thermal processing of bitumen. First, production of refractory molecules can be inhibited by maintaining temperatures below 425°C. The residue obtained at these conditions should remain amenable to further processing. Second, inhibition of condensed aromatics formation above 425°C can be accomplished only by shortening the residence time (reducing the relative importance of second order reactions) or by dilution of the aromatics such as with hydrogen or hydrogen rich molecules. This interpretation appears to be consistent with the vast body of processing literature which has emperically determined that processes operating below 425°C are significantly different from those operating above this temperature where residence time becomes highly important.

Industrial coking processes typically operate at pressures higher than atmospheric. Correspondingly, the effect of pressure (He) on yields and yield structure was determined, holding the temperature constant at 460°C. Results are given in Figure 2. The results show that the amount of coke formed increases steadily with increasing pressure. These results and those acquired for visbreaking of bitumen at elevated pressures suggest that pressure exerts an influence on chemical reactions over and above the effects pressure has on volatility and diffusion of products.

The products from this set of experiments were evaluated in terms of elemental analysis and physical properties. Results are shown in Table 3. Elemental analysis are not shown because variations from the atmospheric pressure results (Table 2) were minor. The API gravity results show interesting curvature at about 80-100 psig. The yield data in Figure 2 suggested that the liquids curve may not be a smoothly decreasing function of pressure, as drawn. Should these deviations in API gravity and yields as a function of pressure prove to be real, it may have interesting implications regarding the effect of pressure on thermal cracking mechanisms.

Catalytic Cracking

Analysis of Uinta Basin bitumen revealed a material that was high in naphthenic character (2). The results are exemplified by the group type analysis of P. R. Spring saturated hydrocarbons where over 60% of the saturates are comprised of substituted decalins and perhydroanthracenes and perhydrophenanthrenes (1). Only 7% of the saturates which represented 27% of the bitumen contained no alicyclic rings. The

highly naphthenic character of aromatic containing molecules is thought to persist in the remaining 73% of the bitumen.

Table 3

Properties of Condensates Derived at Elevated Pressures

Property	Pressure (psig) 0	40	80	120	250
API gravity	26.9	33.4	34.1	37.1	39.2
n_{20}^{D}	1.4998	1.4891	1.4914	1.4830	1.4801
Avg. molecular weight	321		263		265

Naphthenic gas oils are highly responsive to catalytic cracking and give high yields of branched alkanes. Based on this rationale, direct catalytic cracking was attempted. The presence of significant quantities of basic nitrogen, metals, or particulates would be expected to have an appreciable impact on a commercial operation and utilization of catalytic cracking may require some form of feed pretreatment. However, at the present stage of research it is important to assess the chemical responsiveness to catalytic cracking. Preliminary results of this study and a description of catalysts have been previously reported (8).

Gravimetric results for cat cracking under selected conditions are given in Table 4. Results of Bt(1) reveal that significant catalytic activity was present at 412°C; purely thermal cracking (Figure 1) produced only 47% liquids plus gases at this temperature. Results of Bt(2) show that significant cracking occurred with the powdered molecular sieve catalyst. Further, the catalyst exhibited a strong selectivity toward production of liquids rather than gases and the slightly higher API gravity reflects the increased amount of hydrogen retained in the liquids. These trends are expected from molecular sieve catalysts when zeolite catalyzed cracking is operative.

Table 4

Catalytic Cracking Results

Feed (Run)	Catalyst	Mode	Cat/Oil	T°C	Gas	Liquid	Residue (Coke)	°API (Liquid)
Bt(1)	S/A	SB	1.3	412	6	67	26	27.9
Bt(2)	M.S.(f)	SB	1.8	412	1	79	20	29.5
Bt(3)	S/A	SB	1.3	470	11	76	13	25.1
Bt(4)	S/A	B	2.0	460	10	74	16	30.8
M(5)	S/A	B	2.0	460	10	78	12	32.0
Bt(6)	M.S.	B	3.0	460	7	80	13	27.1
VB(7)	M.S.	B	3.0	460	4	83	13	28.8

Symbol Designation: Bt (virgin bitumen); M (pentane soluble maltenes from virgin bitumen); VB (visbroken bitumen, 425°C, 150 psig, ∿11 min.); S/A (Houdry 159CP silica-alumina catalyst); M.S. (Mobil Durabead-8 molecular sieve catalyst); SB (semi-batch Cat A mode); B (batch mode); f (powdered catalyst).

When temperatures were raised to 460-470°C additional yields were experienced. Results of Bt(3) and Bt(4) show good agreement between the two reactor configurations. The batch operation, requiring volatilization of products, exhibited a tendency to retain heavier materials with the coke. The results of runs Bt(3) and Bt(4) are quite encouraging because they exhibit yield and product quality equal to or better than experienced with thermal cracking.

An attempt was made to remove coke precursors by prior deasphalting. Results of cat cracking of the maltenes, which represented 90% of the virgin bitumen, are given in Run M(5). Removal of 10% asphaltenes resulted in a coke reduction of only 4%. In retrospect, this is not too surprising because the asphaltenes from Uinta Basin bitumen, although consisting of the highest molecular weight species present, also contain significant quantities of hydrogen (H/C = 1.2) and contribute to the volatiles product yield. Conversely, not all of the coke precursor aromatics are precipitated due to the effects that the naphthenic and alkyl substituents have on increasing the solubility of the aromatics. Thus, a one-to-one correlation between molecules comprising the asphaltene fraction and coke precursors does not exist.

Results of run Bt(6) suggested that substantial thermal reactions were taking place. Property data of liquids and gas analysis have strong resemblance to the thermally derived products. The thermal vs. catalytic effects are illustrated in the gas analysis for selected runs in Table 5. Compared to the thermal gases the cat cracking gases, Bt(4), exhibited a strong selectivity for production of C_3 and C_4 and gave very high yields of isobutane. Results for the run Bt(6) show some characteristics of cat cracked products but also show many similarities to the thermal products. The results of Bt(6) are presented to illustrate the difficulty which may be encountered through competitive reactions and is not intended to represent optimum results for this catalyst.

Table 5

C_1 to C_4 Gas Analysis

	Thermal (460°C)	Mol-Sieve Run Bt(6)	Sil/Al Run Bt(4)	Hydropyrolysis (525°C)
Methane	41.0	32.3	18.9	27.5
Ethane	16.5	16.1	10.3	18.3
Ethylene	15.1	5.0	4.2	5.5
Propane	10.0	15.4	12.2	23.4
Propylene	11.6	10.2	15.4	2.8
n-butane	1.3	5.4	3.3	10.6
i-butane	1.4	4.0	18.0	7.3
Butylenes	3.1	11.6	17.7	4.6

When the average molecular weight of the feed was reduced from about 700 to about 500 by visbreaking, significantly greater catalytic activity was observed (Run-VB(7)). These results are consistent with the general observation that catalytic activity was strongly enhanced if some reduction of molecular size preceded the contact with the catalyst.

The results of catalytic cracking have shown that the bitumen is highly responsive to catalytic cracking if the molecular size can be reduced to minimize diffusional limitations. It thus appears that a good catalytic cracking feedstock should be derivable from the Uinta Basin bitumen. It is quite possible, that by a more systematic and thorough search for optimum catalysts, process configurations, and process conditions considerable improvements on the results given in Table 4 can be realized.

Hydropyrolysis

The Asphalt Ridge bitumen was subjected to hydropyrolysis in a tubular flow reactor. Yields and process conditions are given in Table 6. Results show that the virgin bitumen can be converted to liquids and gases with little or no coke formation.

Virtually no change in pressure drop across the reactor was observed over the course of the 15 to 20 minute runs. These yield results suggest that molecular hydrogen has successfully inhibited the condensation reactions discussed in the section on coking.

Table 6

Hydropyrolysis Yields and Process Conditions

Reaction Conditions			Yields		
			Weight Percent		
Temp. °C	Pressure psig	Residence Time (Seconds)	Gas	Liquids	Coke
500	1500	18	17	83	0
525	1500	18	27	73	0

Elemental analysis and physical property data for the liquids are given in Table 7. Results show that little change was affected in the elemental composition and hydrogen to carbon ratio. However, physical property data reveals a dramatic increase in API gravity and a large reduction in molecular weight. The percentage hydrogen added was calculated from a material balance on hydrogen and included the amount added to the gases. The amount of hydrogen added to the system appears to be closely related to the amount of gas produced. On the average, the liquid products are slightly more condensed than the starting bitumen. The gases formed derive largely from the paraffins and alkyl substituents present. Pentane asphaltenes amounted to 3.5% of the liquids, were quite hydrogen deficient (H/C = 0.97), and contained a 5% nitrogen concentration.

Table 7

Hydropyrolysis Product Characteristics

		Temperature of Run	
	Feed	500°C	525°C
Carbon	86.2	86.7	86.8
Hydrogen	11.3	11.6	11.4
Nitrogen	1.1	0.8	0.8
Sulfur	0.4	0.3	0.3
Oxygen	0.9	0.3	0.3
C/H ratio	.640	.627	.639
API gravity	12.7	22.1	25.2
Average molecular weight	713	336	321
Refractive index		1.52	1.52
Wt. % H_2 added to total products		0.8	1.2
SCF H_2/bbl feed		600	900

The preliminary results of the hydropyrolysis are particularly interesting because hydropyrolysis promises to be a simple process which can produce a drastic reduction in molecular weight without a high consumption of hydrogen.

Simulated Distillation

Simulated distillation results are given in Table 8 for virgin bitumen and the various liquid products. These results show significant changes in volatility were affected, even in the case of mild visbreaking. The lightest products were those from thermal cracking at 80 psig and catalytic cracking. In both cases, yields were about 74% of the charge material; however, the cat cracking run produced 4% more gases.

The catalytic cracking produced 23% gasoline. This gasoline was found to exhibit a calculated 50% point at 128°C and a calculated research octane of 78. Analytical results showed that the octane number was reduced by the presence of some low octane thermal products in the heavy gasoline range.

Table 8

Simulated Distillation

Corresponding BMCOA Fraction(1)		Cumulative Weight Percent					
No.	Cut Pt.°C	Bt	TC(0)	TC(80)	CC	HP	VB
1	50			1.2	0.9	1.0	
2	76			2.7	2.4	2.2	0.5
3	100		1.2	5.0	8.3	4.5	1.1
4	125		2.3	7.7	11.2	7.3	1.7
5	150		4.2	11.9	14.9	10.6	2.7
6	175		6.3	16.5	18.9	13.5	4.0
7	200	0.1	8.7	21.6	22.8	17.2	5.5
8	225	0.4	11.0	26.5	27.3	20.9	7.4
9	250	1.1	14.7	33.4	32.5	25.6	10.3
10	275	2.4	19.4	40.9	38.2	30.5	13.9
11	305	5.0	25.2	50.3	46.0	37.6	18.6
12	335	7.4	32.5	60.4	54.9	44.5	24.2
13	365	10.4	40.3	69.7	62.9	51.2	29.7
14	395	13.8	49.5	78.6	71.0	58.0	35.8
15	425	17.3	58.8	86.2	78.6	64.5	41.6
16	455	21.7	68.8	91.9	85.2	71.6	48.0
17	485	27.4	80.4	96.2	92.1	77.7	55.6
18	515	32.7	90.6	98.8	96.6	82.1	62.0
19	538	39.8	96.6	100.0	99.1	84.6	67.1
Residue	>538	100	100		100	100	100
10% Point °C		362	211	146	115	145	247
50% Point °C		>538	397	303	321	359	463
90% Point °C			511	444	449	>538	>538

Symbol Designation: Bt (virgin bitumen); TC (thermally cracked @ 0 psig and 80 psig, respectively); CC (cat cracked Bt(4), Table 4); HP (hydropyrolysis, 525°C liquids); VB (Visbreaking, 475°C, 80 psig, ∿8 min.).

The simulated distillation results for the hydropyrolysis liquids reveal a broad boiling point distribution. Although substantial amounts of light material are produced, certain heavier aromatics remain virtually unchanged. These aromatics are present in the hydropyrolysis liquids but went to form coke in the coking and cat cracking conversion processes. The distillation data presented here suggest that the hydropyrolysis liquids, with their relatively low olefin content, would make a good feedstock for refining.

Separation into Compound Types

Separation of total liquid products into saturated, mono-aromatic, di-aromatic, and poly-polar aromatic compound types gives important information regarding the distribution of structural features. Results of the separation are given in Table 9.

Perhaps the most striking feature of these results is the high percentage of purely saturated hydrocarbons. All samples have high concentrations of higher aromatics as well, indicating a very broad distribution of compound types. The

comparatively low percentage of saturates in the hydropyrolysis liquids can be explained on the basis that nearly twice the gases were formed and 12% heavy material is present that was removed with the coke in the other two processes. Elemental analysis revealed that the vast majority of nitrogen and sulfur compounds were retained with the poly-polar aromatics. The high percentage of monoaromatics in the hydropyrolysis liquids seems to indicate that some hydrogenation of higher aromatics has occurred.

Table 9

Compound Type Classification of Products

Fraction	Thermal 460°C, 0 psig	Catalytic Bt(4)	Hydropyrolysis 500°C
Saturates	55.1	62.0	48.5
Monoaromatics	11.7	9.1	15.3
Diaromatics	8.4	5.5	5.6
Poly-polar aromatics	24.8	23.4	30.6
	100	100	100
Percent Recovery	89.6	85.3	94.8

CONCLUSIONS

The unusual chemical nature of Uinta Basin bitumen requires that examination of various primary processes and a search for optimum conversion conditions be made. The principal chemical objective in primary processing is to reduce the molecular weight with a minimum cost in light product yields and a minimum requirement for hydrogen. Coking was shown to produce high yields of liquids and gases with a low sulfur coke as a potentially valuable by-product. Temperature was shown to have a significant effect on total yields in coking but had little effect on volatiles composition. Pressure was shown to have a significant effect both on composition and yields. Catalytic cracking produced high yields of liquids and gaseous products. Further research to find optimum conditions and the most appropriate role for catalytic cracking in bitumen processing is indicated. Hydropyrolysis was shown to convert bitumen in virtually 100% yields to gases and medium volatility liquids with low consumptions of hydrogen. This process shows good potential as a viable primary processing step. Analysis revealed that the structure of products can be significantly affected by various processing sequences studied. Analytical results are highly instructive as to what must be accomplished chemically during the conversion of virgin bitumen. The structure of the products also gives important clues as to the gross mechanisms of conversion. The results of this study provide a basis for further evaluation of the most desirable approach to processing of Uinta Basin bitumen.

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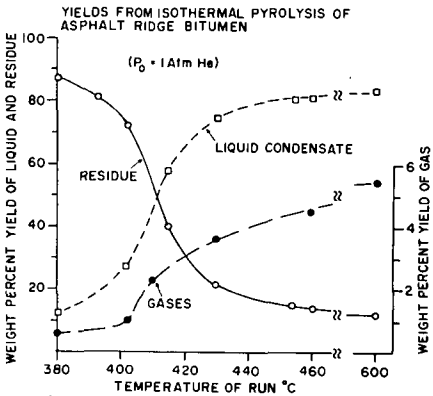

Fig. 1

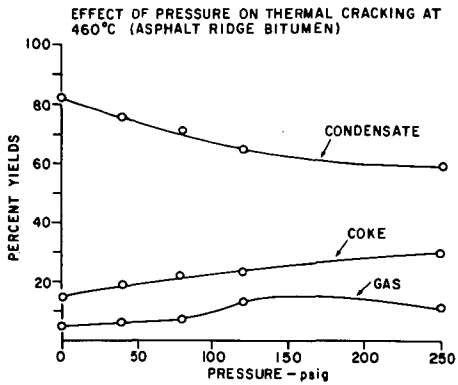

Fig. 2

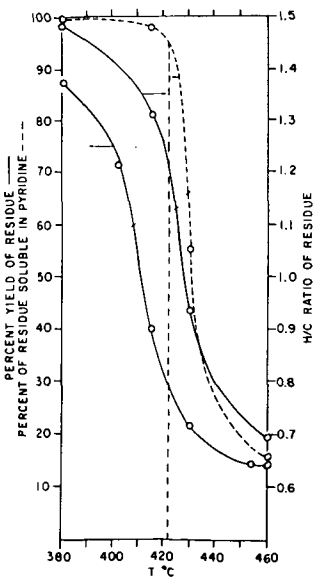

Fig. 3

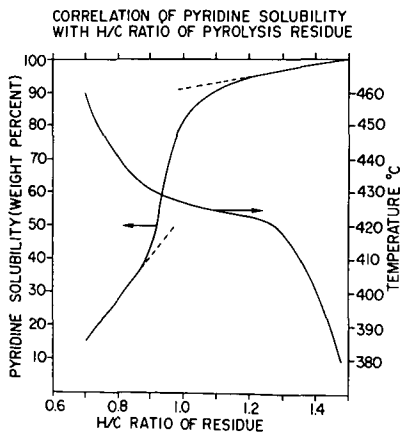

Fig. 4