

## Study of Canadian FCC Feeds from Various Origins and Treatments. 2. Some Specific Cracking Characteristics and Comparisons of Product Yields and Qualities between a Riser Reactor and a MAT Unit

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Ten vacuum gas oil feeds were cracked in a fixed-bed microactivity test (MAT) unit and a modified ARCO riser reactor on separate occasions. Several important observations from the MAT study were reported, including the effects of gasoline precursors on the maximum gasoline yields, light cycle oil (LCO) precursors on the optimum LCO yields, and aromatics in feeds on the conversion levels at which the maximum gasoline yields occurred. The yield profiles were similar, in regard to shape and relative position, between H<sub>2</sub>S-free dry gas and catalytic coke for all but one of the feeds. A method to check the qualities of the MAT and riser data was demonstrated by plotting the coke or total gas selectivity versus the gasoline selectivity. Individual yields of gas, liquid, and coke from MAT at conversions of 55, 65, 70, and 81 wt % were compared with their respective pilot-plant data. MAT results, with the exception of coke yield, were, in most cases, within 15% of the corresponding riser yields. Good linear correlations could be established between MAT and riser yields, except for liquefied petroleum gas (LPG) and LCO. Liquid products from MAT were analyzed for hydrocarbon type, sulfur and nitrogen contents, and density, most of which showed good agreement with those obtained from the riser study. The advantages of hydrotreating some poor feeds to improve product yields and qualities were demonstrated and discussed.

### 1. Introduction

With the long-term increase in oil prices and the continuous decline in conventional oil reserves worldwide, refiners are looking for better ways to utilize natural resources and are showing an increased interest in nonconventional feedstocks, such as those derived from oil-sands bitumens. The Canadian oil-sands resources, mainly in western Canada, are immense, with ~300 billion barrels recoverable, using current technologies.<sup>1</sup> In comparison, the remaining resources of Canadian light and heavy conventional oils that can be economically recovered are estimated to be ~11 billion barrels. The disposition of Canadian oil is determined by the degree to which it can compete on the basis of

price, quality, and availability in individual market areas in Canada and the United States.

Syncrude Canada, Ltd. operates the largest oil-sands bitumen upgrader in the world, producing a synthetic crude oil (SCO) called "Syncrude Sweet Blend", or "SSB". Over the years, Syncrude has been striving for a better quality of SSB, with specific interest in the heavy gas oil (HGO) or vacuum gas oil (VGO) fraction. The current SSB contains more than a desirable amount of VGO, 35–40 vol %, which is usually used as a fluid catalytic cracking (FCC) feed. From 1996 to 1998, Syncrude evaluated 10 existing and potential VGOs, both in the riser pilot plant and the microactivity (MAT) test unit. Riser data were reported previously,<sup>2–5</sup> as were portions of the MAT results.<sup>3–6</sup>

Currently, the MAT units, based on the principle and methodology of ASTM D 3907, continue to be the bench-scale workhorse in the catalyst and petroleum industries. This is due to the inexpensiveness and rapidity in obtaining results with MAT units, compared to the pilot-scale circulating riser units that provide the best simulation of commercial operations. To keep pace with

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the continuing changes in commercial FCC operation and to provide better commercial relevance (i.e., to more realistically simulate the commercial process, with respect to its operation and performance), many modifications have been made to the original ASTM MAT method.<sup>7–11</sup> Essentially, researchers have improved the technology using two approaches. The first has been to modify the fixed-bed ASTM method with respect to (i) the catalyst bed<sup>8,9</sup> (e.g., dilution with inert solids to maintain a constant bed height and using the annular bed versus the conventional cylindrical bed for better heat control), (ii) a much shorter catalyst contact time (due to the introduction of high-activity zeolites),<sup>8,9</sup> (iii) higher feed preheat and reaction temperatures (feeds are increasingly heavier than before), and (iv) catalyst-to-oil (C/O) adjustment protocol (manipulations of catalyst and oil amounts, and the oil injection rate and time, to keep the space time constant or varying).<sup>7,11</sup> The second approach has been to convert the fixed-bed reactor to a fixed-fluidized-bed reactor, such as the Advanced Cracking Evaluation (ACE) unit<sup>9,11</sup> by Kayser Technologies<sup>12</sup> and the Short Contact Time Resid Test (SCT-RT)<sup>10</sup> unit by Akzo Nobel Catalysts.<sup>13</sup> This is to provide enhanced mixing of the catalyst with the oil and prevent channeling of the feed during cracking, enabling a more homogeneous deposition of coke on the catalyst. The advances in MAT technology have made this simple method a useful tool to predict riser yield<sup>7,9,10,14</sup> and product quality,<sup>4,15,16</sup> as well as to rank the catalysts.<sup>8,9</sup> However, numerous pitfalls (e.g., the change in the bed height-to-diameter ratio of a fixed-bed reactor and the possible backmixing in the fluid-bed reactor) have also been identified for the MAT approach, which results in an erroneous catalyst evaluation.<sup>8,9,11,14,17</sup> Thus, the users should be aware of these pitfalls when interpreting the results.

In Part 1 of this study,<sup>6</sup> we compared the general cracking characteristics, based on MAT data, of the 10 VGOs and ranked them as FCC feeds. This paper provides additional results with respect to (i) some specific cracking characteristics, (ii) the comparison of individual yields between the MAT unit and riser reactor on a relative rather than absolute scale, and (iii) the improvements in yield distribution and product quality following the feed treatments.

## 2. Experimental Section

**2.1. Feedstocks.** The 10 feeds described in the companion paper (Part 1)<sup>6</sup> were used in this study. They are listed below in the descending order of their qualities:

- (1) hydrocracker bottoms (HCB, as received);
- (2) hydrotreated virgin VGO (HT-VIR, 343 °C+);
- (3) Rainbow Zama VGO (RZ, 343–525 °C);
- (4) hydrotreated LC–Finer VGO (HT-LCF, 343 °C+);
- (5) hydrotreated coker VGO (HT-C, 343 °C+);
- (6) hydrotreated deasphalted VGO from bitumen (HT-DA, 343 °C+);
- (7) untreated virgin VGO (VIR, 343–525 °C);
- (8) untreated LC–Finer VGO (LCF, 343–525 °C);
- (9) deasphalted oil from LC–Finer resid (DA-LCF, as received); and
- (10) deasphalted oil from bitumen (DA-BIT, as received).

Feed analyses were reported previously.<sup>6</sup>

**2.2. Catalyst.** The equilibrium catalyst Dimension 60 described previously<sup>6</sup> was used in this study.

**2.3. Catalytic Cracking of Feedstocks.** The MAT experiments in series 1<sup>6</sup> were conducted in a fixed-bed reactor system (Zeton Automat IV) that was equipped with regular collection systems for gas and liquid products. For each feed, three runs were conducted at 510 °C, one run was conducted at 500 °C, and two runs were conducted at 520 °C. However, some runs were repeated later. To obtain more liquid product for characterization, a few MAT tests (series 2) were performed in either a fixed-bed reactor (for HT-C and DA-BIT) or a fluid-bed reactor (for HT-DA) that was loaded with 5 g of catalyst (an increase from 4 g in series 1) at 510 °C. In this case, to obtain different conversions for a feed, the C/O ratio was adjusted as in series 1,<sup>6</sup> but a specially designed liquid receiver with an extra large volume (300 mL) was used to collect >99 wt % of the liquid products that were free of contamination by wash solvents (e.g., CS<sub>2</sub>). Yield data obtained in this series of MAT runs<sup>4</sup> were comparable with those in series 1.<sup>6</sup>

The FCC pilot-plant data were obtained from a modified ARCO-type riser reactor for which the operation and methodology have been described by Yui et al.<sup>2</sup>

**2.4. Characterization of Cracked Liquid Products.** Total liquid products (TLPs, 0.5–1.7 mL, depending on the C/O ratio), obtained in series 2 MAT runs, were characterized (without prior separation) for simulated distillation (ASTM 2887) and hydrocarbon types of gasoline by a PIONA analyzer (a specially configured gas chromatograph (GC) with a pre-fractionator). TLPs were also characterized for boiling-point distributions of aromatics (using a GC with a mass-selective detector (GC–MSD), via Robinson method calculation), nitrogen content (using a GC with an Antek nitrogen chemiluminescence detector (GC–NCD)), and sulfur content (using a GC with a Sievers sulfur chemiluminescence detector (GC–SCD)). Sulfur and nitrogen standard solutions, and a mixture of normal paraffins, were used to establish the sulfur and

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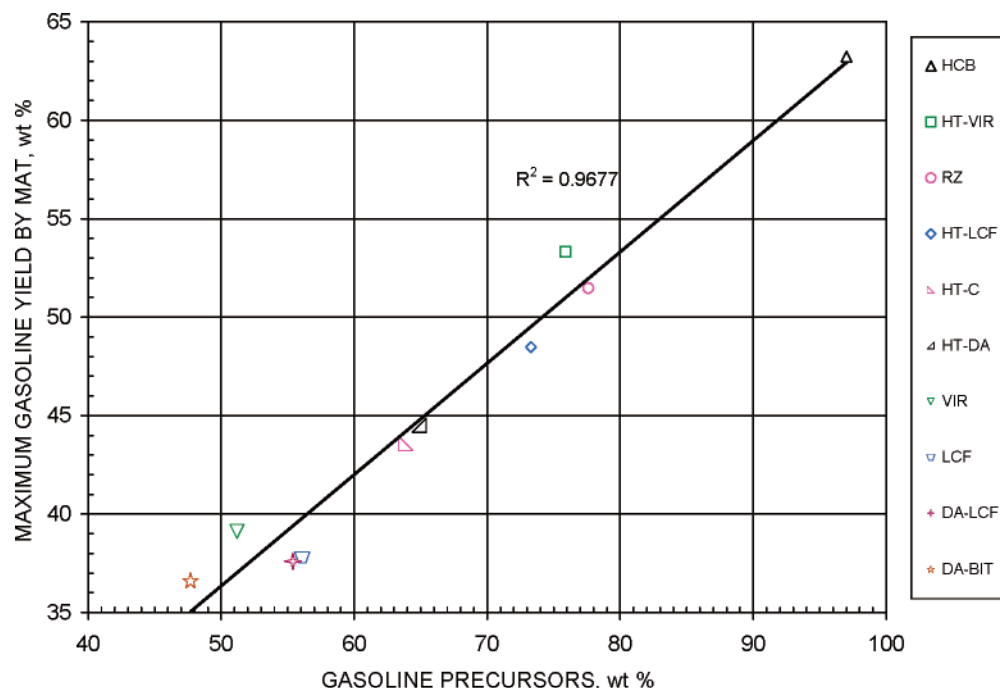
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**Figure 1.** Effect of gasoline precursors concentration on maximum gasoline yield by MAT.

**Table 1. Maximum Gasoline Yield and Optimum LCO Yield**

feed	conversion where overcracking occurred (wt %)	maximum gasoline yield (wt %)	optimum LCO yield (wt %)	precursors (wt %)		aromatics (wt %)
				gasoline	LCO	
HCB	84.7	63.2	11.0	97.0	1.5	9.3
HT-VIR	73.7	53.3	17.8	75.9	12.3	52.3
RZ	79.7	51.5	12.9	77.6	10.1	36.1
HT-LCF	69.7	48.5	18.7	73.3	13.5	52.3
HT-C	72.6	43.6	16.5	63.9	15.8	61.8
HT-DA	70.6	44.5	17.7	64.9	14.9	57.5
VIR	63.3	39.1	22.0	51.2	21.7	65.6
LCF	72.4	37.8	20.3	56.1	17.9	58.4
DA-LCF	71.3	37.6	16.4	55.4	16.6	59.1
DA-BIT	68.7	36.6	19.2	47.7	20.5	61.8

nitrogen calibration factors and the relationship between retention time and boiling point.

### 3. Results and Discussion

**3.1. Some Observations on Cracking Characteristics.** This study features a large number and variety of feedstocks, with complete analyses, cracked in a wide range of C/O ratios in two reaction systems (MAT unit and riser reactor). It is worth reporting below some of the cracking characteristics that do not appear often in the literature.

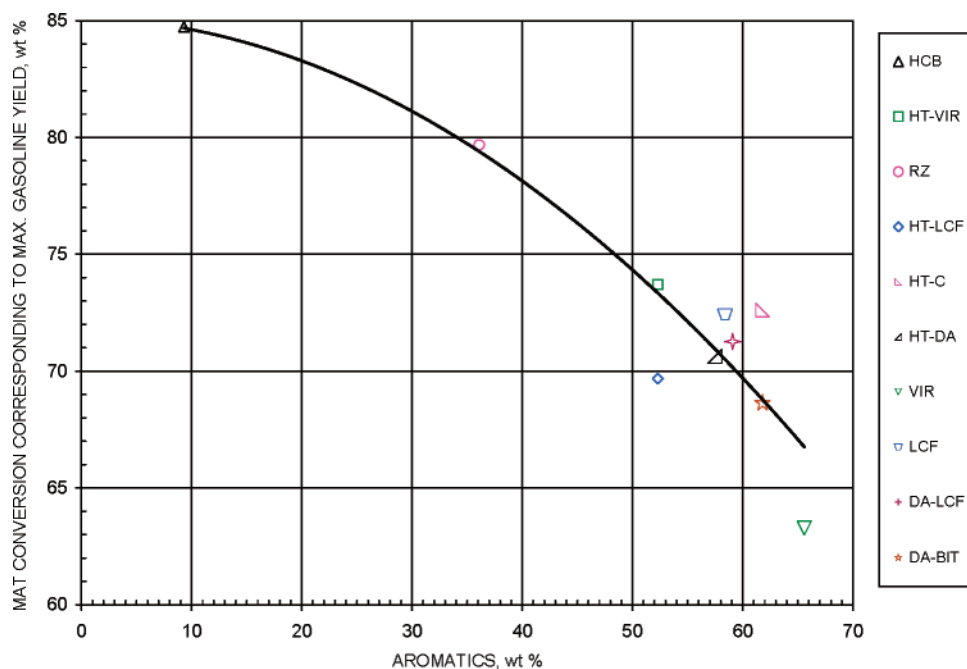
**3.1.1. Overcracking, Maximum Gasoline Yields, and Gasoline Precursors.** Overcracking signified by a maximum gasoline yield at a certain conversion was noticed for some feeds.<sup>6</sup> To achieve the maximum gasoline yield, the reaction severity must be high enough to enhance cracking until the formation rate of gasoline (from feed and LCO) equals the diminishing rate of gasoline (to liquefied petroleum gas (LPG), dry gas, and coke). In this study, for feeds that do not attain overcracking, their approximate maximum gasoline yields were mathematically determined by assuming that the gasoline yield (also, the light cycle oil (LCO) yield, which will be discussed later) followed a parabolic function of conversion. The accuracy of the maximum yield and the exact position of the corresponding conversion for each feed depended on the quality of MAT data and the avail-

ability of data points near the overcracking region. The maximum gasoline yields, the corresponding conversions, and other related data, including the gasoline precursors concentrations for the 10 feeds, are given in Table 1. The gasoline precursors were determined from hydrocarbon types of feeds using a GC-MSD, under the assumption that saturates and monoaromatics were the precursors that predominantly contributed to the production of gasoline and its derived products (i.e., dry gas, LPG, and catalytic coke).<sup>18</sup> Some challenges resulting from the uncertainties in accurate assignment of the hydrocarbon components to the precursor categories have been discussed previously.<sup>19</sup> Figure 1 depicts a linear relationship between the maximum gasoline yield and the gasoline precursors concentration with a good coefficient of determination of  $R^2 = 0.97$ . Figure 2 shows that the higher the aromatics content of the feed, the lower the conversion at which the maximum gasoline yield occurred. This is understandable, because the aromatic rings are not crackable under FCC conditions.

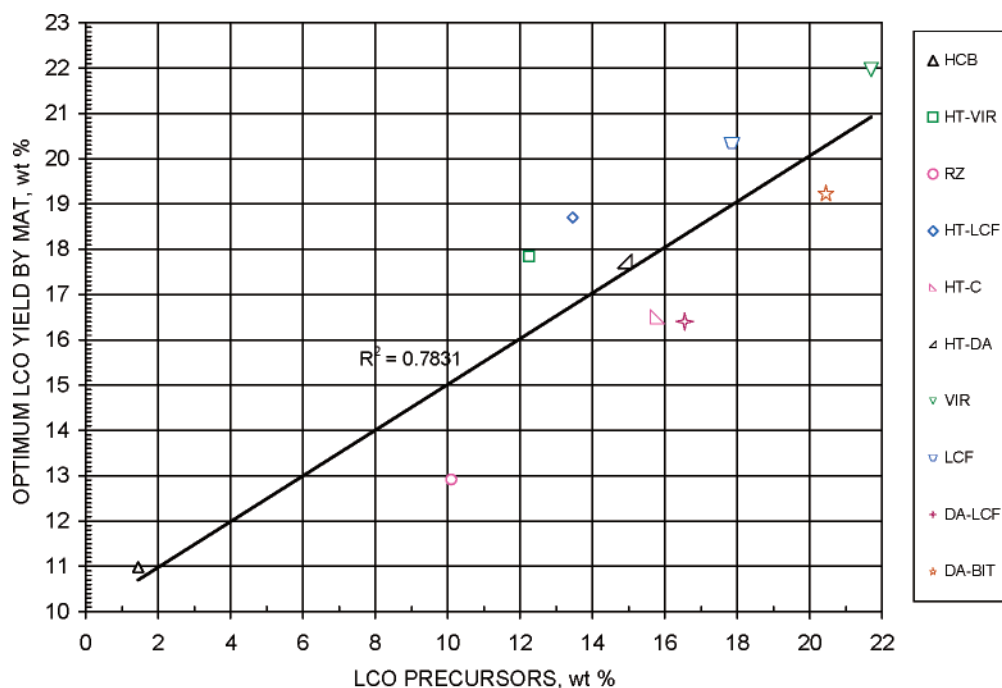
**3.1.2. Optimum Light Cycle Oil Yields and Light Cycle Oil Precursors.** As has been visualized elsewhere,<sup>6</sup> LCO yields tend to converge to zero at 100 wt % conversion

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**Figure 2.** Effect of feed aromatics content on MAT conversion corresponding to maximum gasoline yield.

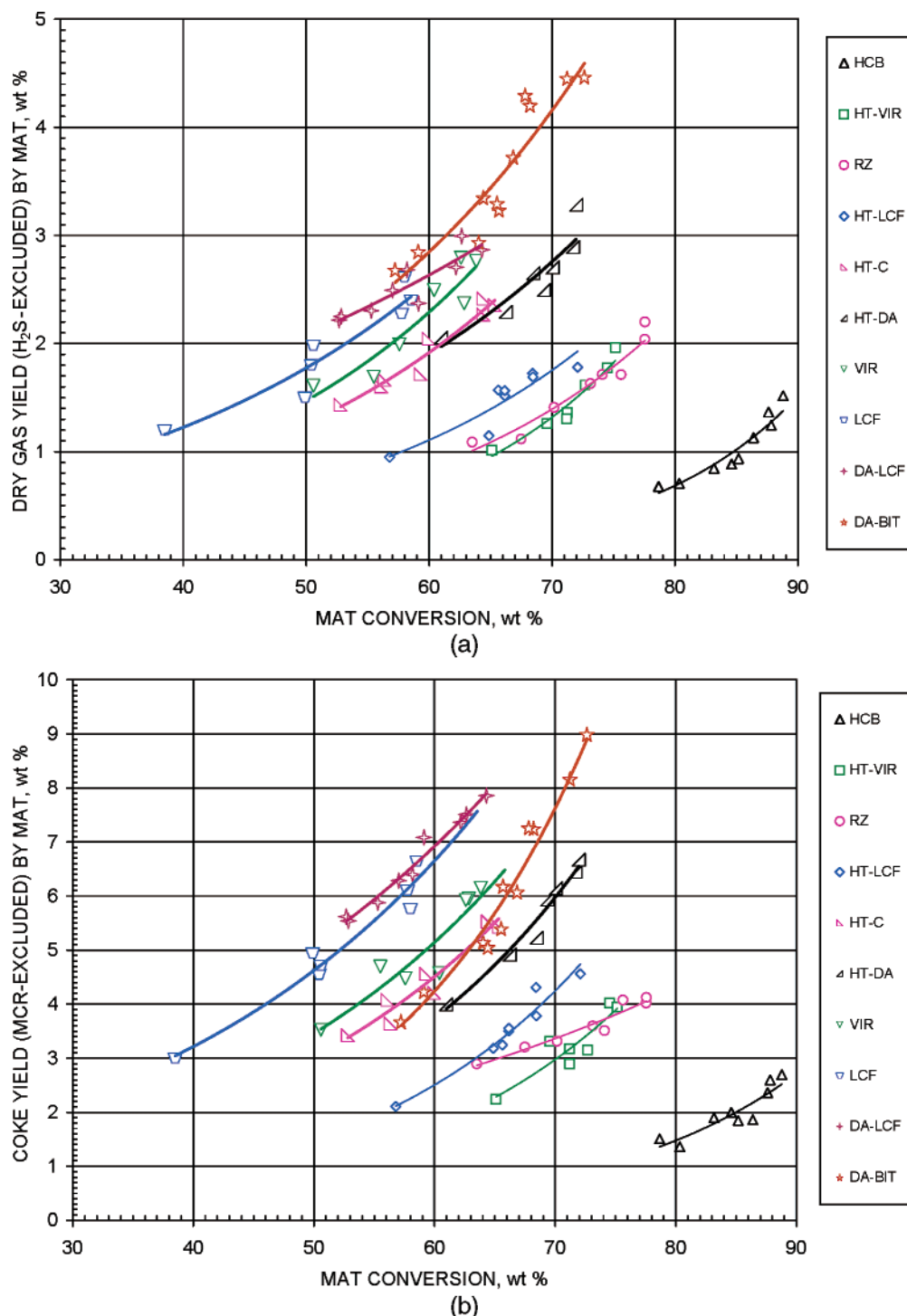


**Figure 3.** Effect of LCO precursors concentration on optimum LCO yield by MAT.

where the feed is excessively converted to gas and coke under extreme conditions. In this study, we define the lowest LCO yield prior to the overcracking of a feed as the “optimum LCO yield”. Optimum LCO yields of the 10 feeds are given in Table 1, along with concentrations of LCO precursors defined as the sum of diaromatics, two-ring aromatic sulfur, and half of the three-ring aromatic sulfur. The definition was based on the assumption that, after removing the side chains of precursors, the core compounds that remained would boil in the LCO range. Figure 3 shows a linear correlation between the optimum LCO yield and the LCO precursors concentration. The resulting  $R^2$  value was somewhat low (0.78), indicating that other factors might be causing the complication.

**3.1.3. Corrected Dry Gas and Coke Yields.** In Part 1 of this study, it was interesting to note the similarity in shape and relative position between yield curves (in yield–conversion plots) of dry gas and coke for the four good-quality feeds.<sup>6</sup> However, other feeds did not exhibit the same phenomena. It was suspected that the inconsistency was caused by either the high feed sulfur, which affected the dry gas yield, or the high microcarbon residue (MCR), which affected the coke yield. To confirm this,  $H_2S$  was excluded from the dry-gas yield and MCR from the coke yield for each feed. The results are depicted in panels a and b of Figure 4, which show similar patterns for all feeds except for DA-BIT, where the coke yield seemed to be overcorrected. Figure 5 shows a good linear correlation (with a y-intercept of





**Figure 4.** (a) Relationship between MAT conversion and  $\text{H}_2\text{S}$ -excluded dry gas yield by MAT. (b) Relationship between MAT conversion and MCR-excluded coke yield by MAT.

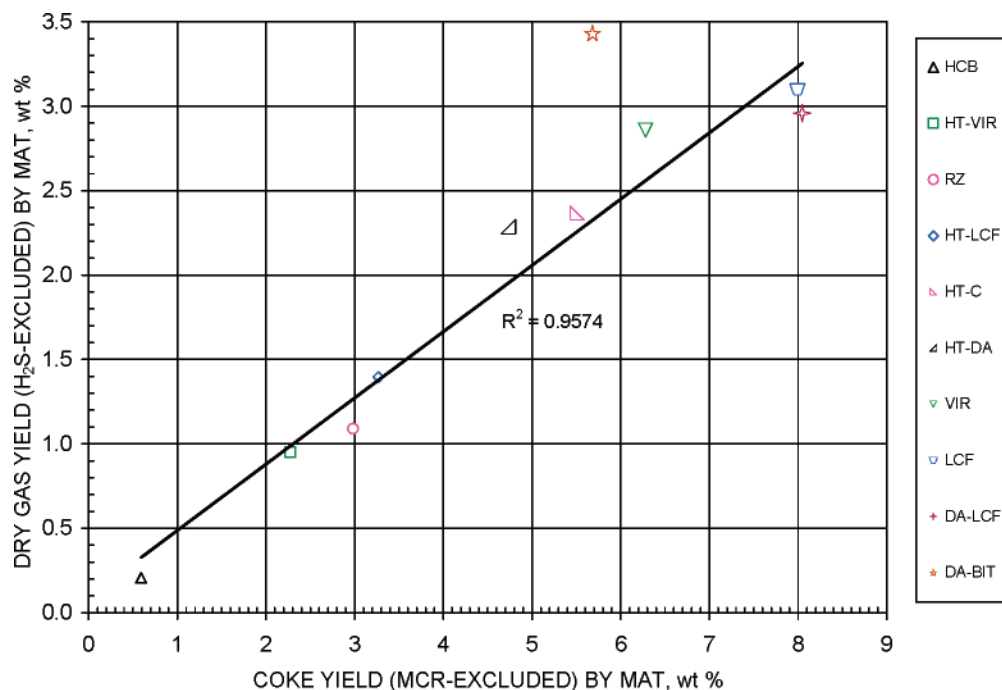
$\sim 0$  and  $R^2 = 0.96$ ) between the corrected dry gas and coke yields at a conversion of 65 wt % for all feeds, excluding DA-BIT. It is likely that the  $\text{H}_2\text{S}$ -free dry gas and the MCR-excluded coke (i.e., catalytic coke) were formed in proportion from common sources, e.g., gasoline and/or butenes.<sup>20</sup> Note that, in Figures 4a and 4b, the ascending orders of both corrected yields at a conversion of 65 wt % for all feeds (i.e.,  $\text{HCB} \ll \text{HT-VIR} \approx \text{RZ} < \text{HT-LCF} \ll \text{HT-DA} \approx \text{HT-C} < \text{VIR} < \text{DA-LCF} \approx \text{LCF} < \text{DA-BIT}$  for dry gas and  $\text{HCB} \ll \text{HT-VIR}$

$< \text{RZ} < \text{HT-LCF} \ll \text{HT-DA} < \text{HT-C} \approx \text{DA-BIT} < \text{VIR} \ll \text{LCF} \approx \text{DA-LCF}$  for coke) corresponded very well with the descending order that was based on the apparent feed ranks ( $\text{HCB} \gg \text{HT-VIR} \approx \text{RZ} > \text{HT-LCF} > \text{HT-C} \approx \text{HT-DA} > \text{VIR} > \text{LCF} > \text{DA-LCF} \approx \text{DA-BIT}$ ), as reported previously.<sup>6</sup>

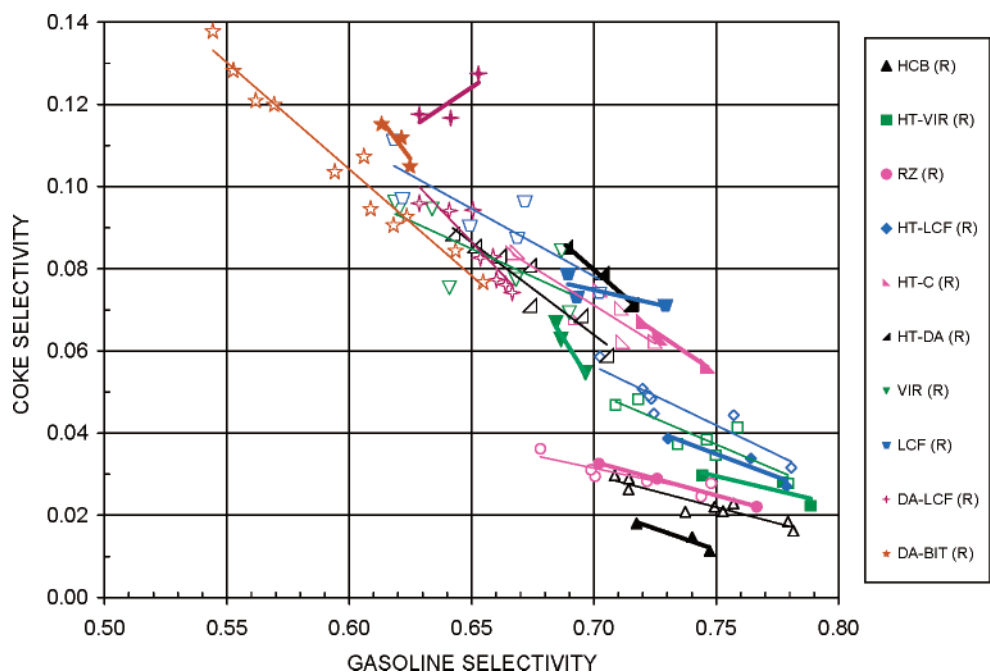
**3.1.4. Checks for Qualities of Microactivity Test and Riser Data.** Ng et al.<sup>21</sup> reported a new method that could validate a simplified four-lump model for gas oil crack-

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**Figure 5.** Relationship between H<sub>2</sub>S-excluded dry gas yield by MAT and MCR-excluded coke yield by MAT at a conversion of 65 wt %.



**Figure 6.** Dependence of coke selectivity on gasoline selectivity for feeds cracked in a riser pilot plant reactor (R, closed symbols) and a MAT unit (open symbols).

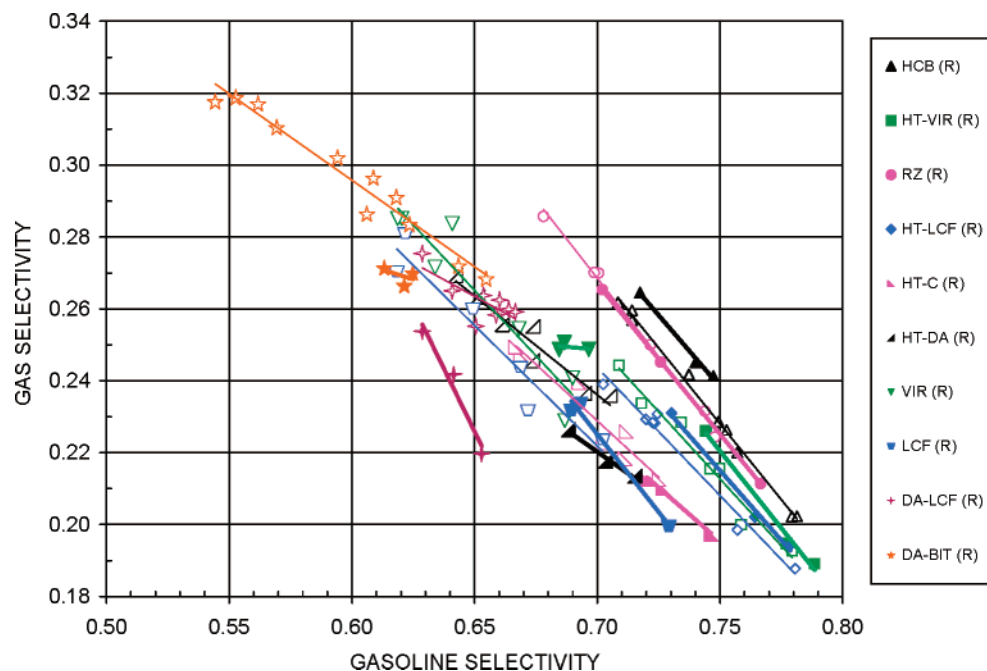
ing that has been proposed by Lee et al.<sup>22</sup> This method indicated that, if the model held true, a plot of coke selectivity (coke yield/conversion) or total gas selectivity ((dry gas + LPG yield)/conversion) versus gasoline selectivity (gasoline yield/conversion) should give a straight line. This relationship could be used to check the quality of test data from a riser reactor or MAT unit (with either a fixed or fluid bed). In case the coke yield from the MAT was determined by in situ regeneration of the spent catalyst, both the coke yield and the

conversion should be corrected against the noncatalytic "feed coke",<sup>23</sup> which is usually reflected by the MCR. The method further demonstrated that, for a given feed-catalyst system, the straight lines established from the riser reactor and MAT data were mostly parallel to each other, indicating that the rate of coke or gas formation from gasoline, relative to the gasoline overall cracking rate (to form coke and light gas), were the same, regardless of the differences in reactor type.

Figure 6 shows the linear relationship between coke selectivity and gasoline selectivity from both MAT and

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**Figure 7.** Dependence of gas selectivity on gasoline selectivity for feeds cracked in a riser pilot plant reactor (R, closed symbols) and a MAT unit (open symbols).

riser reactor studies for the 10 feeds, whereas Figure 7 depicts a similar relationship but between total gas selectivity and gasoline selectivity. For MAT selectivities, corrections were made against the feed coke, using the more realistic  $y$ -intercept value from the coke yield versus the C/O ratio plot for each feed (Figure 7a in the companion paper<sup>6</sup>) instead of the MCR content of the feed. From the two graphs, it is obvious that MAT coke selectivity gave worse correlations with gasoline selectivity than its counterpart (MAT gas selectivity), since the former was sensitive to the correction against the feed coke, because of the relatively smaller coke yields. Some of the riser runs were also far from perfect: two or all three data points were congested in rather narrow areas, rendering the established slopes inaccurate or meaningless. This was particularly serious for the four low-quality feeds (VIR, LCF, DA-LCF, and DA-BIT). Table 2 shows the values of slopes and coefficients of determination ( $R^2$ ) for all of the straight lines in Figures 6 and 7. Some key observations are given below.

(1) Based on the  $R^2$  value, gas selectivity of a feed from either a MAT unit or a riser reactor generally showed better correlation with gasoline selectivity, compared with the corresponding coke selectivity.

(2) In terms of the absolute value of the slope, the better the feed quality, the lower the slope of the line in the coke selectivity plot but the higher the slope in the gas selectivity plot.

(3) With some exceptions for the low-quality feeds, the slope values obtained from a MAT unit and a riser reactor for a given feed were similar in magnitude (i.e., the lines were almost parallel to each other) in the same series of plots. Some factors that contributed to the deviations were discussed in an earlier paper.<sup>21</sup> Essentially, the results here confirmed our previous findings.<sup>21</sup> Note that, of the 10 feeds in this study, five had been chosen to compare their cracking characteristics between fluid- and fixed-bed MAT tests, and for characterization of some liquid products (series 2). The MAT results were

**Table 2.** Slopes and Coefficients of Determination for Various Feed-Reactor Systems

reactor	Coke Selectivity versus Gasoline Selectivity		Total Gas Selectivity versus Gasoline Selectivity	
	slope	$R^2$	slope	$R^2$
HCB Feed				
MAT	-0.16	0.876	-0.84	0.995
riser	-0.21	0.918	-0.79	0.994
HT-VIR Feed				
MAT	-0.25	0.749	-0.75	0.963
riser	-0.14	0.695	-0.86	0.988
RZ Feed				
MAT	-0.13	0.797	-0.87	0.995
riser	-0.16	1.000	-0.84	1.000
HT-LCF Feed				
MAT	-0.29	0.868	-0.71	0.976
riser	-0.22	0.901	-0.78	0.991
HT-C Feed				
MAT	-0.37	0.820	-0.63	0.929
riser	-0.40	0.982	-0.60	0.992
HT-DA Feed				
MAT	-0.45	0.906	-0.55	0.935
riser	-0.52	0.985	-0.48	0.983
VIR Feed				
MAT	-0.27 <sup>a</sup>	0.574 <sup>a</sup>	-0.73	0.907
riser	-0.94 <sup>b</sup>	0.973 <sup>b</sup>	n/a <sup>b,c</sup>	n/a <sup>b,c</sup>
LCF Feed				
MAT	-0.33 <sup>a</sup>	0.742 <sup>a</sup>	-0.67	0.923
riser	-0.13 <sup>b</sup>	0.570 <sup>b</sup>	-0.87 <sup>b</sup>	0.982 <sup>b</sup>
DA-LCF Feed				
MAT	-0.63	0.809	-0.37	0.600
riser	+0.40 <sup>b</sup>	0.649 <sup>b</sup>	-1.40 <sup>b</sup>	0.958 <sup>b</sup>
DA-BIT Feed				
MAT	-0.52	0.964	-0.48	0.958
riser	-0.79 <sup>b</sup>	0.824 <sup>b</sup>	n/a <sup>b,c</sup>	n/a <sup>b,c</sup>

<sup>a</sup> Rather scattered data. <sup>b</sup> Data in a rather narrow range of gasoline selectivity and/or coke (or gas) selectivity. <sup>c</sup> Not available.

reported in a previous publication.<sup>21</sup> In that study, the reactors were loaded with 5 g of Dimension 60 catalyst at a temperature of 510 °C (versus 4 g at 500–520 °C

**Table 3. Comparison of Slopes and Coefficients of Determination in Different Reactor Systems**

reactor	Coke Selectivity versus Gasoline Selectivity		Total Gas Selectivity versus Gasoline Selectivity	
	slope	$R^2$	slope	$R^2$
HCB Feed				
MAT-fixed <sup>a</sup>	-0.16	0.876	-0.84	0.995
MAT-fixed <sup>b</sup>	-0.21	0.964	-0.79	0.997
MAT-fluid <sup>b</sup>	-0.20	0.960	-0.80	0.997
riser	-0.21	0.918	-0.79	0.994
HT-C Feed				
MAT-fixed <sup>a</sup>	-0.37	0.820	-0.63	0.929
MAT-fixed <sup>b</sup>	-0.44	0.975	-0.56	0.984
MAT-fluid <sup>b</sup>	-0.53	0.993	-0.47	0.992
riser	-0.40	0.982	-0.60	0.992
HT-DA Feed				
MAT-fixed <sup>a</sup>	-0.45	0.906	-0.55	0.935
MAT-fixed <sup>b</sup>	-0.45	0.959	-0.55	0.971
MAT-fluid <sup>b</sup>	-0.53	0.984	-0.47	0.979
riser	-0.52	0.985	-0.48	0.983
VIR Feed				
MAT-fixed <sup>a</sup>	-0.27 <sup>c</sup>	0.574 <sup>c</sup>	-0.73	0.907
MAT-fixed <sup>b</sup>	-0.53	0.983	-0.49	0.978
MAT-fluid <sup>b</sup>	-0.67	0.974	-0.33	0.897
riser	-0.94 <sup>d</sup>	0.973 <sup>d</sup>	n/a <sup>d,e</sup>	n/a <sup>d,e</sup>
DA-BIT Feed				
MAT-fixed <sup>a</sup>	-0.52	0.964	-0.48	0.958
MAT-fixed <sup>b</sup>	-0.64	0.929	-0.36	0.803
MAT-fluid <sup>b</sup>	-0.67	0.956	-0.33	0.841
riser	-0.79 <sup>d</sup>	0.824 <sup>d</sup>	n/a <sup>d,e</sup>	n/a <sup>d,e</sup>

<sup>a</sup> From this study (4 g catalyst, 500–520 °C). <sup>b</sup> From previous study<sup>21</sup> (5 g catalyst, 510 °C). <sup>c</sup> Rather scattered data. <sup>d</sup> Data in a rather narrow range of gasoline selectivity and/or coke (or gas) selectivity. <sup>e</sup> Not available.

in the present study), in conjunction with the use of an improved liquid product collection system, as mentioned previously. Table 3 compares all the slope and  $R^2$  values that have been obtained in the two studies from the MAT unit and riser reactor for the five feeds. Note that the results for gas selectivity versus gasoline selectivity have not been reported previously. Table 3 indicates that the MAT data in this study are, generally, less superior in quality, compared with the data from the previous series (based on  $R^2$  values, expected trends of slope, and similarity in slope value between MAT and riser data), probably because of the variation in reactor temperature. It was thus concluded that the linear relationship between selectivities could be used to check the qualities of riser and MAT data. The slope values in Table 3 remained in the same order for a given feed, regardless of the types of reactors and catalyst beds. In this case, feeds of better qualities gave lower absolute slopes in the coke selectivity plot but higher absolute slopes in the gas selectivity plot.

**3.2. Comparison of Individual Product Yields between the Riser Reactor and the Microactivity Test Unit.** The MAT test cannot duplicate the dynamic FCC riser operation, because of fundamental differences in features such as reactor design, hydrodynamics, catalyst contact time, and feed preheat and vaporization between the two systems. However, advances in MAT technology have made this simple tool useful to predict riser behavior through computer models, which are essentially based on data correlations between the two units. In this study, the MAT data at conversions of 55, 65, 70, and 81 wt % were interpolated or extrapolated

from yield–conversion curves in the companion paper (Part 1 of this study).<sup>6</sup> The individual product yields thus obtained were plotted against their riser counterparts that have been reported previously.<sup>2</sup> Assuming a linear correlation, the two sets of yields were examined for (i) the degree of perfection of the correlation, as reflected by the  $R^2$  value, and (ii) the relative position and the coincidence of the trend line representing the data points with the 1:1 line. The most ideal case was a trend line with  $R^2 = 1$  overlapping the 1:1 line.

**3.2.1. Dry Gas.** Figure 8 shows that the data points were well-distributed along the trend line ( $R^2 = 0.95$ ), which was almost coincident with the 1:1 line. At the same conversion, the difference in dry-gas yield between the two units could be maintained within 0.4 wt % absolute, except for VIR, which showed a difference of 0.7 wt % at a conversion of 65 wt %.

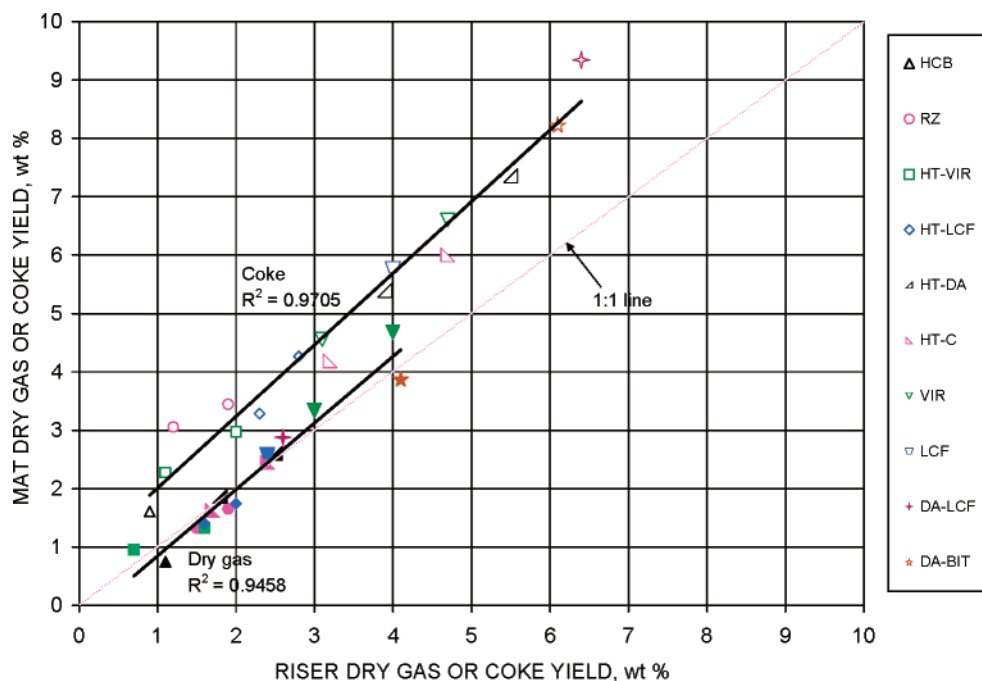
**3.2.2. Liquefied Petroleum Gas.** Figure 9 shows that the data points were rather scattered along the regression line, which intersected, at its midpoint, with the 1:1 line. The rather poor correlation, with only  $R^2 = 0.65$ , could possibly have resulted from the uncertainties in LPG analysis. The LPG, which is partially soluble in TLP and contains significant amounts of less-stable olefins, should be analyzed immediately after the degassing step. This, sometimes, might not be the case in our MAT or pilot-plant operations. Furthermore, LPG yields from both the riser reactor and the MAT were mostly confined to a rather narrow range (9–12 wt % for the riser reactor and 9–14 wt % for MAT). From a statistical standpoint, it is more difficult to obtain a good correlation than in a case where the data (containing the same error as their counterparts) were evenly spread over a wider range. In general, MAT results could be maintained within 20% of the corresponding riser yields.

**3.2.3. Gasoline.** Figure 10 shows a good correlation of gasoline yields between the MAT and riser data, with an  $R^2$  value of 0.96. However, the trend line was slightly below the 1:1 line, indicating that the MAT gasoline yield was generally smaller than its corresponding riser counterpart. At the same conversion, the difference in gasoline yield between the two units was, in most cases, <8% (relative to the riser yield).

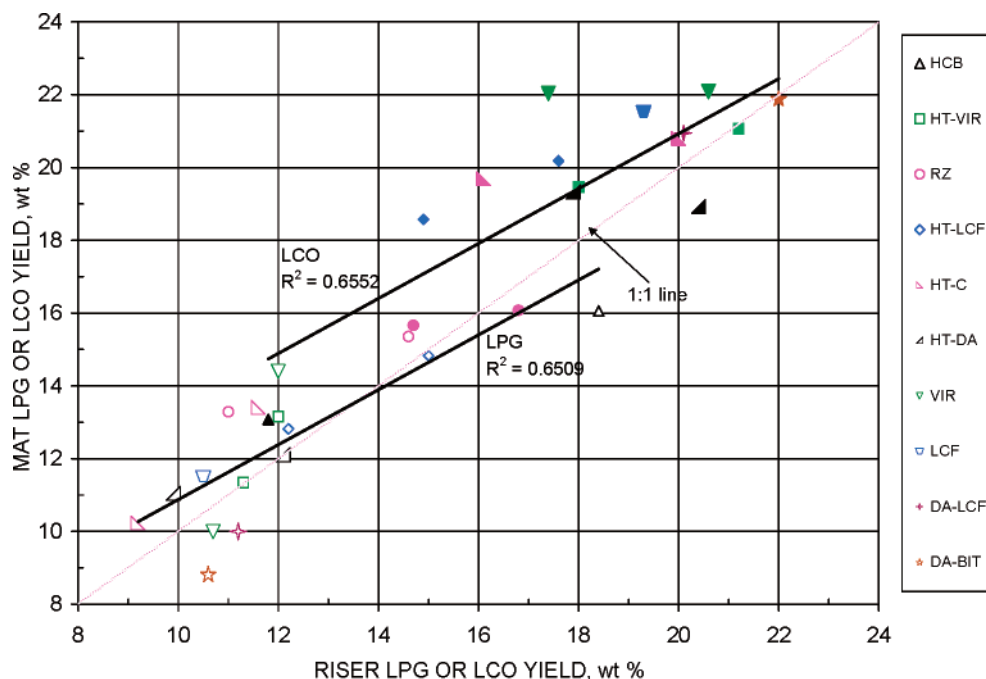
**3.2.4. Light Cycle Oil.** Figure 9 shows a relatively poor correlation of LCO yields between the two units, with an  $R^2$  value of 0.66. This might be caused by both (i) the difference in analytical techniques (the simulated distillation ASTM D 2887 method for the MAT samples versus the two distillation methods ASTM D 2892 (15 theoretical-plate fractionation) and ASTM D 1160 (1 theoretical-plate fractionation) for the pilot plant samples<sup>2</sup>) and (ii) variation of the LCO yields in a narrow range (similar to LPG, LCO yields from both the riser reactor and the MAT unit varied mostly in a rather narrow range (16–22 wt % for both the riser and MAT data)). The trend line was slightly above the 1:1 line, by 0.5–2.8 wt % MAT yield at a given riser yield. Thus, MAT LCO yield was generally greater than its corresponding riser counterpart at the same conversion. The difference in LCO yield between the two units was, in most cases, <20% (relative to the riser yield).

**3.2.5. Heavy Cycle Oil.** Figure 10 shows the good correlation of HCO yields between the MAT and riser





**Figure 8.** Correlation of MAT dry gas (closed symbols) or coke (open symbols) yield with their corresponding riser partner at the same conversion.



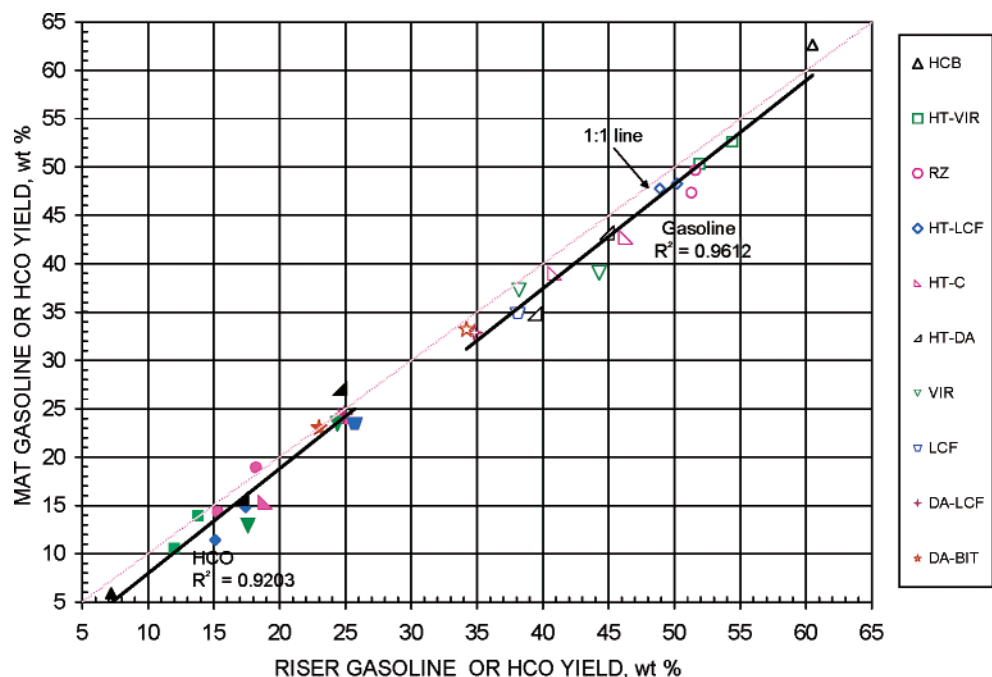
**Figure 9.** Correlation of MAT LPG (open symbols) or LCO (closed symbols) yield with their corresponding riser partner at the same conversion.

data, with  $R^2 = 0.92$ . The regression line was almost parallel to and slightly below the 1:1 line, by 0.4–2.2 wt % MAT yield at a given riser yield. This indicates that the MAT HCO yield was generally lower than its corresponding riser counterpart. At the same conversion, the difference in HCO yield between the two units was, in most cases, <20% (relative to the riser yield).

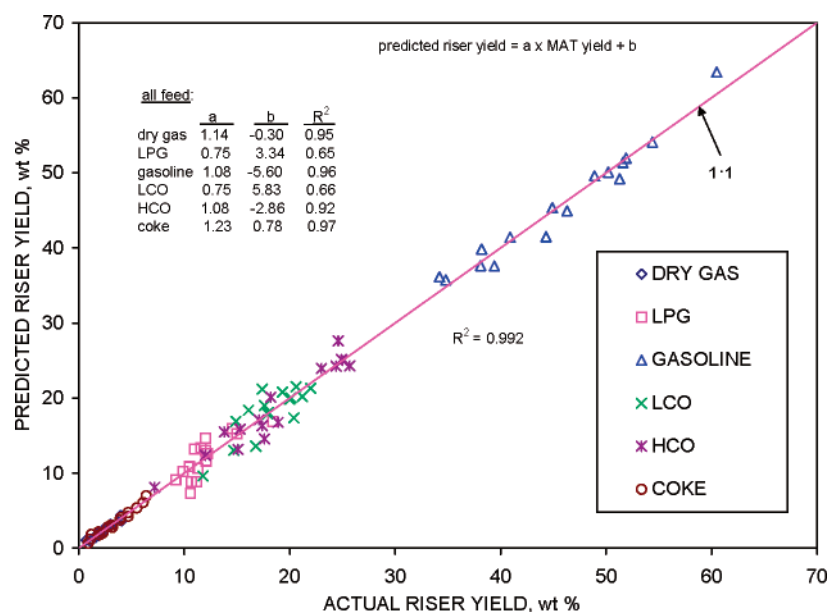
**3.2.6. Coke.** Figure 8 shows that the data points were distributed well and evenly along the trend line, with a high  $R^2$  value of 0.97. However, the trend line was above and greatly deviated from the 1:1 line (by 1.0–2.2 wt % MAT coke yield), rendering the MAT coke

yield much higher than the corresponding riser coke yield, especially for the poor-quality feeds with high MCR (e.g., the three deasphalted feeds). The deviation was caused by the following factors: (i) the non-catalytic feed coke,<sup>23</sup> as part of the total coke in the in situ combustion; (ii) the consistently higher error in coke yield determination, described previously;<sup>6</sup> and (iii) much longer catalyst contact time (30 s in the MAT, versus just a few seconds in the riser reactor), resulting in higher coke formation on the catalyst in the MAT, according to Voorhie's equation.<sup>24</sup> At the same

(24) Voorhies, A. *Ind. Eng. Chem.* **1945**, 37, 318–322.



**Figure 10.** Correlation of MAT gasoline (open symbols) or HCO (closed symbols) yield with their corresponding riser partner at the same conversion.



**Figure 11.** Correlation of predicted riser yield with actual riser yield at the same conversion.

conversion, the difference in coke yield between the two units varied from 30% to 155% (relative to the riser yield).

**3.3. Comparison of Overall Product Yields between the Riser Reactor and the Microactivity Test Unit.** The overall product yields between the two units were best represented by plotting the individual predicted riser yields based on MAT data (predicted riser yield =  $a \times \text{MAT yield} + b$ ) against the corresponding actual riser yields. This is depicted in Figure 11, which also shows the parameters  $a$  and  $b$  and the  $R^2$  values for every single set of correlations. Overall, the data points that represent the predicted and actual riser yields were reasonably close to the 1:1 line.

**3.4. Product Qualities at Different Conversions.** Table 4 shows the properties of liquid product frac-

tions at conversions of 55, 65, 70, and 81 wt % for the 10 feeds. Pilot-plant products were analyzed for sulfur (all fractions), nitrogen (LCO and HCO only), and aromatics (LCO only) contents, the research octane number (RON, gasoline only), the motor octane number (MON, gasoline only), and the cetane number (LCO only). MAT products from HT-DA, HT-C, and DA-BIT were analyzed for sulfur, nitrogen, and aromatics contents, and PIONA analyses (gasoline only), which included (i) density, (ii) aromatics content, (iii) the contents of both saturated and unsaturated naphthenes, iso-paraffins, and  $n$ -paraffins, and (iv) polynaphthenes. Figures 12–17 show the relationships of the aromatics, sulfur, and nitrogen contents with conversion for DA-BIT and HT-DA feeds. General observations are summarized below.

**Table 4. Product Properties at Different Conversions**

analyses	reactor method	55 wt % conversion						65 wt % conversion						70 wt % conversion			81 wt % conversion <sup>a</sup>
		HT-C	HT-DA	VIR	LCF	DA-LCF	DA-BIT	HT-VIR	RZ	HT-LCF	HT-C	HT-DA	VIR	HT-VIR	RZ	HT-LCF	
gasoline																	
S (wppm)	MAT-SCD riser	72	632				6971				50	646					
N (wppm)	MAT-NCD riser	53	570	5500	1550	2030	6600	4	370	80	64	410	4900	7	320	6	1
aromatics (wt %)	MAT-MSD	61.2	52				57				65.0	61.1					
RON	riser	94.9	92.9	95.7	96.0	95.1	-	93.2	91.4	94.3	96.5	95.6	96.9	95.1	92.8	95.7	91.0
MON	riser	82.2	80.5	81.3	82.0	81.3	-	80.6	80.0	80.0	83.0	82.3	83.3	82.5	80.6	80.6	80.3
density at 15.6 °C (g/mL)		0.818	0.802				0.812				0.823	0.815					
s-naphthenes (wt %)		14.7	14.2				12.6				12.5	10.9					
s- <i>i</i> -paraffins (wt %)		11.1	13.1				10.2				10.9	11.1					
s- <i>n</i> -paraffins (wt %)	MAT-PIONA	1.6	2.7				3.1				1.5	1.8					
us-naphthenes (wt %)		2.3	3.9				3.9				1.7	3.5					
us- <i>i</i> -paraffins (wt %)		3.2	6.7				5.3				2.2	5.3					
us- <i>n</i> -paraffins (wt %)		1.3	2.7				1.9				0.8	1.4					
polynaphthenes (wt %)		1.5	2.2				1.9				0.8	1.5					
aromatics (wt %)	64.8	55.0				61.3				69.7	64.9						
LCO																	
S (wt %)	MAT-SCD riser	0.55	0.66				3.67				0.50	0.75					
	MAT-NCD riser	0.41	0.63	3.37	1.54	1.42	3.10	0.13	0.87	0.10	0.49	0.76	4.10	0.13	1.03	0.10	<0.01
N (wppm)	MAT-MSD	540	461				541				520	333					
	riser	1110	1000	750	1520	1500	900	250	390	670	1040	1060	760	290	420	600	3
aromatics (wt %)	MAT-MSD riser	88.0	79.3				84.7				90.1	83.8					
	riser	88.0	78.9	89.1	87.6	81.0	84.7	87.6	71.5	90.3	94.2	89.2	95.0	91.7	79.0	93.8	65.9
cetane number	riser	18.8	24.3	19.0	19.6	19.8	-	20.7	23.5	18.9	18.4	20.7	18.5	21.0	20.8	18.5	23.6
HCO																	
S (wt %)	MAT-SCD riser	1.16	0.92				4.81				1.70	1.15					
	MAT-NCD riser	1.09	0.96	3.92	2.02	2.21	4.06	0.37	1.45	0.30	1.22	1.14	4.15	0.39	1.69	0.32	<0.01
N (wppm)	MAT-MSD	3500	3210				3815				4000	3621					
	riser	3400	2990	2500	3800	4300	2980	1100	1300	2300	3100	3530	2000	1200	1500	2100	4
aromatics (wt %)	MAT-MSD	84.3	73.4				82.3				87.0	74.0					

<sup>a</sup> For a conversion of 81 wt %, the only feed was HCB.

**3.4.1. Aromatics.** Because of the uncrackable nature of aromatic rings at low pressure, FCC is essentially an aromatics-enriching process. Table 4 (for all feeds) and Figures 12 and 13 (for DA-BIT and HT-DA, respectively) indicate that the aromatics content increased as conversion increased for all three fractions, among which LCO showed the highest contents at the same conversion. This was because the aromatics in LCO (mostly diaromatics) were relatively stable, whereas the heavier aromatics in HCO could form coke. Generally, the aromatics content of a product fraction at a given conversion was somewhat proportional to that of the feed. In Table 4, the aromatics contents of LCO from DA-BIT, HT-DA, and HT-C were comparable between the MAT unit and the pilot plant, especially at a conversion of 55 wt %.

**3.4.2. Sulfur.** Table 4 indicates that, for the same feed, the sulfur content of gasoline tended to decrease or change slightly, but that of LCO and HCO increased at higher conversion. The more-detailed results in Figures 14 and 15 (for DA-BIT and HT-DA, respectively) show some concave trends in sulfur with conver-

sion. This observation suggests that, for each product fraction, there could be several major competing reactions:

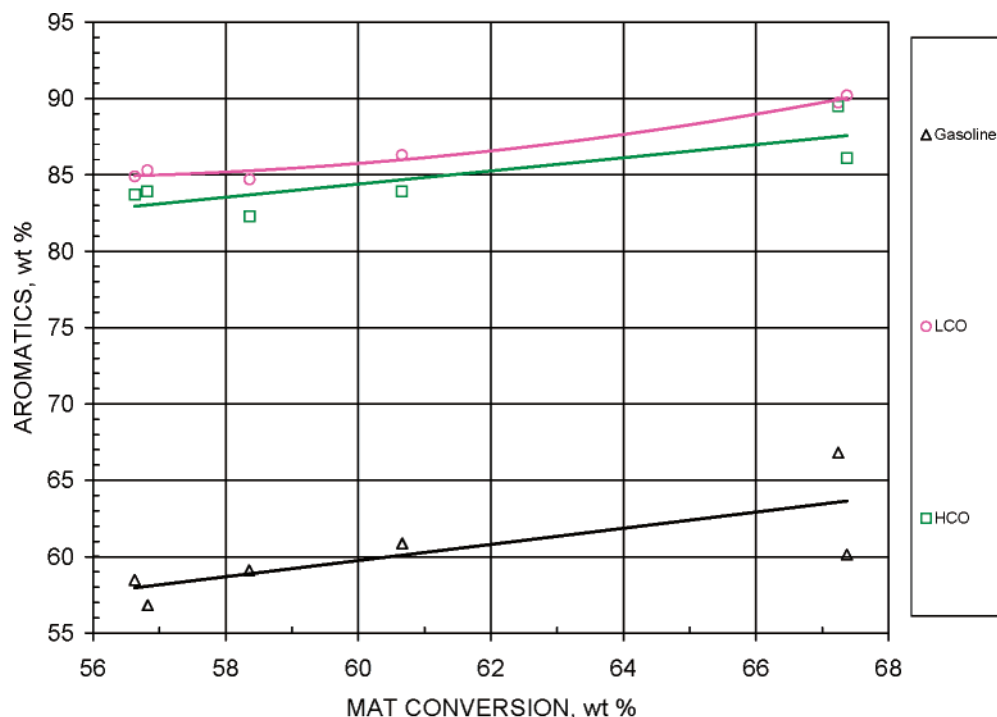
(1) Sulfur removal through the breaking of the S–C bonds, which produces H<sub>2</sub>S (this was more pronounced in the gasoline fraction of the two feeds (see Figures 14 and 15), and in the LCO and HCO fractions of the untreated feed DA-BIT (see Figure 14), which contained more easy-to-crack sulfur species, such as mercaptans and sulfides).

(2) The reduction in molecular size of compounds without affecting the S atom.

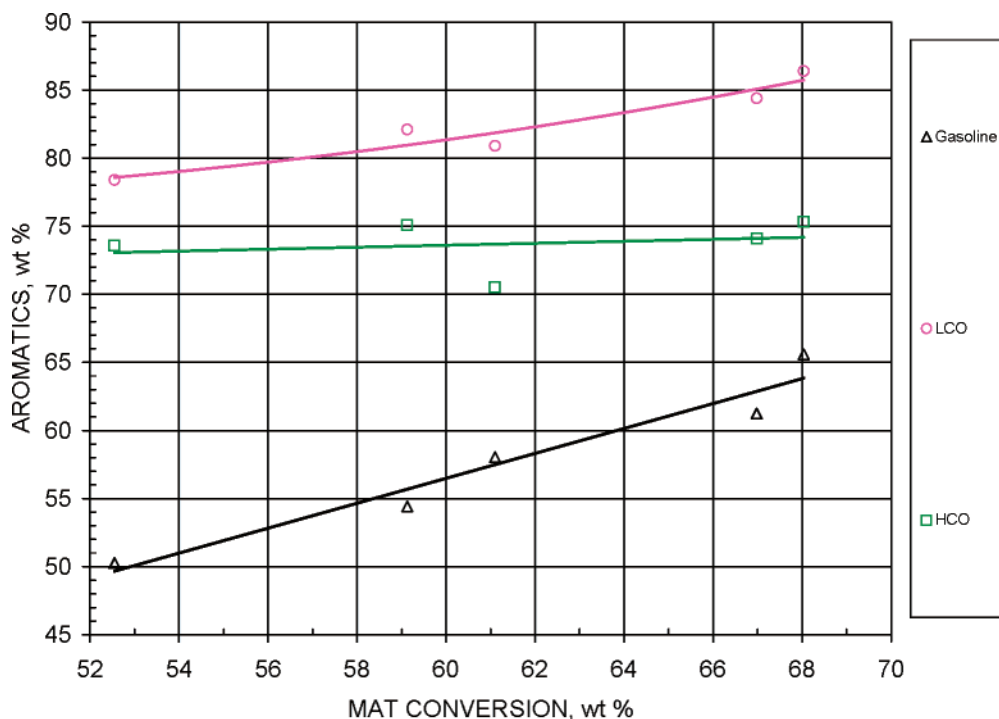
(3) Sulfur enrichment due to the concentration of the sulfur-containing aromatics as conversion increased (this was especially evident in LCO and HCO).

(4) The formation of coke, on the catalyst surface, from the high-molecular-weight aromatics that contained sulfur. This mainly occurred in the HCO fraction.

The observations in Figures 14 and 15 were essentially the net effect of these reactions. In Table 4, the order of sulfur concentrations in each product cut corresponded to the order of the sulfur concentrations



**Figure 12.** Effect of MAT conversion on aromatics concentration of product cut for DA-BIT feed.



**Figure 13.** Effect of MAT conversion on aromatics concentration of product cut for HT-DA feed.

in the feeds, similar to the case of aromatics. It was also noticed that at the same conversion, sulfur contents of each fraction between the MAT unit and the pilot plant were comparable for the same feed. In addition, the sulfur concentration agreed, in order, with the boiling point of a product cut. Table 5 confirms the findings in the literature that, as a rule of thumb, LCO has approximately the same sulfur content as the feed for many FCC units.<sup>15,25</sup>

**3.4.3. Nitrogen.** The trend that nitrogen concentration varied with conversion was determined by the net effect of the major reactions, which were similar to those for

sulfur, except that (i)  $\text{NH}_3$  was released when the light and crackable nitrogen species (e.g., amines and amides) decomposed; (ii) some saturated nitrogen compounds were possibly dehydrogenated under FCC conditions (for example, piperidine was converted to pyridine);<sup>26</sup> (iii) the basic nitrogen species, especially the polyaromatic

(25) Letzsch, W. S.; Ashton, A. G. The Effect of Feedstock on Yields and Product Quality. In *Fluid Catalytic Cracking: Science and Technology*; Magee, J. S., Mitchell, M. M., Jr., Eds.; Studies in Surface Science and Catalysis 76; Elsevier Science Publishers B. V.: Amsterdam, 1993; p 493.

(26) Fu, C. M.; Schaffer, A. M. *Ind. Eng. Chem. Prod. Res. Dev.* **1985**, *24*, 68–75.



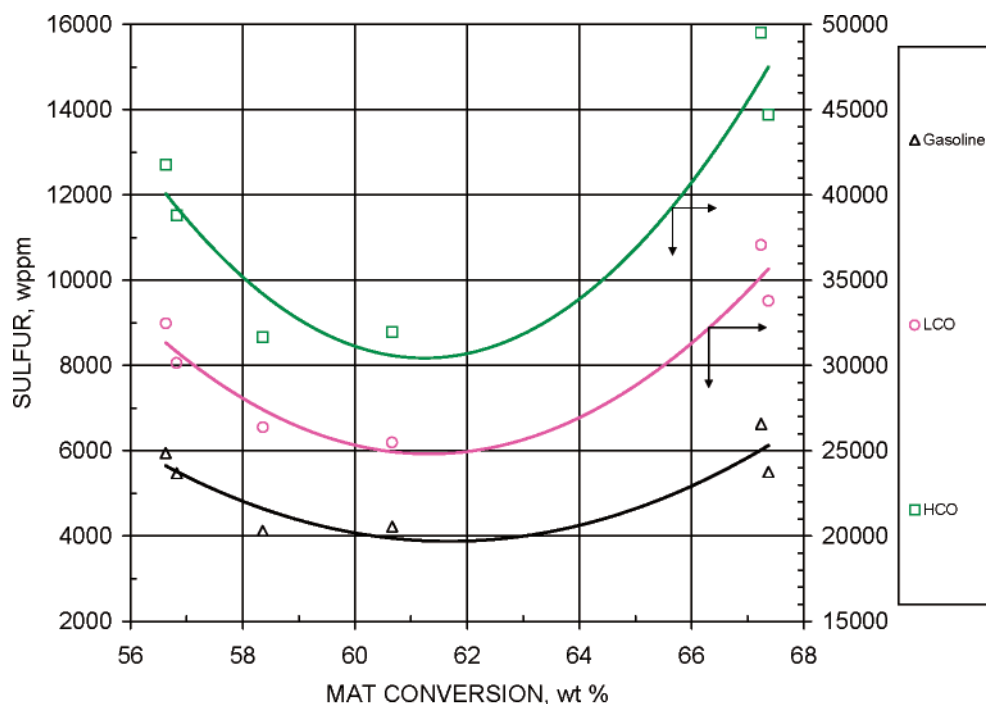


Figure 14. Effect of MAT conversion on sulfur concentration of product cut for DA-BIT feed.

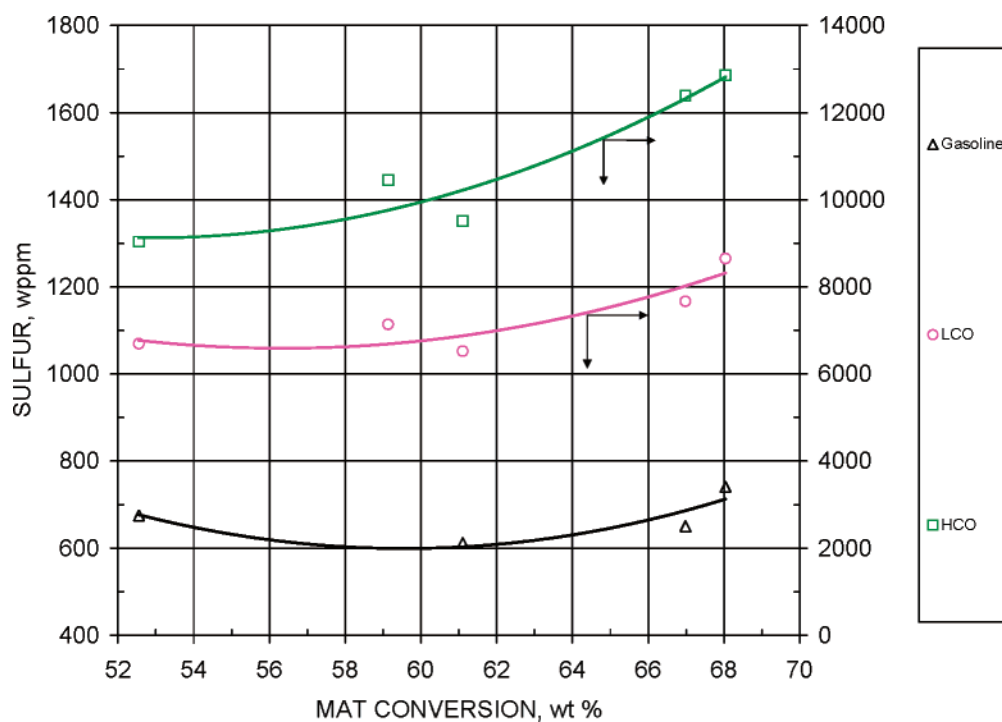


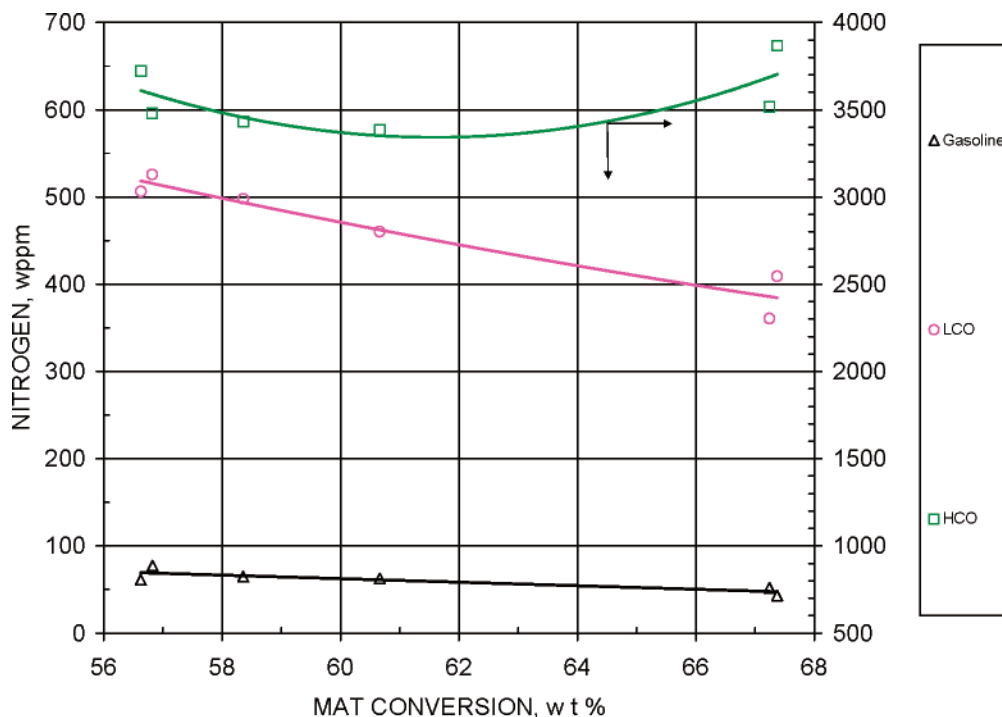
Figure 15. Effect of MAT conversion on sulfur concentration of product cut for HT-DA feed.

Table 5. Comparison of Feed Sulfur with LCO Sulfur

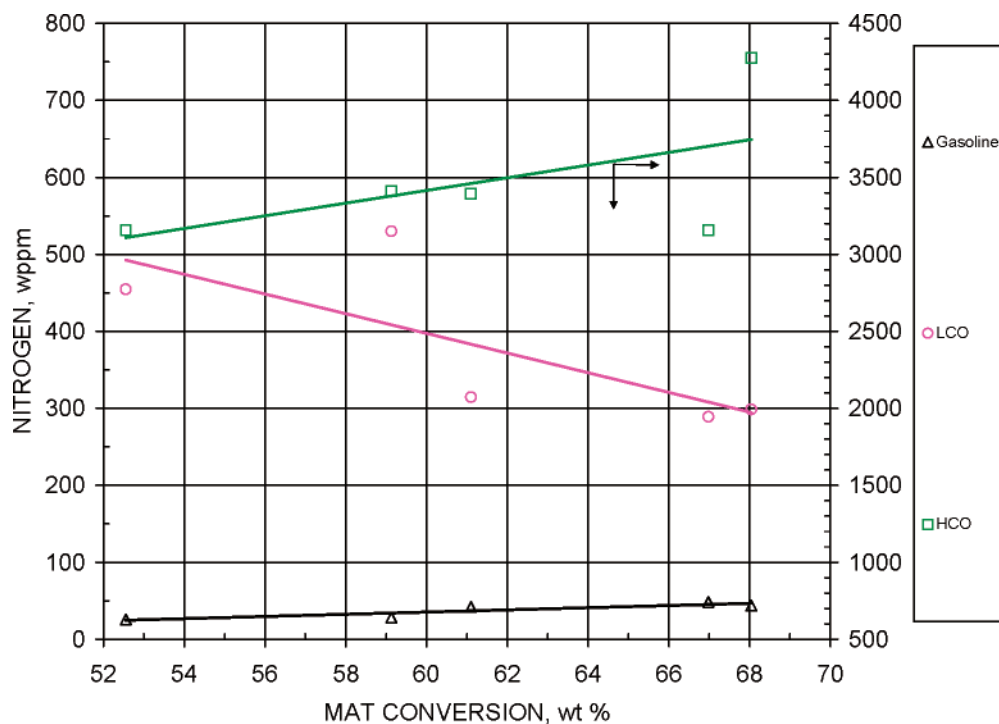
	HCB	HT-VIR	RZ	HT-LCF	HT-C	HT-DA	VIR	LCF	DA-LCF	DA-BIT
feed sulfur content (wt %)	<0.001	0.10	0.92	0.09	0.43	0.70	3.25	1.35	1.52	3.54
LCO sulfur content (wt %)										
MAT, 55 wt % conversion					0.55	0.66				3.67
MAT, 65 wt % conversion					0.50	0.75				
riser, 55 wt % conversion					0.41	0.63	3.37	1.54	1.42	3.10
riser, 65 wt % conversion		0.13	0.87	0.10	0.49	0.76	4.10			
riser, 70 wt % conversion		0.13	1.03	0.10						
riser, 81 wt % conversion	<0.01									

bases, could be irreversibly adsorbed onto the catalyst surface to form the additive coke<sup>27</sup> and partially removed from the liquid product; and (iv) the aromatic

nitrogen species could not be saturated and, therefore, the C=N bond could not be broken under FCC conditions. Thus, the possible routes or reactions that are



**Figure 16.** Effect of MAT conversion on nitrogen concentration of product cut for DA-BIT feed.

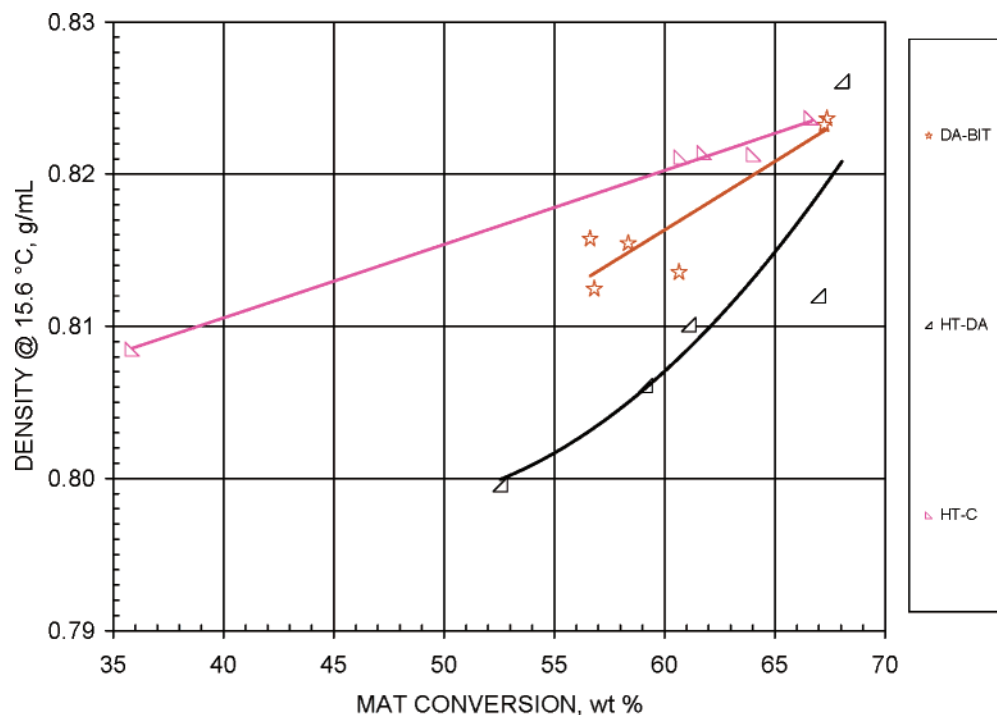


**Figure 17.** Effect of MAT conversion on nitrogen concentration of product cut for HT-DA feed.

responsible for the changes in nitrogen concentrations in the product cuts were more complicated than those for sulfur. Table 4 (for all feeds) and Figures 16 and 17 (for DA-BIT and HT-DA, respectively) show a slight increase or decrease in nitrogen for gasoline but moderate changes (increase or decrease) in nitrogen for LCO and HCO, as the conversion increased. The observed decreases in nitrogen for gasoline and LCO with increasing conversion and for HCO at lower conversion (see Figure 16) seem to suggest that the untreated DA-BIT contained more crackable nitrogen species in all three product fractions than HT-DA (see Figure 17). As

in the case of sulfur, the nitrogen levels in the same product fraction were consistent with those of the feeds. At the same conversion and for the same feed, nitrogen contents of each fraction between the MAT unit and the pilot plant were comparable, except that, in the LCO fraction, nitrogen from the MAT was consistently lower (by ~50%). In addition, the nitrogen concentration agreed, in terms of order, with the boiling point of a product cut.

(27) Venuto, P. B.; Habib, E. T., Jr. *Fluid Catalytic Cracking with Zeolite Catalysts*; Chemical Industries 1; Marcel Dekker: New York, 1979; p 74.



**Figure 18.** Effect of MAT conversion on density of gasoline for feeds DA-BIT, HT-DA, and HT-C.

**3.4.4. PIONA Analyses of Gasoline.** 3.4.4.1. Hydrocarbon Types. Table 4 shows the slight decreases (by <2 wt %, except saturated naphthenes, which decreased by 2–3 wt %) in polynaphthenes, saturated or unsaturated naphthenes, iso-paraffins, and *n*-paraffins, but a significant increase (by 5–10 wt %) in aromatics content of the gasoline fraction for HT-DA and HT-C feeds, as the conversion increased from 55 wt % to 65 wt %. Between the two feeds, HT-C showed smaller changes in hydrocarbon type of the gasoline than HT-DA. Table 4 also indicates that aromatics contents of gasolines determined by PIONA were higher by 3–5 wt % than those obtained using a GC–MSD. This was mainly attributed to the difference in analytical methods, rather than the difference in cut points of gasolines (IBP–200 °C for PIONA analysis versus IBP–220 °C using a GC–MSD).

**3.4.4.2. Density.** Table 4 and Figure 18 show that, at the same conversion, gasoline from HT-DA had the lowest density, followed by those from DA-BIT and HT-C. This observation is a reflection of the aromatics contents in the gasolines. As the conversion increased, the density of gasoline fraction from each feed increased and approached each other at a higher conversion, because of the gradual depletion of crackable saturates and unsaturates in gasoline.

**3.4.4.3. Octane Numbers.** The octane rating of a gasoline measures its knocking characteristics, as determined by a standard ASTM engine test. The research octane number (RON) reflects the fuel performance under low-severity engine operation (city driving conditions), whereas the motor octane number (MON) simulates more-severe operations (highway driving conditions). Table 4 indicates that, for the same feed, the RON and MON values increased by 0.12–0.38 and 0.08–0.38, respectively, for each weight percent increase in conversion. This was primarily due to the aromatics enrichment in gasoline at a higher conversion<sup>28,29</sup> where

the low-octane *n*-paraffins and saturated naphthenes were also reduced through cracking to form LPG. Table 4 also indicates that, generally, at the same conversion, the more aromatics in the feed, the higher the gasoline octane numbers.

**3.4.5. Cetane Number of Light Cycle Oil.** The cetane number is a rating for diesel fuel and is comparable to the octane numbers for gasoline. This number indicates the ability of a fuel to ignite quickly after being injected into the cylinder of a diesel engine. A fuel with a long ignition delay in a high-speed diesel engine tends to produce rough operation. Contrary to the octane numbers, the cetane number of a fuel decreases as its aromatics content increases. Table 4 shows that, for the same feed, the cetane number decreased by 0.04–0.54 (except for HT-VIR, which had an increase of 0.06) for each weight-percent increase in conversion. Generally, at the same conversion, more-aromatic feeds produced LCOs with lower cetane numbers.

**3.5. Improvement in Product Yield and Quality after Feed Treatment.** In this study, VIR and LCF feeds were hydrotreated at 380 °C, 1276 psig, and an LHSV value of 1 h<sup>−1</sup> using a typical NiMo catalyst, whereas DA-BIT was hydrotreated under typical LC–Finer operating conditions to produce HT-VIR, HT-LCF, and HT-DA, respectively. Hydrotreatment of these feeds not only reduced the impurities and aromatics<sup>6</sup> but also significantly improved the yield structures and the product qualities upon cracking. Table 6 shows the augmentation of the gasoline yield at the expense of dry gas, LPG, and coke, with no change in cycle oil (LCO + HCO) content, when the conversion increases from 55 wt % to 65 wt %. Generally, in each product fraction after hydrotreatment, decreases in the sulfur, nitrogen, and aromatics contents but increases in the cetane

(28) O'Connor, P. Presented at the Ketjen Catalyst Symposium, Scheveningen, The Netherlands, May 1988, Paper F-1.

(29) Corma, A.; Orchillés, A. V. *J. Catal.* **1989**, *115*, 551.

Table 6. Improvements in Yield Profile and Product Quality

product	reactor	55 wt % conversion						65 wt % conversion								
		DA-BIT	HT-DA	diff.	LCF	HT-LCF	diff.	DA-BIT	HT-DA	diff.	LCF	HT-LCF	diff.	VIR	HT-VIR	diff.
Yields (wt %)																
dry gas	MAT	3.9	1.9	-2.0	2.6	0.9	-1.7	5.1	2.6	-2.5	3.7	1.4	-2.3	4.7	1.0	-3.7
	riser	4.1	1.8	-2.3									4.0	0.7	-3.3	
LPG	MAT	8.8	11.0	2.2	11.5	8.8	-2.7	12.5	12.1	-0.4	15.3	12.8	-2.5	14.4	11.3	-3.1
	riser	10.6	9.9	-0.7									12.0	11.3	-0.7	
gasoline	MAT	33.3	34.8	1.5	34.9	42.8	8.0	36.4	43.2	6.8	37.3	47.8	10.5	39.0	50.3	11.3
	riser	34.2	39.4	5.2									44.3	51.9	7.6	
LCO	MAT	21.9	17.9	-4.0	21.5	21.1	-0.4	20.4	19.3	-1.1	21.2	20.2	-1.0	22.0	21.1	-1.0
	riser	22.0	20.4	-1.6									17.4	21.2	3.8	
HCO	MAT	23.1	27.1	4.0	23.5	23.9	0.4	14.6	15.7	1.1	13.8	14.8	1.0	12.9	13.9	1.0
	riser	23.0	24.6	1.6									17.6	13.8	-3.8	
coke	MAT	8.2	5.4	-2.8	5.8	1.9	-3.8	11.2	7.4	-3.8	8.2	3.3	-4.9	6.6	2.3	-4.3
	riser	6.1	3.9	-2.2									4.7	1.1	-3.6	
Product Properties																
gasoline																
S (wppm)	MAT	6971	632	-6339				4643	646	-3997						
	riser	6600	570	-6030									4900	4	-4896	
N (wppm)	MAT	75	30	-45				52	42	-10						
	aromatics (wt %)	57	52	-5				62.4	61.1	-1.3						
RON	riser												96.9	93.2	-3.7	
MON	riser												83.3	80.6	-2.7	
LCO																
S (wt %)	MAT	3.67	0.66	-3.01				3.00	0.75	-2.25						
	riser	3.10	0.63	-2.47									4.10	0.13	-3.97	
N (wppm)	MAT	541	461	-80				411	333	-78						
	riser	900	1000	100									760	250	-510	
aromatics (wt %)	MAT	84.7	79.3	-5.4				88.3	83.8	-4.5						
	riser	84.7	78.9	-5.8									95.0	87.6	-7.4	
cetane number	riser												18.5	20.7	2.2	
HCO																
S (wt %)	MAT	4.81	0.92	-3.89				3.87	1.15	-2.72						
	riser	4.06	0.96	-3.10									4.15	0.37	-3.78	
N (wppm)	MAT	3815	3210	-605				3511	3621	110						
	riser	2980	2990	10									2000	1100	-900	
aromatics (wt %)	MAT	82.3	73.4	-8.9				86.5	74.0	-12.5						

number were observed. The only negative impact was that the octane numbers decreased, because of the lower aromatics content in gasoline.

#### 4. Conclusions

(1) Based on linear correlations, yields of maximum gasoline and optimum light cycle oil (LCO) could be estimated from the precursors concentrations of gasoline and LCO, respectively. The higher the aromatics content of the feed, the lower the conversion at which the maximum gasoline yield occurred.

(2) Yield profiles of H<sub>2</sub>S-free dry gas were similar in shape and relative position to those of microcarbon residue (MCR)-excluded coke for all feeds except DA-BIT. Quite possibly, H<sub>2</sub>S-free dry gas and catalytic coke were formed in proportion from common sources, e.g., gasoline and/or butenes.

(3) Microactivity test (MAT) and riser data could be checked for quality from plots of coke (or total gas) selectivity against gasoline selectivity. The slope values obtained from MAT and riser data for a given feed under the same test conditions should be similar in magnitude (i.e., the lines were almost parallel to each other). In terms of the absolute value of the slope, the better the feed quality, the lower the slope of the line in the coke selectivity plot but the higher the slope in the gas selectivity plot.

(4) MAT yields could be correlated with riser pilot-plant results, although their absolute values could be different. Generally, except for coke yield, the bias in MAT yields, relative to those of the riser pilot plant, could be maintained within 15%.

(5) Analyses using a gas chromatograph with a mass-selective detector (GC-MSD) indicated that, at a higher conversion, the aromatics concentrations of all three liquid product fractions increased, among which LCO had the highest aromatics concentration. PIONA analyses also confirmed the increase in aromatics content and the decreases in saturates and unsaturates with conversion in the gasoline fraction. The enrichment of aromatics enhanced the octane numbers of gasoline but reduced the cetane number of LCO. For the same reason, an aromatics-rich feed produced gasoline with higher octane numbers but LCO with a lower cetane number.

(6) Regardless of the cracking units, the LCO that was produced had approximately the same sulfur content as the feed.

(7) Generally, at the same conversion and for the same feed, the sulfur, nitrogen, and aromatics contents of each product fraction from the MAT unit were comparable in magnitude with their individual counterparts from the riser reactor.

(8) The hydrotreatment of low-quality feeds not only reduced their impurities and aromatics but also significantly improved the yield structures and the product qualities upon cracking.

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