

## JET FUELS FROM SHALE OIL BY SINGLE-STAGE HYDROCRACKING

A. M. Tait and A. L. Hensley  
Amoco Oil Company

### ABSTRACT

Extensive screening of novel catalysts has led to the development of a single catalyst capable of the direct upgrading of a whole shale oil into high yields of jet fuels on a once-through basis. To maximize jet fuels a catalyst must have the ability to sequentially saturate, denitrogenate, and hydrocrack the feedstock in the presence of high levels of contaminants such as organic nitrogen compounds and ammonia while maintaining high selectivity toward jet fuel boiling-range material. Catalysts incorporating these functions, along with high temperature stability, were developed by optimization of both chemical and physical properties. The effectiveness of the final single catalyst for the direct upgrading of an Occidental shale oil has been demonstrated in a 100-day test. The feed, containing approximately 15 wt% JP-4 material and 13,000 ppm nitrogen, was upgraded to a water-white product containing approximately 75 wt% JP-4 material and 1 to 3 ppm nitrogen. The hydrogen consumption was 1800 to 1900 SCFB.

### INTRODUCTION

Development of new processes and catalysts to enable U.S. refiners to produce conventional products from unconventional raw materials such as shale oil, tar sands, coal liquids, and heavy petroleum residues is especially important now because of national concerns for the price, quality, and stability of supply of petroleum products. Various sources have estimated that U.S. reserves of shale and tar sands oil are more than four times that of conventional oil and could provide a secure source of energy for about 100 years if economic means can be found to convert these reserves to usable products.

Given this impetus, the U.S. Air Force and Wright-Patterson Air Force Base entered into a 19-month contract with Amoco Oil late in 1979 to develop a catalyst for increased jet fuel production from shale oil. Although other companies have conducted more extensive process and design work, Amoco's investigation was limited to the development of improved catalysts. However, in order to test catalysts, a processing scheme was required, and we chose to develop a single catalyst capable of the direct conversion of the shale oil into jet fuel boiling-range material on a once-through basis.

The contract called for four major tasks:

- I. A process variable study on existing proprietary catalysts.
- II. A catalyst composition study, i.e., metals concentration and support.

III. A catalyst physical properties study.

IV. An activity maintenance test on the preferred catalyst.

Results have been presented previously for the first two tasks.

Table I shows analytical data for three shale oils. Although such oils are basically similar to petroleum crudes with respect to chemistry (i.e., the same types of compounds are present but in different relative amounts), they do exhibit some unique properties.

Shale oils typically have high pour points dictating on-site processing or the use of wax modifiers or heated transportation pipelines for off-site processing. The H/C atomic ratios are on the low end of the scale for petroleum crudes and hence upgrading will require additional hydrogen to produce equivalent product qualities. The high nitrogen content of up to two or more percent is an order of magnitude higher than for petroleum crudes and represents the major upgrading difficulty since organic nitrogen compounds act as severe poisons for downstream catalytic cracking and reforming processes and cause product instability.

Thus, to maximize jet fuels from shale oils, a catalyst must have the ability to sequentially saturate, denitrogenate, and hydrocrack the feedstock in the presence of high levels of contaminants such as organic nitrogen compounds and ammonia while maintaining high selectivity towards the jet fuel boiling-range material.

#### RESULTS AND DISCUSSION

The Occidental shale oil was used throughout the study. Although the oil contained 26 ppm arsenic and about 60 ppm iron plus nickel, it was not pretreated nor was a guard chamber used to remove these contaminants.

The initial process variable study on existing proprietary catalysts indicated that a catalyst containing cobalt, chromium, and molybdenum salts on an alumina support could effectively remove nitrogen and effect moderate conversion of the feed into JP-4 jet fuel boiling-range material. Initial product qualities at one set of processing conditions are shown in Table II. For this catalyst, nitrogen removal was found to be first order in nitrogen and hydrogen pressure.

The next study on catalyst composition included optimization of the metal oxide concentrations and the support composition. Catalysts were prepared with various combinations of metal oxides on alumina and screened at 780°F, 1800 psig and 0.5 LHSV. The optimized metal oxide loadings were determined to be 1.5% cobalt oxide, 10% chromium oxide and 15% molybdenum oxide. Although the presence of the chromium oxide actually lowered denitrogenation activity, the 10% level was required to impart high temperature stability to the catalyst.

For the support composition, catalysts with the optimized metal loadings were prepared on different supports. The most active catalysts were

prepared on supports of alumina, 20% silica on alumina, and 30% Ultrastable (US) sieve on alumina. Results are shown in Figure 1 in a plot of relative activity for denitrogenation versus days on oil. The activities given are based on first-order kinetics and are relative to the 1.5% CoO/10% Cr<sub>2</sub>O<sub>3</sub>/10% MoO<sub>3</sub> catalyst (Activity = 100) prepared on the same alumina as was used for the catalysts previously mentioned. These results indicate a 60% to 100% increase in nitrogen removal activity when acid functions are introduced into the support.

Table III shows how the increased activity affects product qualities for these three systems. Compared to the alumina system, the 20% silica/alumina and the 30% US sieve/alumina catalysts gave almost complete nitrogen removal. The presence of silica did not, however, affect other product qualities whereas incorporation of the US sieve resulted in a significant increase in cracking activity, resulting in a lower pour point and a high yield of JP-4 boiling-range material.

Based on these results, the US sieve-containing catalyst appeared promising for the direct hydrocracking of the shale oil. Consequently, additional catalysts with various US sieve contents and the optimized metal loadings were prepared and screened at 780°F, 1800 psig and 0.5 LHSV. Figures 2 and 3 summarize pertinent results.

The effect of increasing sieve content from 20 to 50 wt% was to almost double the JP-4 yields from approximately 40 to 77 wt% with a corresponding decrease in both the diesel and gas oil fractions. The C<sub>1</sub>-C<sub>4</sub> gas make increased moderately from 3.7 to 5.6 wt%. It should be noted that the yield structures for the catalyst containing 20 wt% sieve were not much different from the pure alumina based catalyst. At the 50% sieve level, approximately 95% of the product boiled below 650°F. As expected, the increase in JP-4 yield was accompanied by a smooth increase in the hydrogen consumption from approximately 1400 SCFB to approximately 1900 SCFB, Figure 3.

For the three sieve catalysts, activity maintenance for jet fuel production is detailed in Figure 4. Both the 20% and 30% sieve-containing catalysts initially give high yields of JP-4 but rapidly lost activity to give lined out yields of approximately 50 and 35 wt% JP-4. For comparison, the nonsieve-containing catalyst yielded a constant 38 wt% JP-4 over the same time period. The 50% US sieve catalyst maintained the higher activity for JP-4 production and appeared to undergo a less severe loss in activity.

The estimated JP-4 yields used in Figure 4 were obtained from Figure 5, which represents a correlation between JP-4 yields from simulated distillation data and whole product API gravities. The solid data points represent all previously tested US sieve-containing catalysts whereas the open points represent all other catalysts previously tested, independent of support type or metals loading, and all 50% US sieve alumina catalysts tested subsequently. The correlation can be represented by:

$$\text{JP-4, Wt\%} = 3.46 \text{ API}^{\circ} - 98$$

Simulated distillation data agreed within one to two percentage points with actual distillation data for all samples so that Figures 4 and 5

represent actual yields of JP-4 to a high degree of accuracy. This correlation proved valuable for monitoring catalyst cracking activities on a daily basis.

Results from the previous task indicated that the 1.5/10/15 catalyst on a 50% US sieve/alumina support was the system of choice for further investigation. The catalyst resulted in low product nitrogens and gave highest yields of JP-4 material with the lowest cracking activity decline rate.

To this point, catalyst physical properties were kept within fairly narrow ranges for sets of catalyst within each task. With the metals optimized, and the support type and composition determined, the next task was designed to optimize the support physical properties.

Eight supports, consisting of 50% US sieve in alumina, were prepared to give a range for each of three physical properties as detailed in Table IV. These variations were achieved by modification of the alumina component, since modification of the sieves themselves could destroy their original nature and their inherent activity for cracking.

Data for the screening runs at 780°F and 1800 psig are given in Table V. Since the previous tasks had demonstrated that high sieve-containing catalysts could reduce the nitrogen content to less than 10 ppm at 0.5 LHSV, the possibility existed that all eight of the above-detailed catalysts could exhibit similar high nitrogen removal at that space velocity and hence negate the purpose of the task. To avoid that possibility, each catalyst was additionally tested at the higher space velocity. At constant sieve content, the relationship between JP-4 yield and hydrogen consumption for these eight catalysts is shown in Figure 6. Hydrogen consumption appears to increase linearly with JP-4 yields in the range of approximately 40 to 70 wt%. (See also Figure 3.) Below approximately 40 wt% JP-4, hydrogen consumption increased with little increase in product JP-4, probably as a result of saturation reactions required prior to cracking reactions. Above approximately 70 wt% JP-4, hydrogen usage appears to increase more rapidly than JP-4 content, probably as a result of additional long-chain paraffin cracking which, in addition, reduces product pour point.

A relationship between pour point and JP-4 yield for these eight US sieve-containing catalysts is given in Figure 7, which indicates a rapid drop in JP-4 yield for whole products with pour points greater than about 40°F. Data for the 20%, 30%, and 50% US sieve catalysts tested previously can also be represented by Figure 7.

The effect of product nitrogen on JP-4 yield is shown in Figure 8. The results indicate that JP-4 yield remained at approximately 30 wt% for product nitrogen above 600 ppm and increased with decreasing nitrogen content. To produce a product with approximately 50 wt% percent JP-4, product nitrogen must be reduced to approximately 10 ppm. Product nitrogen must be virtually eliminated to produce JP-4 yields of approximately 70 wt% or more.

Hydrogen usage to achieve these levels of product nitrogens is shown in Figure 9. About 1550 SCFB of hydrogen was required for 10 ppm product nitrogen (50% JP-4 yield). About 400 SCFB additional hydrogen was required to decrease product nitrogen to near zero and to increase JP-4 yields to 80%. These results are instructive in that correlations important to the overall hydrocracking scheme have been developed within this set of catalysts.

Nitrogen removal kinetic plots for these catalysts are shown in Figure 10. Of the eight catalysts tested, only one, 3838-023, performed well at both 0.5 and 0.75 LHSV with respect to nitrogen removal in particular, conversion, and activity maintenance at the lower throughput. Nitrogen removal for this catalyst appears to be first order as shown in Figure 10, whereas all other catalysts display less than first-order (or mixed-order) kinetics. This type of kinetic behavior is perhaps a reflection upon nitrogen removal efficiency and suggests an axial dependence on nitrogen content, or an accelerating nitrogen removal reaction promoted by the sieve itself.

In general, it is difficult to obtain correlations between the physical properties of catalysts containing molecular sieves and catalyst performance because of the complexity of the systems. Figure 11, however, does reflect a correlation between catalyst average pore diameters (calculated as  $4V \times 10^4/A$ ) and product nitrogen. At 0.75 LHSV, the correlation is reasonable but is somewhat less so at 0.5 LHSV. Both sets of results indicate that greatest nitrogen removal occurs with the catalysts of smallest average pore diameters. The two best catalysts in the series, 3838-023 and 3838-039, have APD's close to 700A, but only the former is "efficient" at both space velocities and has the highest cracking activity and best activity maintenance. Comparison of the pore size distributions for these two catalysts indicates a sharper distribution of pores for catalyst 3838-023 when compared to catalyst 3838-039. All other catalysts in this series, with one exception, have broader pore size distributions. Other catalyst physical properties, namely surface area and pore volumes, did not show any correlation with product nitrogens.

Results from the catalyst physical properties study indicated that for high denitrogenation and cracking activity the preferred support of 50% US sieve in alumina should have pores of average pore diameters near 700A combined with a high surface area and a sharp pore size distribution.

Some data for an activity maintenance test using the preferred catalyst are detailed in Table VI. Start-of-run conditions were 0.4 LHSV, 2000 psig hydrogen, and 770°F and were chosen to maximize hydrogenation and hydrocracking reactions while allowing for an increase in reactor temperature in case catalyst deactivation occurred.

In contrast to all other previous tests, the activity maintenance test was subjected to numerous unit upsets during the first 50 days on stream. As a result of some of these upsets, catalyst activity was seriously reduced. To compensate, reactor temperature was raised 150°F over the first 48 days on stream to maintain high yields of JP-4 material.

As a result of these unit upsets, the test was extended to 103 days with processing conditions held constant at approximately 786°F, 0.4 LHSV, and 2000 psig for the periods 49 through 93. For the last ten days, reactor temperature was deliberately raised to 790°F and then lowered to 780°F in order to obtain the cracking temperature response.

Figure 12 shows product nitrogens as a function of days on oil. With the exception of those upsets which affected product nitrogens (shown as solid points), product nitrogens were maintained generally in the 1 to 3 ppm range throughout the test. As indicated previously (Figure 8), 10 ppm product nitrogen would reduce JP-4 yields to approximately 50 wt% or less whereas a JP-4 yield of >70 wt% would require <2 ppm nitrogen in the product. High cracking activity to produce JP-4 is critically dependent upon very low product nitrogen levels.

Daily JP-4 yields, estimated from product API gravities and Figure 5, are shown in Figure 13. The solid symbols represent upsets affecting JP-4 yields or cracking activity. The following points can be drawn from Figure 13.

- (i) For the first ten days on oil at 770°F, cracking activity declined as reflected in the drop in JP-4 yields from approximately 82 wt% to approximately 68 wt%.
- (ii) The unit upset of day 19 (unit depressurized, subjecting catalyst to high temperature without hydrogen) seriously affected catalyst cracking activity at 775°F as reflected in the drop in JP-4 yields from approximately 80 wt% to approximately 67 wt%. This loss in activity was also reflected in the JP-4 yields at 777°F being lower than initially achieved at 775°F.
- (iii) The unit upset on day 43 (very little hydrogen flow for 16 hours) also seriously affected cracking activity as evidenced by the poor temperature response upon raising temperatures from 777°F to 786°F.
- (iv) At 786°F, over approximately a 50-day period, cracking activity declined steadily as indicated by the drop in JP-4 yields from about 80 to 67 wt%. This decline may have been affected by the upset on day 65.

In order to calculate catalyst life at a specified JP-4 yield, temperature response factors need to be calculated. This was done by using the data at the end of the test at 785°F (period 93), 790°F (period 96), and 780°F (period 101) assuming zero-order kinetics, no nitrogen inhibition in the actual cracking zone, and constant activity. Hydrocracking reactions in the presence of nitrogen are generally zero order over the total catalyst system, and in this case all samples contained <10 ppm nitrogen.

Using a constant JP-4 yield of 50 wt%, temperature response factors of 62.5, 67.9, and 65.6 Kcal mole<sup>-1</sup> were calculated for the three temperature couples, the average being 65.4 Kcal mole<sup>-1</sup>. This value is not unusual for full-range, high-boiling feedstocks containing large amounts of nitrogen.

Based upon the temperature response factor, a catalyst life of approximately four and one-half months can be calculated for a constant JP-4 yield of 75 wt% by increasing reactor temperatures from 775°F to 800°F at 2000 psig and 0.4 LHSV. However, due to the operational problems encountered in the test, this should be considered a minimum life and six months is probable. A deactivation rate of approximately 0.18°F/day was calculated from the data for periods 53 and 93 using zero-order kinetics.

Within the same constraints, catalyst life would be longer for lower JP-4 yields. As discussed previously, several unit upsets seriously affected catalyst activity and one of these upsets occurred during the period used to calculate the activity decline rate. Thus, the projected life for constant 75% JP-4 yields should be viewed as a rough estimate. Detailed process variable studies which were not part of this contract would be needed to more accurately define a deactivation rate.

The data for the distillations of the products from the activity test to produce JP-4 and JP-8 jet fuel fractions are given in Table VII. All samples for periods 1 through 73, with the exception of those samples containing more than 10 ppm nitrogen or having an API gravity less than 45°, were combined to yield approximately four gallons of product. The composite was washed with water and then dried. Two distillations to yield JP-4 and JP-8 fractions were completed. The JP-4 yield was 76 wt% on the composite product with a JP-8 yield of 61 wt%. The analytical data indicates that the samples would meet all specifications with perhaps one exception. The pour point of -40°F for the JP-8 fraction is high in view of the freeze point specification of -58°F. However, the simulated distillation data indicates an end point very close to the specified limit. A slightly lower temperature cut point, and perhaps a slightly lower initial point, would lower the pour point and hence bring the freeze point to the specified value.

Based on the qualities measured, with one exception, saleable jet fuels were produced in high yields by the single-catalyst process.

#### CONCLUSIONS

A single-catalyst system capable of direct hydrocracking of a whole shale oil containing large amounts of nitrogen has been developed. The novel catalyst, consisting of cobalt, chromium, and molybdenum salts on a base of 50% US sieve in alumina is multifaceted in that it combines both the saturation and denitrogenation activity of alumina with the cracking activity of the sieve. The combination is more effective than alumina alone for hydrocracking with the cracking zone confined to that part of the bed at the bottom where the nitrogen content has been reduced to <10 ppm. This cracking zone would vary with changes in process conditions.

The ability of the optimized catalyst to hydrocrack a whole shale oil into high yields of jet fuel boiling-range material was demonstrated in

a 103-day (approximately 2500 hours) test. Although several unit upsets marred the results and perhaps affected catalyst activity, a high yield of JP-4 boiling-range material was sustained. The whole product was water white in color and contained only a few ppm nitrogen. Even though unit operations were poor during the catalyst life test, a minimum life of 4.5-month was demonstrated and a catalyst life of six months is expected for the specified 75 wt% yield of JP-4 boiling-range material. It should be emphasized that a guard bed to remove arsenic and iron was not used for the life test. The presence of such a bed should extend the catalyst life considerably.

**Table I**  
**Selected Shale Oil Properties**

	<u>Tosco</u>	<u>Paraho</u>	<u>Occidental</u>
API°	21.0	20.2	23.8
Pour Point, °F	75	90	60
H/C	1.56	1.61	1.67
N, Wt%	1.88	2.18	1.32
S, Wt%	0.75	0.66	0.64
O, Wt%	1.39	1.16	1.33

**Table II**  
**Initial Product Qualities**  
**Co/Cr/Mo on Alumina**  
(1800 psig, 0.55 LHSV, 790°F)

	<u>Product</u>	<u>Feed</u>
API°	39	23.8
Pour Point, °F	80	60
Nitrogen, ppm	116	13,200
JP-4, Wt%*	37	15.5 **
650°F-, Wt%	74	44
SCFB Hydrogen	1400	-

\* 20% distilled at 290°F, 90% distilled at 470°F

\*\* Heavy JP-4 fraction, IBP of 290°F

**Table III**

**Effect of Support Composition on Product Qualities**

	<u>Al<sub>2</sub>O<sub>3</sub></u>	<u>20% SiO<sub>2</sub>/ Al<sub>2</sub>O<sub>3</sub></u>	<u>30% US Sieve/ Al<sub>2</sub>O<sub>3</sub></u>
API <sup>o</sup>	39.2	39.7	44.6
Nitrogen, ppm	83	<10	< 5
Pour Point, °F	80	65	30
JP-4, Wt%	38	38	54
650°F-, Wt%	76	77	87
SCFB Hydrogen	1400	1400	1660

**Table IV**

**Catalyst Physical Properties**

(50% US Sieve/alumina)

<u>Catalyst ID 3838-</u>	<u>Surface Area m<sup>2</sup>/g</u>	<u>Pore Volume cc/g</u>	<u>Avg Pore Diameter (4 V/A), °A</u>
023	280.5	0.477	68.0
028	255.2	0.545	85.5
030	222.4	0.505	90.8
031	312.5	0.824	105.4
034	305.0	0.589	77.2
035	276.3	0.784	113.4
037	280.4	0.710	101.3
039	234.0	0.417	71.4

**Table V**

**Product Qualities from Catalysts with Different Physical Properties**

0.5 LHSV

<u>Catalyst ID 3838-</u>	<u>Nitrogen, ppm</u>	<u>Pour Point °F</u>	<u>650°F-, Wt%</u>	<u>JP-4, Wt%</u>	<u>SCFBH</u>
023	1	-50	92.5	79.5	1930
028	4	35	86.5	62.7	1670
030	600	75	65.6	29.6	1190
031	76	70	72.5	36.8	1390
034	5	55	71.2	50.6	1520
035	46	65	75.8	43.9	1380
037	77	70	74.0	39.9	1360
039	1	40	79.5	57.1	1660

0.75 LHSV

023	44	75	67.5	33.8	1310
028	1510	75	83.0	30.1	1300
030	1240	75	65.5	29.4	1190
031	985	75	62.6	30.1	1200
034	--	--	--	--	--
035	1950	75	64.6	29.3	1120
037	1560	--	66.4	28.3	1150
039	289	75	60.4	33.3	1260

**Table VI**  
**Product Qualities from the Activity**  
**Maintenance Test**

Day	3	9	17	19	27	32	39	46	53
Temperature, °F	770.1	770.3	775.8	774.5	777.2	777.1	777.5	777.0	786.0
API°	52.4	46.0	51.2	47.0	48.8	49.2	48.9	42.4	50.3
Nitrogen, ppm	2	1	1	2	1	2	6	11	3
Sulfur, ppm	18	133	728	36	64	92	234	22	60
Pour Point, °F	-30	5	-10	20	-15	-15	20	60	-15
650°F., Wt%	86.7	87.7	84.4	-	91.1	91.7	88.6	88.6	94.4
JP-4, Wt%	84	89	79	-	72	79	67	49	77
SCFBH	1960	1770	1740	1740	1850	1800	1800	1515	1920
Day	80	67	73	80	87	93	96	101	
Temperature, °F	785.5	785.4	788.0	788.0	785.8	785.5	789.7	779.9	
API°	49.6	47.4	48.4	49.9	48.1	47.4	50.3	43.8	
Nitrogen, ppm	2	15	1	1	30	1	1	10	
Sulfur, ppm	36	229	76	70	121	20	85	100	
Pour Point, °F	5	10	10	-5	-10	5	-10	55	
650°F., Wt%	89.4	89.3	90.9	91.7	90.2	89.4	93.2	84.5	
JP-4, Wt%	70	68	73	73	70	67	76	57	
SCFBH	1890	1740	1810	1850	1850	1720	1940	1400	

**Table VII**  
**Jet Fuel Qualities**

	Composite	JP-4	JP-8
API°	48.7	49.4 (48-57)	43.4 (37-51)
Weight %	100	70	01
Carbon, Wt%	86.82	85.99	86.10
Hydrogen, Wt%	14.17	14.00 (13.6)	13.88 (13.6)
Nitrogen, ppm	1.1	0.7	1.1
Pour Point, °F	-5	-85	-40
Viscosity (40°C), cst	1.33	-	-
Aromatics, Vol%	-	16.0 (25.0)	16.0 (25.0)
Olefins, Vol%	-	1.0 (5.0)	2.5 (5.0)
Distillation, D-2637			
IBP, °F	-47	22	250
10%	203	190	322 (267)
20%	268	238 (206)	353
30%	321	278	390
40%	372	312	413
50%	410	346 (305)	436
60%	448	377	461
70%	487	405	489
80%	547	440	520
90%	624	490 (482)	564
EP, °F	789	663 (608)	622 (626)

Values in parenthesis are maximum (minimum for hydrogen content) specification limits.

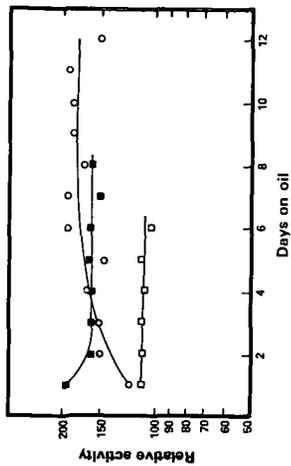


Figure 1 — Effect of Support Type on Relative Denitrogenation Activity for Various Catalysts. o, Alumina; □, 30% US Sieve Alumina; ■, 20% Silica Alumina

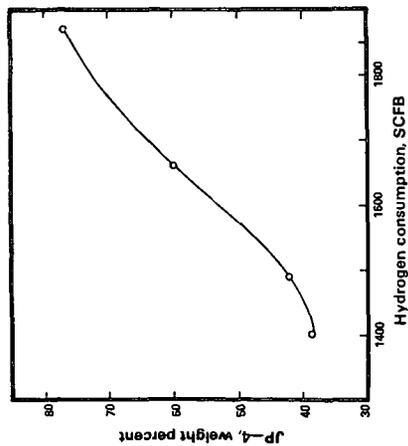


Figure 3 — Correlation Between JP-4 Yields and Hydrogen Consumption for Catalysts Containing 0, 20, 30, and 50% US Sieve

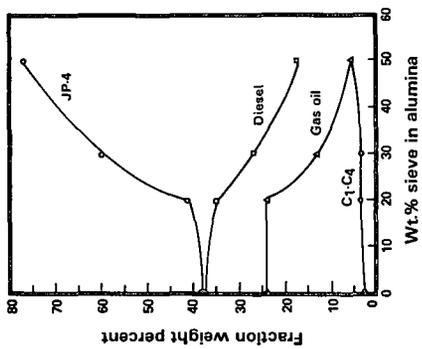


Figure 2 — Product Yield Structures as a Function of US Sieve Content in the Support

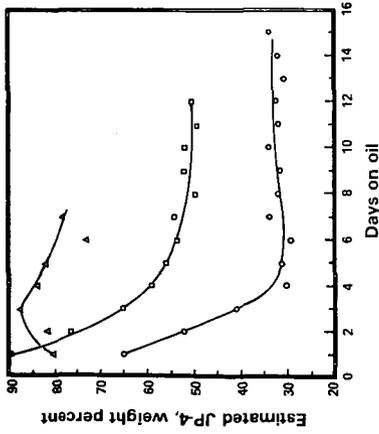


Figure 4 — Estimated Daily Yields of JP-4 for Catalyst of Different Sieve Content, o, 20%; □, 30%; and △, 50% US Sieve

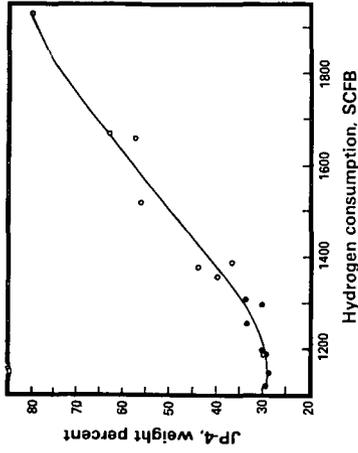


Figure 6 — Correlation Between JP-4 Yields and Hydrogen Consumption for Catalysts Containing 50% US Sieve, o, 0.75 LHSV; □, 0.5 LHSV

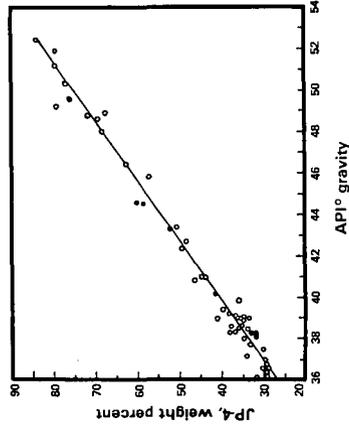


Figure 5 — Correlation Between Product API Gravity and JP-4 Yields

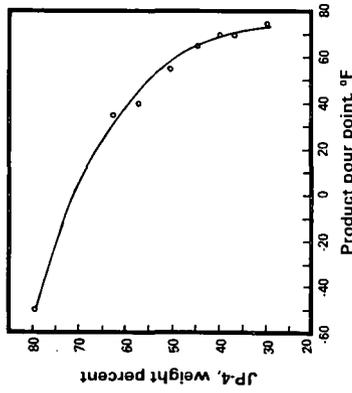


Figure 7 — Correlation Between Product Pour Point and JP-4 Yields for Catalysts Containing 50% US Sieve

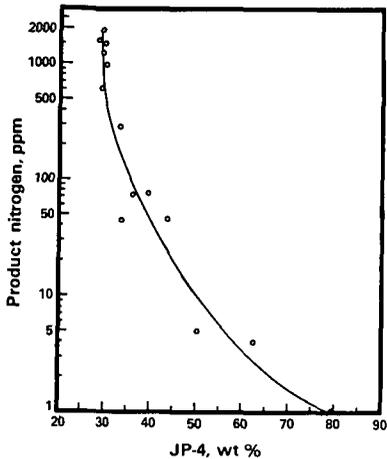


Figure 8 — JP-4 Yields as a Function of Product Nitrogen for Catalysts Containing 50% US Sieve

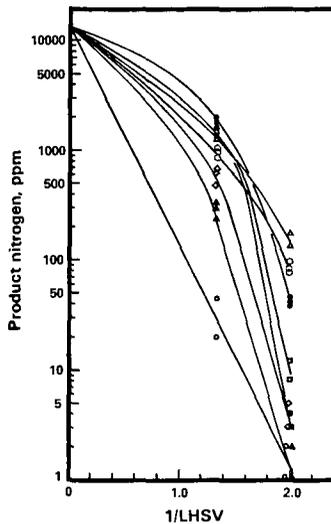


Figure 10 — Effect of Space Velocity on Product Nitrogens for Catalyst with Different Physical Properties. Catalysts 3838-023 (○); -028 (□); -030 (△); -031 (◊); -034 (◊); -035 (●); -037 (■); -039 (▲).

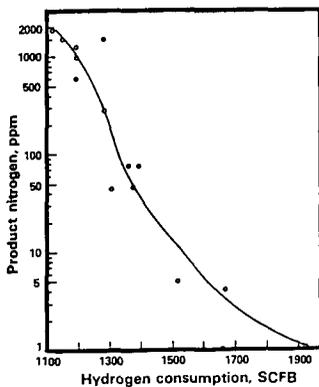


Figure 9 — Hydrogen Consumption as a Function of Product Nitrogen for Catalyst Containing 50% US Sieve

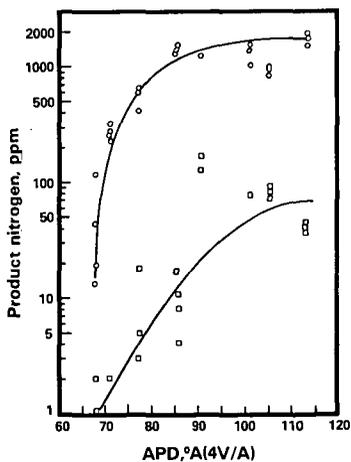


Figure 11 — Correlation Between Catalyst Average Pore Diameters and Product Nitrogen for 50% US Sieve Alumina Catalysts. ○, 0.75 LHSV; □, 0.5 LHSV.

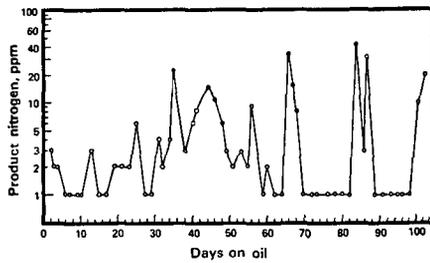


Figure 12 — Product Nitrogen as a Function of Days on Oil for the Activity Maintenance Test

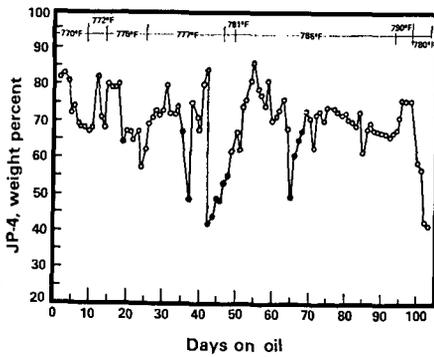


Figure 13 — Daily JP-4 Yields for the Activity Maintenance Test