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HYDROCRACKING ATHABASCA BITUMEN WITH ALKALI METAL PROMOTED  
CoO-MoO<sub>3</sub>-Al<sub>2</sub>O<sub>3</sub> CATALYSTS

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by

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ABSTRACT

Alkali metal promoters (lithium, sodium and potassium) were added to catalysts used to hydrocrack Athabasca bitumen, in order to decrease the coke deposition which causes catalyst deactivation. Sodium and potassium promoters decreased the catalyst coke content, the catalyst surface area, and the pitch, oxygen, sulphur and nitrogen conversions. On a unit surface area basis, the sodium and potassium promoters increased the pitch and oxygen removal reaction rates. For all the lithium promoted catalysts both conversion and pitch, oxygen, sulphur and nitrogen removals on a unit surface area basis exhibited a maximum. Sulphur and nitrogen removals decreased with increasing potassium content. The results are explained in terms of the changes in catalyst electronic properties caused by the addition of the promoters.

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Heavy oils and bitumen from the Canadian oil sands deposits are beginning to be used on a commercial scale to supplement conventional crude oil. The fact that the hydrogen-to-carbon ratio is considerably higher in heavy oils and bitumen than in coal or biomass means that less hydrogen has to be added to these materials to convert them into commercially acceptable fuel oils. The addition of hydrogen is normally a costly process. As a result, it is generally less expensive to make liquid fuels from these materials than from coal or biomass.

If heavy oils and bitumen are converted to distillate fuels using a hydrocracking process rather than the delayed coking process (1) used by Great Canadian Oil Sands or the fluid coking process (2) used by Syncrude, the yield of liquid fuels will be approximately 10-15 wt.% higher (3). The higher liquid yield from the hydrocracking process is offset by two disadvantages. First, more hydrogen is consumed in the process. The cost of the higher hydrogen consumption is partially offset by the higher hydrogen content in the liquid product and therefore the improved product qualities. Second, the cost of catalyst replacement for catalytically hydrocracking pitch, bitumen or residuum feedstocks is much larger than for hydrocracking distillate feedstocks. The more costly catalyst replacement is caused by the greater rates of coke and metals deposition on catalysts used to process these higher molecular weight feedstocks. One method of decreasing the catalyst replacement cost is to use catalysts having lower concentrations of expensive active ingredients (4).

Recent cost studies have shown that the thermal hydrocracking process is preferable to the coking processes in some situations (5). If the catalyst replacement costs can be decreased sufficiently the economics of catalytic hydrocracking may approach those for thermal hydrocracking. These considerations indicate that there is a need for the development of catalysts which have a longer usable life and therefore have a lower processing cost per barrel of oil.

In bitumen hydrocracking, initial catalyst deactivation is strongly related to coke deposition (6). Decreased coke deposition has been reported (7) when alkali or alkaline earth compounds were added to catalysts used for hydrocarbon transformations such as dehydrogenation. Improved initial reaction results have been reported recently when similar catalysts were used for the water gas shift reaction (8) and for coal liquefaction studies (9). Unfortunately, neither coke formation on the catalyst nor catalyst life were measured in these investigations (8,9). The work described in this paper investigated the use of alkali metal promoters in  $\text{CoO-MoO}_3-\gamma\text{Al}_2\text{O}_3$  catalysts having low concentrations of cobalt and molybdenum. The catalysts propensity for coke formation was one of the variables of primary interest.

### Experimental

The catalysts used in this study were prepared by spraying aqueous solutions of the appropriate species onto 5 kg of alpha-alumina monohydrate powder (Conoco Catapal SB - 20 wt.%, Catapal N - 80 wt.%) in a mix muller. Cobalt and molybdenum were added as solutions of cobalt nitrate and ammonium paramolybdate respectively. Lithium carbonate, because of its low solubility, was added as a colloidal suspension. A small amount of stearic acid was added before the mulled powder was extruded into 3.18 mm diameter extrudates (L $\approx$ 3D). The extrudates were dried at 110°C overnight and then calcined at 500°C for approximately 8 hours.

Samples of the prepared catalysts were analyzed for cobalt and molybdenum content by a standard atomic absorption technique. Lithium, sodium and potassium concentrations were determined by a standard flame photometer after dissolving the extrudates in hydrochloric acid. The measured chemical compositions of the catalysts are reported in Table 1.

The catalysts were also characterized with respect to their physical properties as shown in Table 2. Pore volume data were obtained on a Micro-meritics model 910 mercury intrusion porosimeter. The shapes of the penetration and retraction curves were similar for all the catalysts. Specific surface areas were calculated using the BET method from nitrogen adsorption isotherms measured with a gravimetric quartz spring balance.

The Athabasca bitumen was obtained from Great Canadian Oil Sands Ltd. at Fort McMurray, Alberta, and its general properties are shown in Table 3. Catalyst evaluation experiments were performed in a bench-scale fixed-bed reactor system, described elsewhere (4). The reactor was filled completely with extrudates and the bitumen, mixed with hydrogen (purity = 99.9 wt.%), was fed into the bottom of the reactor. Each catalyst was evaluated at a pressure of 13.9 MPa and a temperature of 450°C with a liquid volumetric space velocity of 0.29 ks<sup>-1</sup> based on the total empty reactor volume. Hydrogen flow rate was set at 36.0 mL/s at S.T.P. The reactor was kept at steady state for one hour preceding, and for two hours during, the liquid product collection period. Prior to the evaluation experiments each catalyst was presulphided in the presence of bitumen and hydrogen for approximately 14.4 ks. The feedstock and liquid products were analyzed for carbon, hydrogen, sulphur, nitrogen, oxygen and the fraction boiling above 525°C. Hydrogen and carbon elemental analyses were performed using a Perkin Elmer model 240 analyzer. The sulphur, nitrogen and distillation analyses methods have been described elsewhere (4). Oxygen was determined via neutron activation analysis using a neutron generator.

To accurately determine the coke concentration on a used catalyst by the weight lost on ignition method requires the removal of any liquid reaction products remaining on the surface or in the pores of the catalyst, before combustion. For pure compounds and lower boiling point products, a variety of deoiling techniques have been used (e.g., purging with N<sub>2</sub> gas, evacuation, stripping with steam, washing with acetone). However, for higher boiling point compounds more involved liquid removal approaches are needed. In one study the liquid reaction products were removed from a NiO-MoO<sub>3</sub>-Al<sub>2</sub>O<sub>3</sub>

catalyst, which had been contacted with a gas oil (b.p. 343-525°C), by purging with a hydrogen stream while slowly heating over a two hour period to 525°C (10).

For this investigation the above procedure was modified, since 48 wt.% of the bitumen feedstock used in this study boiled above 525°C. This modification consisted of determining the coke concentration on both the used catalyst and a fresh reference catalyst. The fresh reference catalyst was presaturated with the appropriately matched liquid product obtained from the corresponding catalyst evaluation experiment. During presaturation, the fresh reference catalyst was evacuated and then saturated with liquid reaction product for approximately 0.9 ks at 55.3 MPa and room temperature. Paired catalyst samples (i.e. presaturated and used) were then deoiled in a hydrogen stream (73 mL/s at S.T.P.) while the temperature was raised over a one hour period to 600°C. The samples were kept at 600°C for 0.9 ks then allowed to cool to 200°C in the flowing hydrogen stream. The paired catalysts were then weighed and left overnight in a muffle furnace at 600°C. The change in weight after oxidation in the muffle furnace was ascribed to coke removal from the catalysts. Each of the weight changes was expressed as a percentage of the final catalyst weight (i.e. coke free catalyst basis). The amount of coke on the fresh reference catalyst was ascribed to coke formed during deoiling from the hydrocarbon product adhering to the catalyst. The amount of coke on the reference catalyst was subtracted from the amount of coke on the used catalyst to obtain the coke values reported in Figure 7. This empirical definition of coke is used to represent the amount of coke on the used catalyst.

### Results

Figure 1 shows the surface areas of all of the alkali metal promoted catalysts. The surface areas of the lithium catalysts exhibited a maximum at a metal to molybdenum ratio of about 1.5. Thereafter the surface areas decreased with increasing lithium content. For both the sodium and potassium containing catalysts the surface areas decreased continuously with increasing metal to molybdenum ratio.

The conversion data for +525°C pitch, oxygen, sulphur and nitrogen are shown in Figures 2,3,4 and 5 respectively. From a practical viewpoint the conversion data are the most important since they show what actually happened to the feedstock. On this basis, it is apparent that the addition of small amounts of lithium will improve the conversion, whereas in general, conversion decreases with the addition of sodium or potassium.

Although the data are scattered there are definitely some similarities between the surface areas shown in Figure 1 and the conversion results. The conversion results with the lithium catalysts all have a maximum, although the maximum does not coincide with the maximum in surface area. The sodium and potassium catalysts show a decrease in surface area with increasing metal to molybdenum ratio. Similarly the conversion decreases with increasing metal to molybdenum ratio for sodium and potassium catalysts. The only exception to this is the oxygen conversion curve for potassium. As a result of the similarity between conversion and surface area an attempt was made to plot the reaction results on a unit surface area basis. These results are also shown in Figures 2,3,4 and 5. Most of the discussion will emphasize the reaction results per unit surface area.

The reaction data on a unit surface area basis may be placed in two groups. Both the pitch removal and oxygen removal per unit surface area increase with increasing metal to molybdenum ratio. The nitrogen and sulphur removals per unit area also show some similarities. For all the lithium catalysts there is a maximum in the sulphur and nitrogen heteroatom removal per unit surface area with increasing metal to molybdenum ratio. The potassium catalysts show a decrease in both sulphur and nitrogen removals (per unit area) with increasing metal to molybdenum ratio. The sodium results are generally intermediate between those of lithium and potassium not showing as large a change in either sulphur or nitrogen removal per unit area with changing metal to molybdenum ratio.

The hydrogen to carbon ratios in the liquid products produced by the various catalysts are shown in Figure 6. These results are somewhat similar to the conversion data in that there is a maximum in the curve for the lithium catalysts whereas the sodium and potassium catalysts show a decreasing hydrogen to carbon ratio with increasing metal to molybdenum content.

The coke contents of the catalysts at the end of the reaction are shown in Figure 7. Both the sodium and potassium catalysts had decreasing coke with increasing metal to molybdenum ratio. This was similar to the surface area and conversion results for these catalysts. In contrast, for the lithium catalyst the coke content was roughly the reverse of the surface area and conversion results.

### Discussion

The surface area of all the catalysts is governed mainly by the surface area of the support and not of the minor ingredients such as molybdenum, cobalt, or the alkali metal compound. Figure 1 indicates that the addition of alkali-metal compounds caused a change in surface area. The lattice of the catalyst support, gamma alumina, is considered to have the spinel ( $MgAl_2O_4$ ) structure (11). For gamma alumina, the unit cell of the spinel lattice contains 32 oxygen atoms,  $21 \frac{1}{3}$  aluminum atoms and  $2 \frac{2}{3}$  vacancies. It is conceivable that some of the alkali metal ions could occupy these vacancies. The ionic radii of lithium, sodium, and potassium ions are 68 pm, 97 pm, and 133 pm respectively. In comparison the aluminum and magnesium ions in the  $MgAl_2O_4$  spinel lattice have ionic radii of 51 pm and 66 pm respectively. When these numbers are compared it appears that the lithium ions might fit into the spinel lattice, whereas the sodium and potassium ions would be too large.

The lithium atoms are also small enough to fit into the 74 pm radius holes (12) between the sulphur atoms in  $MoS_2$  layers. On this basis there are at least three possible positions for lithium atoms: a lattice position in the alumina spinel, an intercalation position between the sulphur layers of  $MoS_2$ , and a non-lattice position which disrupts the structure or phases of the catalyst. Undoubtedly there will be a distribution among all possible positions.

The size of the alkali metal species may help to explain the effects shown in Figure 1. The sodium and potassium ions are too large to fit into the lattice positions of the spinel and therefore may disrupt its structure causing a loss in surface area. In contrast some of the lithium



ions may be able to occupy positions without disrupting the catalyst structure. It may be that as the total amount of lithium in the catalyst increases, the proportion of lithium located at non-lattice positions also increases. Presumably the non-lattice lithium atoms would disrupt the catalyst structure causing a decrease in surface area as was observed at high lithium to molybdenum atomic ratios.

The addition of alkali metal compounds will affect the electronic properties of the catalyst. The surface of the alumina support is known to contain Lewis acid sites, which are electron acceptors. Morrison(13) has discussed the relationship between the electronic properties of a surface and surface acidity. Lewis acid sites (a chemical concept) can be associated with electronic acceptor surface states (an electronic concept). The effects of sodium on surface acidity (14) and lithium on electrical properties (15) of substances containing  $\text{MoO}_3$  have been reported. When alkali metals are located in the bulk of the alumina they will have electrons which might be donated to the conduction band of  $\text{MoS}_2$ , the conduction band of the alumina, or some of the electron acceptor surface states of the alumina support. When this latter phenomenon occurs some of the Lewis acid sites are effectively removed.

Many aspects of the reaction data shown in Figures 2 to 6 may be interpreted in terms of the catalyst coke content shown in Figure 7. Generally accepted reaction mechanisms for coke formation can be related to the electronic properties of the catalyst. Free radicals from thermal reactions and other molecular species which can participate in electron transfer reactions may donate electrons to the catalyst when they are adsorbed on its surface. Similarly, species which form carbonium ions on the catalyst surface may donate electrons when they are adsorbed. These adsorbed species can then dehydrogenate and polymerize to form coke. By increasing the electron density within the catalyst, the propensity to transfer an electron from an adsorbed species to the catalyst will decrease, resulting in weaker bonds between the adsorbed species and the catalyst. This should decrease the average lifetime of the adsorbed species on the catalyst and therefore decrease the time available for the adsorbed species to be converted into coke.

The addition of some alkali metal compounds is one way of increasing the electron density of the catalyst. In addition to affecting the bond strength between the adsorbed species and the catalyst, the additional electrons may tend to inhibit dehydrogenation and polymerization reactions. Wentreck and Wise (17)

have shown that increasing the n-conductivity of a catalyst decreases its hydrogenation characteristics. It is known that a catalyst will influence the forward and reverse reactions in the same way. Therefore increasing the n-conductivity should decrease the dehydrogenation characteristics of the catalyst as well. This should decrease coke formation since dehydrogenation is one of the primary steps in coke formation.

Acid catalysts, which contain electron acceptor surface states and have p-conductivity, are used for polymerization reactions. For example, commercial processes which produce gasoline components by polymerizing butenes use sulphuric acid and phosphoric acid catalysts. By increasing the n-conductivity, the catalyst should become more basic and its polymerization characteristics should decrease. Again this should decrease coke formation since polymerization is the other primary step in coke formation.

The changing electron density of the catalyst has been invoked to explain the extent of the coke forming reactions (polymerization and dehydrogenation). On this basis smaller amounts of coke on the catalyst would be expected as the alkali metal content of the catalyst increased. The results in Figure 7 follow this trend for all the sodium catalysts, all the potassium catalysts and the lithium catalysts having lithium to molybdenum ratios below 1. Unfortunately this concept does not hold for the results obtained at lithium to molybdenum ratios above 1, and no satisfactory explanation for them can be offered at the present time.

The pitch removal per unit area shown in Figure 2 is governed by two effects. The first involves the amount of coke on the catalyst. It was shown previously (6) that there are two types of coke formed on hydrocracking catalysts. One is a reactive substance which is subsequently converted to reaction products. The other is an unreactive substance which blocks catalytic sites. Figure 7 shows that for sodium and potassium catalysts the coke content decreases with increasing metal to molybdenum ratio. Assuming that this reflects smaller amounts of unreactive coke, one would expect the reaction rate, that is pitch removal (per unit area), to increase as greater quantities of alkali metals are added to catalysts.

The second effect involves the electronic properties of the catalyst. As mentioned previously the presence of alkali metals in the alumina matrix can remove some of the Lewis acid sites. If the cracking reaction occurs by a carbonium ion mechanism, acid sites are required. Since the addition of alkali metals would decrease the surface acidity therefore it would also decrease the cracking reaction rate. Alternatively, the cracking reaction might occur by an electron transfer mechanism (16) in which an electron from the reacting hydrocarbon species is transferred to the catalyst surface. The addition of alkali metals would increase the supply of electrons at the surface and thereby decrease the tendency for electron transfer which could tend to decrease the rate of cracking.

The results in Figure 2 can now be explained. For the sodium and potassium catalysts, pitch removal increases with increasing metal to molybdenum ratio. Therefore in terms of the above two effects it would appear that the decrease in the surface coverage by coke was the overriding effect. Catalyst coke content will also explain the results for the lithium catalysts. The greater pitch removal at lower lithium to molybdenum atomic ratios corresponds to the lower coke contents, shown in Figure 7. At higher lithium to molybdenum ratios the pitch removal started to decrease corresponding to the increasing catalyst coke content.

The oxygen conversions shown in Figure 3 are generally large. One can speculate that deoxygenation reactions are relatively fast and that the oxygen atoms which contact the surface have been removed. On this basis the unreacted oxygen atoms may be sterically hindered from contacting the catalyst surface by the hydrocarbon molecule. When pitch conversion (molecular weight reduction) occurs the molecular fragments which result from the cracking reaction may have their oxygen atoms exposed. These oxygen atoms would then be able to contact the catalyst surface and react. If this is correct the hydrodeoxygenation results should tend to follow the pitch removal results. When the unit area curves in Figure 2 and 3 are compared, it is apparent that they do have similar shapes.

Some of the curves for sulphur removal per unit area (Figure 4) are similar to those for nitrogen removal (Figure 5). The sodium catalysts are the exception. The differences between sulphur and nitrogen removal with sodium catalysts may be related to the differences in C-S and C-N bond strengths.

The increase in sulphur and nitrogen removal per unit area with increasing lithium content in the catalyst is consistent with the intercalation model of Farragher and Cossee (12) and with the p-conductivity model of Wentreck and Wise (17). The intercalation model ascribes increased activity of the catalyst to the "goodness of fit" of the promoter ion into the 74 pm radius hole between the  $\text{MoS}_2$  sulphur layers. The addition of  $\text{Co}^{++}$  ions (ionic radii = 72 pm) to the catalyst is known to cause a large increase in catalyst activity. This observation is in accordance with the intercalation model. Since the ionic radius of lithium is 68 pm, it should fit into the hole reasonably tightly and therefore should cause an increase in activity. Also the addition of lithium ions into the  $\text{MoS}_2$  lattice could increase its p-conductivity in the same way that cobalt addition does. Wentreck and Wise (17) found that there was an increase in catalytic activity with increasing density of p-conductors, within the catalyst, when cobalt ions were responsible for the p-conductivity. Both of these models explain the increase in sulphur and in nitrogen removal observed at lower lithium contents as shown in Figure 3 and 4.

The decrease in sulphur removal and nitrogen removal observed with the catalysts having larger lithium contents can be explained in terms of catalyst coke content. The effects described above still occur in these catalysts. However, they are superseded by the increased coke content on the catalysts having larger lithium contents. The greater quantity of coke blocks a larger number of catalytic sites and is therefore responsible for the lower sulphur and nitrogen removals.

Sodium and potassium ions are too large to fit between the  $\text{MoS}_2$  layers, or into the  $\text{Al}_2\text{O}_3$  lattice. Presumably they can exist in the solid in positions which disrupt the catalyst structure. These species can donate their electrons both to the electron acceptor surface states on the alumina support and to the  $\text{MoS}_2$ . Donation of electrons to  $\text{MoS}_2$  should increase its p-type character and therefore decrease the desulphurization (18) and denitrogenation rates.

For the sodium and potassium catalysts there are two counteracting effects. First the decrease in the amount of coke on the catalysts, shown in Figure 7, should increase the reaction rate. Second the increase in the n-type character of the  $\text{MoS}_2$  should decrease the reaction rate. The fact that most of the data in Figures 3 and 4 show a decrease in reaction rates indicates that the n-type character was the predominant effect.

Figure 4 shows that as the metal to molybdenum ratio increased, sulphur removal decreased for the potassium catalysts and increased for the sodium catalysts. These different results can be ascribed to the relative influence of the electronic properties and the coke content of the catalysts. For the sodium catalysts, the increasing sulphur removal can be explained in terms of the dominance of their decreasing coke content. For the potassium catalysts the decreasing sulphur removal can be explained in terms of the dominance of the increasing n-type character. Because the ionization potential of potassium is lower than that of sodium, potassium will lose its electrons more easily. Therefore, the potassium catalysts will have a larger increase in n-type character than the sodium ones. This would explain why the n-type character is dominant for potassium catalysts and why the sulphur removal decreases.

The decreases in nitrogen removal and nitrogen conversion with increasing metal to molybdenum ratio are greater than the corresponding values for sulphur. This suggests that the p-type character or acidic properties of the catalyst are more important for denitrogenation than for desulphurization. The respective reaction mechanisms involve the cleavage of carbon-nitrogen or carbon-sulphur bonds. The single bond strength is higher for C-N (69.7 kcal/gmole) than for C-S (62.0 kcal/gmole). Doelman and Vlugter (19) have suggested that the rate controlling step in denitrogenation may be nitrogen removal from reaction intermediates such as anilines. They noted that the free electron pair on the nitrogen atom gives the C-N bond in aniline a double bond character. The double bond strength for C=N is 147 kcal/gmole. If the electron pair can be fixed on the nitrogen atom, the C-N bond will be easier to break. The greater the p-type character or acidic properties of the catalyst, the more likely that the electron pair will be associated with the nitrogen atom. Since the C-S bond does not have a double bond character, the p-type character of the catalyst may be more critical for denitrogenation. The difference in bond strengths is undoubtedly one of the factors which contribute to the difference between denitrogenation and desulphurization.

The hydrogen to carbon ratios shown in Figure 6 are for the total liquid product. They are only a partial indication of the amount of hydrogenation which is occurring, since they do not reflect changes in the gas phase hydrogen to carbon ratio. Wentreck and Wise (18) have pointed out that

the hydrogenation reaction has some parallels with the hydrodesulphurization reaction. Although the shapes of the curves in Figure 6 are not absolutely identical to those for the sulphur conversions in Figure 4 they are sufficiently similar that they support the viewpoint of Wentreck and Wise.

Catalyst deactivation is known to be caused by coke deposition (6). The decreased coke deposition shown in Figure 7 suggests that the **alkali** catalysts would have a longer useful life. It is not currently known what the exact relationship between catalyst coke content and catalyst life will be. At present we are planning to construct an apparatus capable of unattended operation over long periods with which we expect to perform catalyst life studies. Such an apparatus should provide the potential to elucidate a relationship between catalyst coke content and catalyst life.

### Conclusions

In conclusion, it may be said that the addition of small amounts of lithium to the catalyst produced the best results. With small amounts of lithium on the surface, the coke content decreased, the highest conversions for all reactions were obtained, and the reaction rate per unit surface area increased in every case. Therefore, based on the data shown in Figures 2 to 5, one can conclude that the reaction rates are highest with lithium. Similarly if the coke content is an indication of catalyst life, it would appear that the catalyst life would be considerably extended using a small amount of lithium promoter. This suggests that catalysts of this type may contribute to the commercial development of a catalytic hydrocracking process suitable for residuum feedstocks.

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TABLE 1

Chemical Composition of the  $\text{CoO-MoO}_3\text{-Al}_2\text{O}_3$  Catalysts Prepared with Lithium, Sodium and Potassium Carbonate Promoters

Catalyst Group	Mo (wt %)	Co (wt %)	Alkali Metal (wt %)	Co/Mo (atomic)	Metal/Mo (atomic)
Lithium Carbonate	1.37	0.889	0.087	1.05	0.88
	1.43	0.865	0.175	0.99	1.70
	1.55	0.905	0.482	0.95	4.31
	1.45	0.835	0.901	0.93	8.57
Sodium Carbonate	1.37	0.834	0.269	0.99	0.82
	1.37	0.842	0.564	1.0	1.72
	1.23	0.834	1.44	1.10	4.87
	1.35	0.873	2.92	1.05	9.02
Potassium Carbonate	1.37	0.897	0.430	1.06	0.77
	1.34	0.849	0.787	1.03	1.44
	1.38	0.928	2.05	1.10	3.64
	1.37	0.912	4.14	1.09	7.44
Without Metal Carbonate	1.39	0.92	0	1.08	0

TABLE 2

Physical Properties of the  $\text{CoO-MoO}_3\text{-Al}_2\text{O}_3$  Catalysts Prepared with Lithium, Sodium and Potassium Carbonate Promoters

Catalyst Group	Promoter Metal (wt.%)	Bulk Density (g/ml)	Specific Surface Area ( $\text{m}^2/\text{g}$ )	Pore Volume (ml/g)
Lithium Carbonate	0.087	0.67	236	0.502
	0.175	0.65	246	0.529
	0.482	0.69	226	0.518
	0.901	0.62	221	0.543
Sodium Carbonate	0.269	0.62	229	0.556
	0.564	0.65	222	0.555
	1.44	0.67	213	0.520
	2.92	0.69	198	0.507
Potassium Carbonate	0.430	0.63	235	0.542
	0.787	0.64	219	0.580
	2.05	0.65	213	0.557
	4.14	0.66	180	0.511
Without Metal Carbonate	0	0.66	233	0.519

TABLE 3

General Properties of Athabasca Bitumen

Specific Gravity, 16/16°C	1.009
Ash (wt.%) 700°C	.059
Iron (ppm)	358
Nickel (ppm)	67
Vanadium (ppm)	213
Conradson Carbon Residue (wt.%)	13.3
Pentane Insolubles (wt.%)	15.5
Benzene Insolubles (wt.%)	0.72
Sulphur (wt.%)	4.48
Nitrogen (wt.%)	0.43
Oxygen (wt.%)	0.95
Carbon (wt.%)	83.36
Hydrogen (wt.%)	10.52
+525°C Residuum (wt. %)	48.03

CAPTIONS FOR FIGURES

- Figure 1. Specific Catalyst Surface Area ( $m^2/g$ ) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 2.  $+525^{\circ}C$  Pitch Conversion - Wt.% (solid line, circles) and  $+525^{\circ}C$  Pitch Removed -  $mg/m^2$  (dotted line, squares) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 3. Oxygen Conversion - Wt.% (solid line, circles) and Oxygen Removed -  $mg/m^2$  (dotted line, squares) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 4. Sulphur Conversion - Wt.% (solid line, circles) and Sulphur Removed -  $mg/m^2$  (dotted line, squares) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 5. Nitrogen Conversion - Wt.% (solid line, circles) and Nitrogen Removed -  $mg/m^2$  (dotted line, squares) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 6. Hydrogen to Carbon Atomic Ratio in the Liquid Product versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.
- Figure 7. Catalyst Coke Content ( $mg/m^2$ ) versus the Alkali Metal to Molybdenum Atomic Ratio in the Catalyst.

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