HEAVY MINERALS FROM ALBERTA'S OIL SANDS

JOHN OXENFORD AND JULIAN COWARD – SYNCRUDE CANADA LTD.; SRDJ BULATOVIC – SGS

ABSTRACT

There are currently two operators producing oil from the surface-mineable portions of Alberta's oil sands (Syncrude Canada Ltd. and Suncor Inc.) and two other companies are proposing to enter the industry (Albian Sands in 2002 and True North in 2004). Tailings from the two current oil sands plants contain approximately 220,000 tonnes per year of recoverable TiO_2 and approximately 80,000 tonnes per year of recoverable zircon. This represents approximately 6% of the world's TiO_2 consumption and approximately 9% of the world's zircon production. With the commissioning of plants by Albian Sands and True North, and the announced expansion of plants by Syncrude and Suncor, it is expected that these tonnages could quadruple in the next ten years. All of these operators have at least 50 years of reserves even at these expanded production rates.

The occurrence of heavy minerals in Alberta's oil sands has long been known and is well documented in the literature. There have been a number of attempts to produce market-grade products from this resource and the results of this work have been quite mixed. Typically, researchers have used the normal mineral dressing techniques of the industry and have found the mineral assemblage does not respond to these techniques all that well. This has led to the widely held suspicion that there must be some difficult metallurgical problems associated with this resource.

There are three main problem areas that have created difficulties for previous researchers:

1. The bitumen coating on the sand grains;
2. Secondary mineralization such as pyrite, siderite and calcite
3. A high proportion of aluminosilicates (approximately 25%) that have the same gravity, electrostatic and magnetic properties as other minerals in the heavy mineral suite.

Recent work by SGS shows that these problems can be largely overcome with some novel approaches. The bitumen can be removed by washing with a solvent in the presence of a demulsifier. The pyrite can be removed by flotation. And the titanium and zircon minerals can be separated by selective flotation followed by conventional electrostatic and magnetic separation.

INTRODUCTION

THE ATHABASCA OIL SANDS

The Athabasca oilsand deposits are located in Northern Alberta, Canada (Figure 1). The oilsand deposits are Cretaceous age McMurray Formation and cover an area in Alberta of over 30 000 square kilometers. The McMurray Formation is an oil bearing quartz sand containing up to 18% by weight of extra heavy oil or bitumen. This is one of the largest hydrocarbon accumulations in the world, with an estimated 1800 * 10^9 barrels of contained oil or over four times the amount in Saudi Arabia. Of the oil contained in the Athabasca Formation, about 10% is recoverable by surface mining techniques, and over half could be recovered by in-situ methods.
The recoverable oil from the Athabasca oil sands is sufficient to supply Canada's current oil needs for several hundred years.

GEOLOGY/RESERVES

In the mid-1990's, the Federal Government entered into Mineral Development Agreements (MDA's) to assist in the development of new non-energy mineral resources. One of the sponsored projects was an assessment of the potential of heavy minerals from the oil sands. The scope of the proposed project is set out in the Agreement (Owen, 1996) and includes an assessment of the geology, mineral distribution, metallurgical processes and potential markets.

The MDA examined samples from cores from virtually all the geological facies within the leases of Syncrude Canada Ltd., Gulf Oil, and Suncor. From this work it was concluded (McCosh, 1996) that the heavy minerals in the oil sands are controlled by the natural sorting during the deposition of the grains during the Cretaceous period. The largest amount of heavy minerals occur in the overbank levee and in the swamp marsh deposits in the fluvial environment.

The heavy mineral concentrations are fairly consistent over most of the Athabasca McMurray Formation, and no rich concentrations have been found. The heavy minerals are typically fine grained (d_{50} less than 100 µm). There has been no post-depositional re-working of sediments as is typical of so many heavy mineral deposits. The post-depositional environment is a reducing one and secondary mineralization is common. Some secondary minerals often occur as intergrowths or inclusions in other minerals which can lead to problems in mineral processing.

Titanium concentrations average about 0.35% (as TiO_2) in feed grade oil sands (i.e. oil sands containing over 9 wt% bitumen), but can vary from 0.08% to 1.6% in some samples. No significant variation in titanium content has been found in different leases, or in different areas of the McMurray Formation. Zirconium is about one order of magnitude less concentrated in the ore than titanium, averaging 0.032% as ZrO_2. The zirconium assays are more variable than the titanium values, and zirconium ranges from about 0.001% to 0.13% . Some of this variation is attributed to sampling and analysis problems (McCosh, 1996) and some can be attributed to the relative accuracy of the analytical technique at these concentrations.

Other valuable materials that were identified in the oil sands include rare earths, and trace amounts of palladium, platinum and gold. None of these materials occurs in high enough grades to consider for economic extraction.

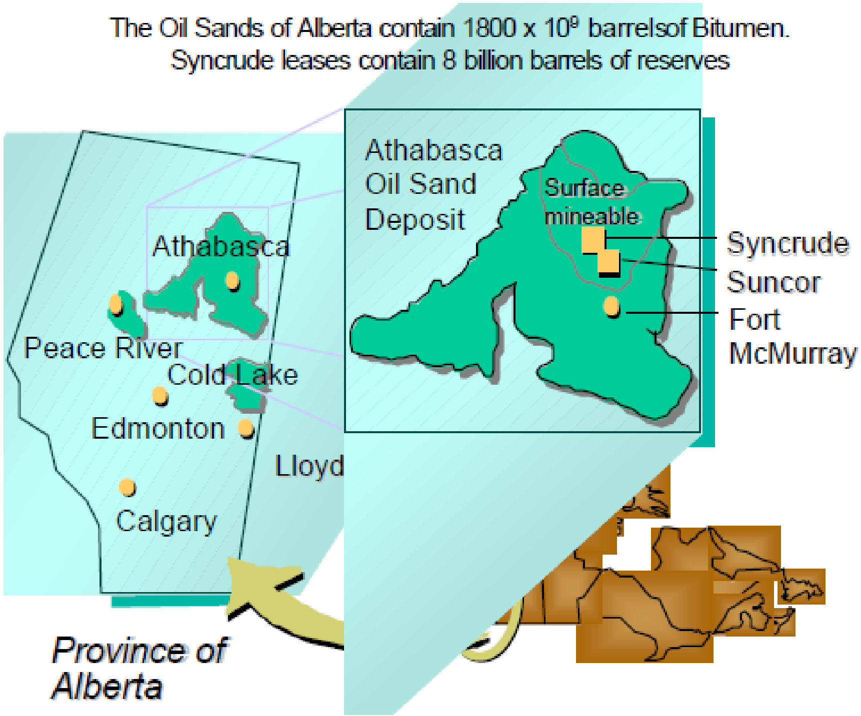

Figure 1 Location of the Oil Sands in Canada

OIL SANDS PLANTS

At present there are two large scale oil sands mining operations in the Athabasca region:

- Syncrude Canada Ltd. has been operating since 1978. Current annual production rate is about 80 million barrels per year of upgraded Syncrude Sweet Blend (SSB).
- SUNCOR has been operating since 1967. Current annual production rate is about 40 million barrels per year of upgraded product.

Upgraded crude oil from these two oil sands plants represents about 17% of the total oil consumption in Canada and over 1% of the North American needs.

As well as the oil sands mining plants, there are a number of in-situ bitumen recovery operations from the deeper oil sands, with the largest plant being the ESSO Cold Lake operation. Although these plants produce bitumen, they do not recovery any significant amounts of heavy minerals from the oil sands.

OIL SAND MINING

The first stage in any typical oil sand mining operation is to remove the trees, muskeg and any reclaimable soil material. This material is stored for later reclamation of the mined out area. The overburden is then stripped using a truck and shovel fleet.

The underlying oil sand is mined using large mining shovels, transported in mining trucks, and sized in double roll crushers. The oil sand is then mixed with water in a processing tower to create an oil sand slurry, and this slurry is pipelined to a central extraction plant. In this plant, the bitumen froth is floated off in large separation vessels, and recovered for further processing into synthetic crude oil. The clean sand from the extraction process is transported as a slurry to a sand disposal area, and the water in the tailings is clarified and then recycled back to the extraction process. The bitumen froth from the extraction process is diluted with naphtha to reduce the viscosity, and passed through inclined plate separators and a centrifuge plant to remove the remaining water and solids from the oil (Figure 2).

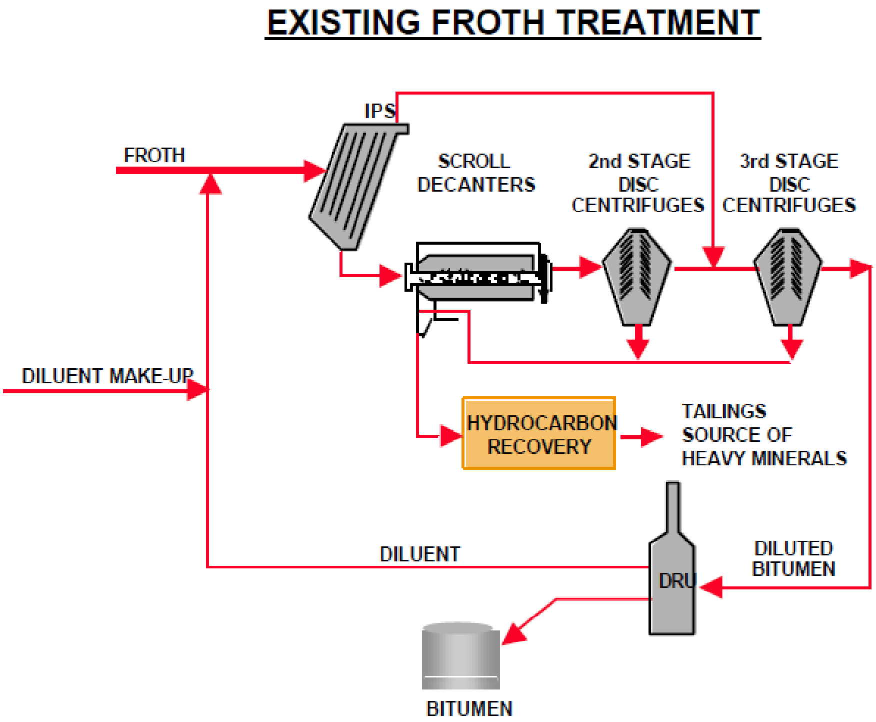

Figure 2 Froth Treatment Plant

The clean diluted bitumen is then piped to the bitumen upgrading area, where the bitumen is upgraded to produce a synthetic crude oil, that is pipelined to markets. Heavy minerals are generally oleophilic and hence they are recovered with the bitumen when it is extracted from the oil sands. Therefore, when the final water and solids are removed from the bitumen in the froth treatment plant, these tailings contain significant amount of heavy minerals (Figure 2). Currently, these centrifuge tailings are disposed of in the tailings area.

OIL PLANT EXPANSION

Both Syncrude and SUNCOR are constructing expansions that will roughly double the production within the next 10 years. In addition, two other companies have announced new oil sands plants in the Athabasca oil sands:

- Albian (Shell Oil with partners) is constructing a $C3.5 billion oilsands plant to produce almost 60 million barrels per year of upgraded product by 2002.
- True North (Koch Energy plus partners) is planning a $C2 billion plant to produce 70 million barrels per year of bitumen by 2008.

All four plants have sufficient reserves on their own leases to continue production for over 50 years at the planned rates. With the planned and ongoing expansions, the production of oil from these plants is expected to rise considerably as shown in Table 1.

VARIATION IN HEAVY MINERAL IN THE FEED

The amounts of titanium and zirconium minerals in the Syncrude centrifuge plant tailings were sampled and reviewed during part of the 1995 MDA study and again in 1999. The grades as TiO_2 and ZrO_2 in the dry feed are shown in Figure 3. Some variations in grades are seen, but the titanium averages about 10% TiO_2, and the zirconium averages about 2% ZrO_2. Based on the 2000 production at Syncrude, it is estimated that the Syncrude centrifuge tailings contain about 200,000 tonnes of TiO_2, and about 60,000 tonnes of zircon each year. Extrapolating this data to the future, the contents of titanium and zircon in the tailings from all the oil sands plants can be estimated to increase in the future as shown in Table 1.

Taylor (1999) estimates the world production of ilmenite in the 1998 as about 3200 kt/year and rutile as 520 kt/year. When this is combined with the world slag production, it gives a total production of contained TiO_2 of approximately 4600 kt/yr. Total annual world production of zircon is about 1000 kt/yr. Based on these data, the tailings from the oil sand plants are estimated to contain the equivalent of about 6% of the worlds current consumption of TiO_2, and about 9% of the zircon. By 2010, the oil sands tailings could contain over 20% to 30% of the worlds titanium and zircon needs.

Table 1 Current and expected production rates from the oil sand in Alberta

YEAR	1995	2000	2005	2010
OIL SANDS MINING PLANTS OIL PRODUCTION (million Bbls/year)	102	115	275	370
TOTAL CENTRIFUGE PLANT TAILINGS (Mt/yr as dry solids)	2.5	2.9	7.0	10.0
TITANIUM CONTENT (kt/year, as TiO_2)	250	290	700	1000
ZIRCON CONTENT (kt/year, as $ZrSiO_4$)	75	90	200	280

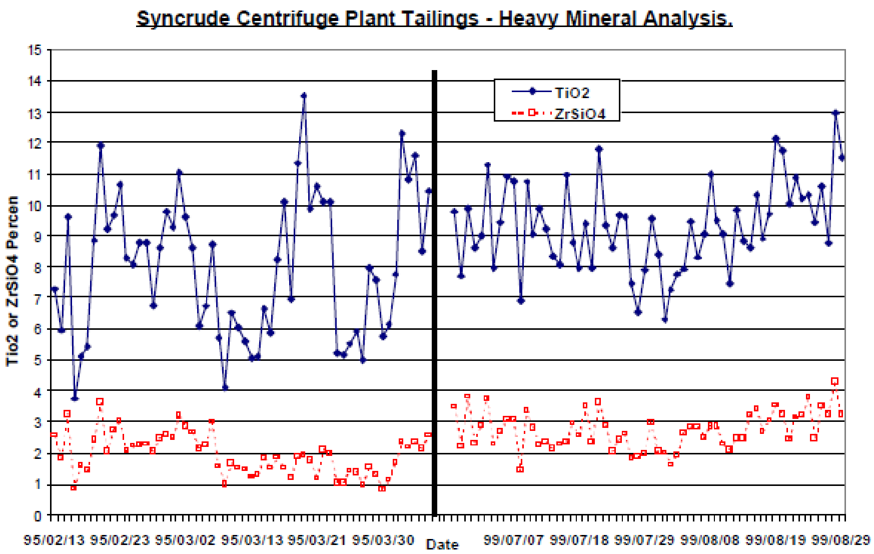

Figure 3 Concentration of Heavy Minerals in the Syncrude Centrifuge Tailings

DISCUSSION

PREVIOUS WORK

The occurrence of heavy minerals in the Athabasca oil sands has long been known for some time (Blair (1950), Scotland and Benthin (1954), and Owen (1996)). The first research work to examine options to recover these minerals appears to be that of the research staff of Syncrude Canada Ltd. (Schutte and Trevoy, 1981). This work was undertaken in 1976/77 and was widely published. This work had to be undertaken on tailings from various pilot plants as tailings from Syncrude's froth treatment plant (Plant 6) did not become available until after startup in early 1978. Schutte and Trevoy calcined the tailings to remove bitumen and secondary minerals such as pyrite and siderite, and then produced a bulk heavy mineral concentrate using gravity separation. They processed this concentrate using electrostatic separation to produce some TiO_2-rich streams and some ZrO_2-rich streams. None of these streams approached marketable quality.

In 1981, Syncrude shipped approximately 400kg of heavy mineral concentrate to Mineral Deposits in Queensland, Australia for testwork. This sample was prepared by calcining Plant 6 tailings at 700^{0}C followed by gravity separation. Mineral Deposits succeeded in producing a few hundred grams of near-marketable rutile and zircon from this bulk concentrate (Balderson, 1982). Mineral Deposits' mineral analysis for this sample differs significantly from all analyses before and since. It is not known if this is a result of differing analytical techniques or differences in the sample.

In the mid-1980's, Ityokumbul earned a PhD from the University of Western Ontario for his work on separation of heavy minerals from Athabasca oil sands tailings (Itykumbul et al., 1985) Ityokumbul was the first researcher in the literature to have used froth flotation as part of the separation process and his work resulted in the granting of Canadian Patent 1,326,571. Ityokumbul used flotation to prepare a bulk concentrate, which was then calcined. The calcined product was treated by gravity methods to remove fines, silica, and some of the "light heavies" and this final concentrate was treated using conventional electrostatic and magnetic methods. None of the products produced would appear to have been of marketable grade.

In the mid-1990's, the Federal/Provincial Mineral Development Agreement (MDA) undertook an extended study on heavy mineral distribution within the Athabasca deposit along with an extensive research effort on flowsheet development. The MDA followed generally established procedures in its flowsheet development. A cyclone was initially employed to remove much of the fines and silica and then the cyclone underflow was calcined to remove bitumen and secondary minerals. Gravity and magnetic separation was then used to produce mineral concentrates, but none of the products produced was of marketable grade. The MDA also initiated a number of mineral analyses of the heavy mineral fraction and these were quite conflicting. This has added to the uncertainty in being able to assess the potential of this resource (Coward and Oxenford, 1997).

METALLURGICAL CHALLENGES

The metallurgical challenges associated with this heavy mineral resource are highlighted in the mineral analysis as shown in Table 2 (Bulatovic, 2000). The bulk of the TiO_2 occurs in altered ilmenite, pseudorutile and leucoxene while there is only a small portion of unaltered ilmenite and rutile. Table 2 also shows that approximately 25% of the heavy mineral suite is made up of garnets and other ferro-silicates. As shown in Table 3, these have similar gravity, electrostatic and magnetic properties to the altered ilmenite, leucoxene and other valuable heavy minerals. To add to the metallurgical difficulties, some of the garnets would appear to be low in iron and tend to report to the nonmagnetic, non-conductor fractions. As a result, separation of the valuable heavy minerals using the conventional technology of the industry is extremely difficult, if not impossible. This unusual mineral assemblage explains some of the difficulties experienced by various researchers and some of the unusual assays obtained. For instance, some of the results obtained by Mineral Deposits (Balderson, 1982) show ilmenite fractions with 30% TiO_2 and 15% Al_2O_3 while the MDA (Owen, 1996) reports zircon fractions with 60% ZrO_2 and 10% Al_2O_3.

One of the other major metallurgical challenges associated with this resource is the presence of bitumen coating on the heavy minerals. This coating occurs because these minerals are preferentially "oil wet", and in the process to remove bitumen from oil sand, these minerals report to the bitumen fraction. As a result, when the heavy minerals are finally removed from the bitumen concentrate by centrifuging, they are well coated with bitumen.

Table 2 Typical heavy mineral assemblage from Alberta oil sands

MINERAL	% Wt.
Opaques:	
Altered Ilmenite	23
Leucoxene	16.6
Pyrite	4.0
Rutile	4.0
Ilmenite	2.8
Goethite	1.6
Non-Opaques:	
Tourmaline	16.7
Zircon	15.2
Garnet	6.0
Staurolite	4.8
Siderite	3.0
Calcite	0.6
Kyanite	0.6
Apatite	0.6
Others: - Monazite: - feldspars, -micas	0.5

The normal process for bitumen removal has been by calcination at around 700^{0}C. This achieves a number of objectives.

- It removes the bitumen and any other carbonacious material entirely.
- It also removes the secondary minerals such as calcite, siderite and pyrite.

However, the process also oxidizes the Fe^{II} in the ilmenite to Fe^{III} which greatly reduces its magnetic susceptibility. This reduction in magnetic susceptibility increases the difficulty in separating the altered ilmenite and leucoxene from the ferro-silicates. This is highlighted by (Liu, 2001) in Figure 4 where he shows the reduced yield of magnetic product with increased oxidation temperature.

However, as Figure 5 shows, the magnetic susceptibility will increase quite dramatically under reducing conditions (Liu , 2001). This has not been explored by any of the researchers and might offer some potential processing options.

Table 3 Separation characteristics of heavy minerals

MINERAL	SPECIFIC GRAVITY	MAGNETIC PROPERTY	ELECTROSTATIC CONDUCTIVITY
Ilmenite	4.5-5.0	Magnetic	Conductor
Altered Ilmenite	4.0-5.0	Magnetic	Conductor
Leucoxene	3.5-4.5	Weakly Magnetic	Conductor (generally)
Rutile	4.2	Non-magnetic	Conductor
Zircon	4.6-4.7	Non-magnetic	Non-conductor
Pyrite	4.9-5.2	Weakly Magnetic	Conductor
Tourmaline	3.0-3.2	Weakly Magnetic	Non-conductor
Garnet	3.4-4.2	Weakly to non-magnetic	Non-conductor
Staurolite	3.7-3.8	Weakly Magnetic	Non-conductor

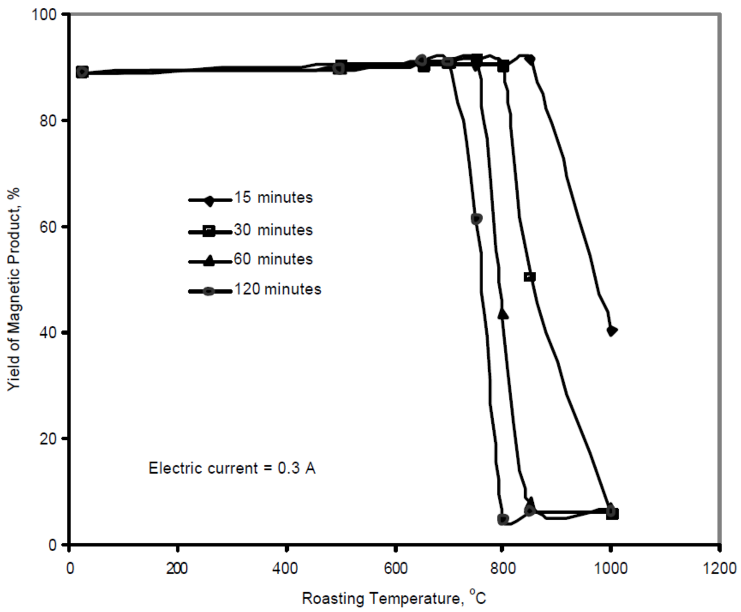

Figure 4 Effect Of Temperature On Recovery

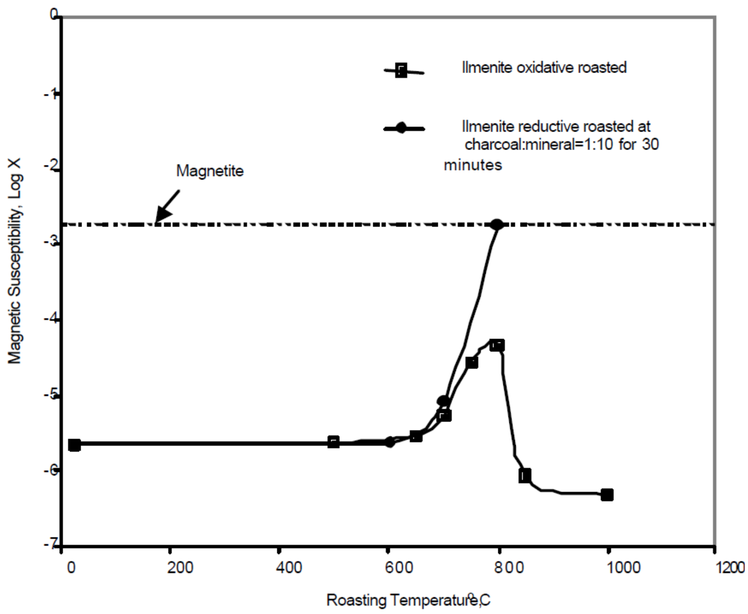

Figure 5 Effect of temperature on magnetic susceptibility

FLOTATION STUDIES

NEW APPROACH IN BENEFICIATION OF ATHABASCA HEAVY MINERALS

The MDA process development work showed, among other things, that it was extremely difficult, if not impossible, to produce market-grade products using the conventional metallurgical processes of the industry. It was obvious that a new alternative approach was necessary to resolve the process concerns. Extensive research work (Bulatovic, 1999) was conducted to develop an alternative method by which commercial grades of zircon, ilmenite and rutile could be produced from the Athabasca heavy mineral suite. Essentially, the new approach consisted of the following steps:

- Upgrading of centrifuge plant tailings stream which contains the heavy minerals to produce high-grade bulk concentrate, using agglomeration flotation in a hot pulp.
- Sequential flotation of zircon-titanium from either calcined or de-oiled bulk concentrate.
- Upgrading of zircon and the separation of individual titanium concentrates

In each step, a new technology was employed where either new reagents and/or a new process were applied.

UPGRADING OF HEAVY MINERAL SAND USING AGGLOMERATION FLOTATION

The objective of this study was to develop a flotation technique by which a high-grade zircontitanium bulk concentrate could be produced, suitable for further processing. In this study, the following two approaches were examined:

- Bulk flotation of zircon and all titanium minerals, including ilmenite, pseudorutile and leucoxene.
- Semi-bulk flotation of zircon, ilmenite and pseudorutile, followed by leucoxene flotation from the bulk flotation tailing.

BULK FLOTATION OF ZIRCON AND ALL TITANIUM MINERALS

The bulk flotation of zircon and all titanium minerals was examined using agglomeration flotation at elevated temperatures (75-85°C). The procedure essentially involved the use of a fatty acid plus alcohol mixture as an agglomerate. The hot pulp was stage conditioned with alkali, silica depressant and fatty acid mixture, followed by flotation of the bulk concentrate. Flotation recovery of heavy minerals was found to be a function of both pH and flotation temperature.

Figure 6 shows the effect of pH on zircon and titanium recovery in the bulk concentrate. The data in Figure 6 indicated that high recoveries could be obtained at a higher pH value (i.e. above pH 11).

UPGRADING OF HEAVY MINERAL SAND USING AGGLOMERATION FLOTATION

The objective of this study was to develop a flotation technique by which a high-grade zircontitanium bulk concentrate could be produced, suitable for further processing. In this study, the two following approaches were examined:

- Bulk flotation of zircon and all titanium minerals, including ilmenite, pseudorutile and leucoxene.
- Semi-bulk flotation of zircon, ilmenite and pseudorutile, followed by leucoxene flotation from the bulk flotation tailing.

The flotation temperature also had a significant impact on heavy mineral recovery. Figure 7 shows the effect of temperature on heavy mineral recovery. The minimum flotation temperature required to obtain high heavy mineral recoveries was 70°C. The maximum recovery was obtained at a temperature of 80°C.

Typical metallurgical results obtained from agglomeration flotation are shown in Table 4.

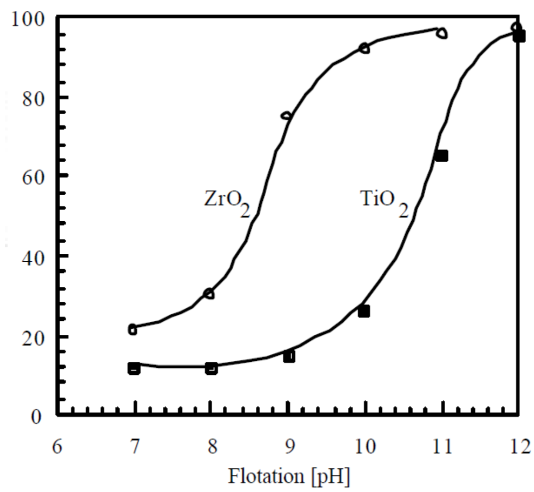

Figure 6 Effect of pH on heavy minerals bulk flotation using agglomeration method

SEMI-BULK FLOTATION OF ZIRCON-ILMENITE PSEUDORUTILE FOLLOWED BY LEUCOXENE FLOTATION

The conditions used in the semi-bulk flotation were similar to that used in bulk flotation, except that starch was used to depress leucoxene. Leucoxene was recovered from the semi-bulk tailing after de-sliming using an ester collector in acid pH (4.5). Typical results obtained using this method are shown in Table 5.

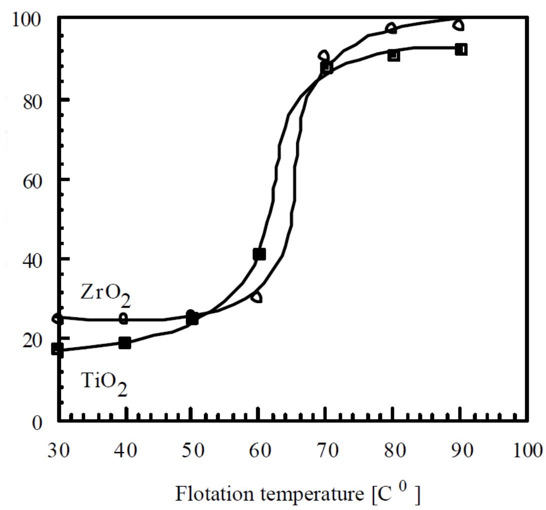

Figure 7 Effect of temperature on heavy mineral bulk flotation

Table 4 Bulk flotation results using agglomeration technique

PRODUCT	WT %	ASSAYS %				(%) DISTRIBUTION			
		ZrO_2	TiO_2	Fe_2O_3	SiO_2	ZrO_2	TiO_2	Fe_2O_3	SiO_2
Bulk Concentrate	47.67	7.1	27.6	13.0	33.3	99.4	97.0	81.7	26.1
Bulk Tailing	52.33	0.04	0.77	2.65	85.8	0.6	3.0	18.3	73.9
Feed (Calc)	100.0	3.38	13.6	7.59	60.8	100.0	100.0	100.0	100.0

Table 5 Semi-bulk flotation results

PRODUCT	WT (%)	ASSAYS (%)		(%) DISTRIBUTION	
		ZrO_2	TiO_2	Fe_2O_3	SiO_2
Bulk ZrO_2/ TiO_2 Concentrate	42.4	8.23	27.8	99.3	86.1
Leucoxene Rougher Concentrate	5.1	0.14	28.8	0.2	10.7
Leucoxene Rougher Tailing	52.5	0.03	0.82	0.5	3.2
Feed (Calc)	100	3.51	13.7	100	100

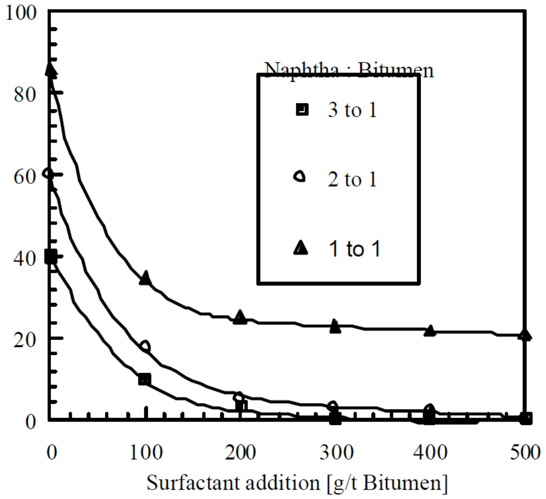

Figure 8 Effect of level of surfactant on bitumen removal at different naphtha:bitumen ratios

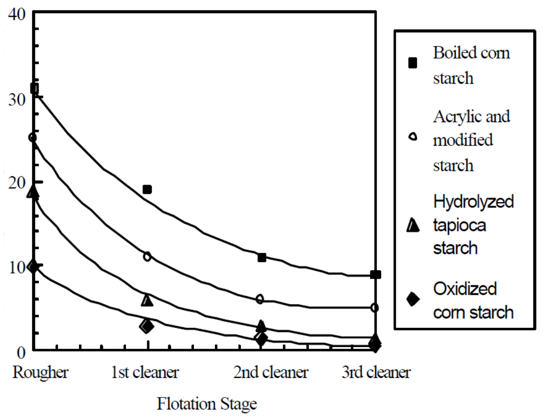

Figure 9 Effect of different starches on titanium displacement in the zircon concentrate

REMOVAL OF BITUMEN FROM BULK CONCENTRATE

The bulk concentrate produced by agglomeration flotation was coated with bitumen and contained between 4% and 8% bitumen by weight. In this study, two options of bitumen removal were examined. These included:

- Calcination of the bulk concentrate before sequential ZrO_2/TiO_2 flotation. Calcination temperature of about 550°C for a time period of 60 minutes was sufficient to remove all the bitumen. In this process, all the pyrite present in the concentrate was converted to oxides.
- De-oiling of the bulk concentrate. This process involved scrubbing of the bulk concentrate in the presence of naphtha and surfactant, followed by removal of liquidated bitumen in a cyclone. Successful removal of bitumen was dependent on the naphtha:bitumen ratio and level of surfactant additions. The effect of the level of surfactant and the naphtha to bitumen ratio is illustrated in Figure 8.

Effective bitumen removal was achieved at a higher surfactant additions and higher naphtha :bitumen ratio.

Selective zircon-titanium flotation was achieved when using either of two bitumen removal methods. However, each method had its advantages and disadvantages, some of which included:

- Using the calcination method, a sharper ZrO_2/TiO_2 separation was achieved due to the fact that the sulphides were converted to oxides and thus did not interfere with the separation. Environmental concern is a problem using this method.
- De-oiling provided additional recovery of bitumen. Pyrite removal, however, represented a problem because a fairly large amount of pyrite, in the form of middlings, was difficult to recover and interfered with sequential ZrO_2/ TiO_2 separation. In addition, a pyrite flotation stage had to be added. Pyrite was floated before zircontitanium separation.

SEQUENTIAL ZIRCON-TITANIUM FLOTATION

ZIRCON FLOTATION

A treatment process, involving sequential zircontitanium flotation, was studied on a number of heavy mineral complex deposits (Bulatovic, 1988 and 1993). In these instances, innovative processes were developed.

The Athabasca heavy mineral sand was quite unique from a zircon-titanium separation standpoint, because the titanium was represented by a variety of minerals, including ilmenite, rutile, pseudorutile and leucoxene. Leucoxene, in particular, was difficult to depress during zircon flotation. Efforts in this study were placed on finding an effective titanium depressant and a selective zircon collector.

Different, modified starches were evaluated for titanium depression. The effects of these different starches on zircon-titanium flotation are illustrated in Figure 9.

From the data shown in Figure 9, the oxidized cornstarch was the most effective titanium depressant. Other starches examined were not effective depressants. In these experiments, small additions of NaF were made, together with starch.

The collector types examined included primary amines (Armac C) and modified mixtures of primary and secondary amines. Figure 10 shows the effect of the different amine collectors on the rate of zircon flotation. The modified mixture of primary and secondary amines (i.e. collector 3CG) gave the highest rate of zircon flotation, along with the highest zircon recovery.

Armac C was not an effective zircon collector in the case of the Athabasca heavy mineral sand. One interesting feature of this zircon-titanium separation method was that tourmaline and garnet group of minerals floated together with the zircon, which otherwise would cause a selectivity problem in the subsequent titanium flotation circuit.

ZIRCONIUM UPGRADING

The zirconium produced by flotation was relatively low grade (25-30% ZrO_2) and contained light gangue minerals and monazite. Typical flotation metallurgical results are shown in Table 6.

Further upgrading of the flotation concentrate was achieved using a combination of gravity and high-gradient magnetic separation. The separation flowsheet is shown in Figure 11.

The final concentrate grade produced from this flowsheet assayed 65.1% ZrO_2 and 1.16% Hf, as shown in Table 7.

TITANIUM FLOTATION AND UPGRADING

Titanium was recovered from the zircon tailing also using a flotation technique. The zircon tailing was preconditioned with acid and deslimed before titanium flotation.

The depressant system employed in this study was H_2SiF_6 plus Oxalic Acid with additions of a small quantity of sodium silicate added to the cleaners. A large portion of the testwork was devoted to the evaluation of collectors, because both concentrate grade and titanium recovery were highly dependent on the type of collector used. Collectors from the PL500 series were the focus of this study (Bulovbic, 2000). These collectors were a mixture of different phosphoric acid esters and succinamates, modified with either a fatty alcohol sulphate or an amphoteric compound. The effect of several of these collectors on titanium flotation and upgrading are illustrated in Figure 12.

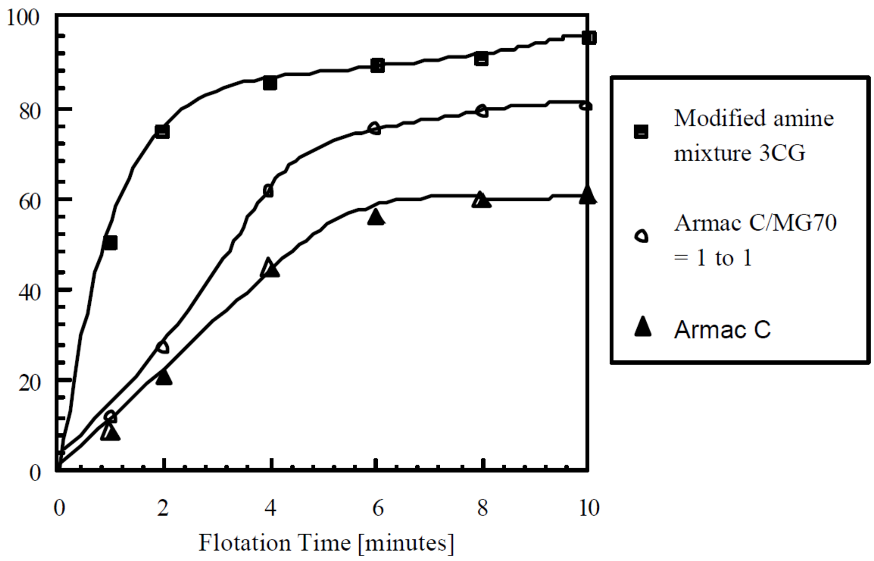

Figure 10 Effect of type of amine collector on the rate of zircon flotation

Table 6 Typical metallurgical results obtained on sequential zircon-titanium flotation

PRODUCT	WT (%)	ASSAYS (%)		(%) DISTRIBUTION	
		ZrO_2	TiO_2	Fe_2O_3	SiO_2
ZrO_2 Cleaner Concentrate	26.45	28.5	0.68	89.1	0.6
ZrO_2 Rougher Concentrate	30.45	25.7	2.33	92.5	2.5

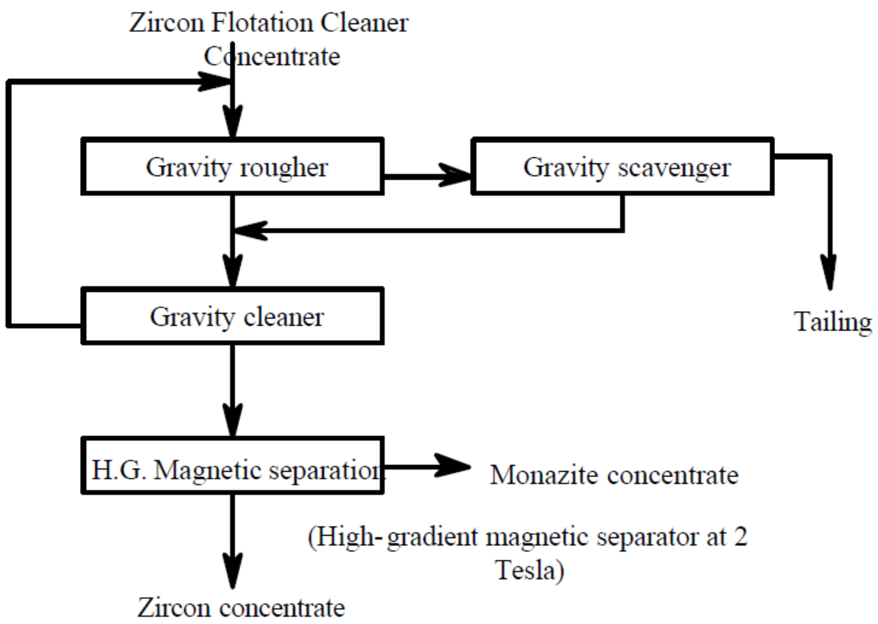

Figure 11 Zirconium upgrading flowsheet

There were significant differences in the grade/recovery relationship with the use of different collectors. Collector PL501 gave the best metallurgical results from the collectors examined. The metallurgical results obtained in the batch tests are shown in Table 8.

Table 7 Zirconium upgrading test results

PRODUCT	WT (%)	ASSAYS (%)				(%) DISTRIBUTION		
		ZrO_2	Hf	Fe_2O_3	TiO_2	ZrO_2	Fe_2O_3	TiO_2
Zirconium Final Conc*	35.67	65.1	1.16	0.15	0.23	81.2	0.6	10.6
Monazite Product **	5.3	35.6	-	6.7	0.86	6.6	4.1	5.9
Gravity Middlings	6.07	27.8	-	15.6	0.5	5.9	10.9	4.0
Gravity Tailing	52.96	3.4	-	13.8	1.16	6.3	84.4	79.5
Feed (Calc)	100	28.6	-	8.66	0.77	100	100	100

*(2 tests non-mag) **(2 tests low-mag)

Table 8 Titanium metallurgical results obtained in the batch tests

PRODUCT	WT (%)	ASSAYS (%)		DISTRIBUTION (%)	
		ZrO_2	TiO_2	ZrO_2	TiO_2
ZrO_2 Rougher Concentrate	30.45	25.7	2.33	92.5	2.5
TiO_2 Cleaner Concentrate	35.57	1.0	70.1	4.2	86.6
TiO_2 Rougher Concentrate	46.19	0.87	55.8	4.7	89.5
TiO_2 Rougher Tailing	23.36	1.09	9.89	2.8	8.0
Feed (Calc)	100.00			100.00	100.00

FRACTIONATION OF THE TITANIUM FLOTATION CONCENTRATE

The titanium concentrate produced by flotation was in fact a bulk concentrate containing ilmenite, rutile alterations and leucoxene. Preliminary laboratory studies were performed to examine the possible production of individual titanium concentrates, including ilmenite, rutile and leucoxene. The separation method involved (Figure 13) included low intensity magnetic and electrostatic separation.

The fractionation test results are shown in Table 9.

About 18.5% of the titanium present in the concentrate was represented by an ilmenite fraction, assaying 64.4% TiO_2. The largest portion of titanium was represented by a pseudorutile + rutile mixture and assayed 74.6% TiO_2. The leucoxene fraction was represented by 23.5% of the total titanium, assaying 65% TiO_2 and 11.7% SiO_2.

The treatment process involving flotation and upgrading of the corresponding concentrate, using a physical separation method gave reasonably good metallurgical results but further refining of this process is required to become a commercial process.

CONCLUSIONS/FUTURE WORK

POTENTIAL PRODUCTION QUANTITIES AND QUALITIES

Based on 1996 production levels, it is estimated that the following annual production levels could be achieved from the processing of Syncrude's tailings:

- Rutile (>95% TiO_2) 20,000 tonnes
- Pseudorutile/leucoxene (>75% TiO_2) and Altered ilmenite/leucoxene (65%-75% TiO_2) >130,000 tonnes
- Ilmenite (64% TiO_2) 40,000 tonnes
- Zircon 50,000 tonnes

Table 9 Titanium bulk flotation concentrate fractionation test results

PRODUCT	WT (%)	ASSAYS (%)				(%) DISTRIBUTION	
		ZrO_2	TiO_2	Fe_2O_3	SiO_2	ZrO_2	TiO_2
Low intensity mags (ilmenite conc)	20.1	0.24	64.4	90.3	1.3	5.1	18.5
Conductor (rutile conc)*	42.4	0.42	74.2	17.2	1.8	19	44.9
Middlings (rutile middling)*	12.3	0.75	74.8	12.6	4.5	9.9	13.1
Non-Conductor (leucoxene conc)	25.2	2.45	65.4	6.56	11.7	66.0	23.5
Feed	100.0	0.94	70.1	16.5	4.5	100.0	100.0

*electrostatic separation

ECONOMICS AND RELIABILITY OF SUPPLY

The conventional oil and gas industry, probably more than any other industry in the resource sector, is extremely cyclic in nature. When commodity prices are high, production is maximized and variable expenditures on such items as exploration and drilling are undertaken. When commodity prices are low, high-cost production is shut in and variable expenses are minimized.

This is not the case for the oil sand industry. The extremely high capital investments required to establish these operations, demand that production levels be maximized at all times regardless of the business cycle. It is reasonable to assume, therefore, that the production levels as outlined in this paper will be achieved regardless of the price of oil. The only uncertainty might be the level of production to be achieved from those projects still in the planning stages. It should also be remembered also that each of the operators has reserves to sustain production for in excess of 50 years, even at the expanded production rates that have been proposed.

Although the metallurgical flowsheet required for Athabasca oil sand mineral suite is a little more complex that is normal in the industry, this added complexity and cost is more than offset by the elimination of mining, tailings disposal and environmental remediation charges. Coward and Oxenford (1997) show that there are a number of business options possible based on the level of processing undertaken in the Fort McMurray area. Some of these options could be quite attractive if the metallurgical concerns could be overcome. These options could be even more attractive because of the recent changes in the tax rules for resource developments.

FUTURE WORK

Further work includes some or all of the following:

- Undertake further testwork to resolve some of the issues around the high TiO_2 products. Efforts will focus on reducing SiO_2 levels.
- Undertake further testwork to improve the quality of the zircon product by reducing the Fe_2O_3 and TiO_2 levels.
- Continue work to better understand the fundamental properties of the individual minerals within this mineral suite.
- Prepare samples for market evaluation.
- Continue efforts to raise the profile of this major resource and highlight its potential to become a valuable future supply option.

ACKNOWLEDGEMENTS

The authors thank Syncrude Canada Ltd. for permission to publish this paper. The authors also wish to acknowledge the valuable contributions and advice received from so many colleagues from the industry and from Syncrude Canada, SGS and the University of Alberta.

REFERENCES

Balderson, G F, March 1982. Test Work on Scroll Centrifuge Tailings from Syncrude Canada Ltd., Mineral Deposits Limited Report No. 46.123.1/1.

Blair, S M, 1950. Development of the Alberta Bituminous Sands - Report On The Alberta Bituminous Sands, Report, Bechtel Corp and UOP, Edmonton.

Bulatovic, S, et al., April 3, 1993. Process development for beneficiation of Wimmera (Australia) fine mineral sand, Report of Investigation, LR4366.

Bulatovic, S, June 1998. Process development for beneficiation of Grass Creek (USA) zirconium titanium heavy mineral sand, Report of Investigation, LR4177.

Bulatovic, S, 1999. The recovery of zircon and titanium from Athabasca heavy mineral sand, Report of Investigation, LR5358 and LR5569.

Bulatovic, S, June, 2000. An Investigation of the Recovery of Zirconium and Titanium from Athabasca Oil Sand Samples Lakefield Research Final Report LR5569.

Bulatovic, S, de Silvio, E, 2000. Process development for impurity removal from tin gravity concentrate, Minerals Engineering, Volume 13, No. 8-9.
Coward, J E and Oxenford, J, 1997. Heavy Mineral Potential of Athabasca Oil Sands, TiO_2 97 Conference, Intertech Conferences.

Ityokumbul, M T, Kosaric, N, Bulani, N, and Cairns, W L, 1985. Froth Flotation for the Beneficiation of Heavy Minerals from Oil Sand Tailings, AOSTRA Journal of Research, 2(1), 59-66.

Liu, Q, January 2001. Impact of Residual Bitumen Removal Methods on the Separation of Heavy Minerals in the Oil Sand Tailings, First Progress Report, COURSE Project Number 1398, University of Alberta.

McCosh, R, September 1996. Geology Executive Summary from Mineral Development Agreement, Final Report, Alberta Chamber of Resources.

Owen, M, 1996. Mineral Development Agreement, Final Report, Alberta Chamber of Resources.

Scotland, W A and Benthin, H, 1952-1954. Exploration of the Alberta Bituminous Sands. Unpublished report of the Alberta Department of Energy.

Taylor, R, 1999. Potential for Commercial Development of Heavy Minerals from Oil Sand Tailings. TZ Mineral International Report, 332/023.

Trevoy, L W, and Schutte, R, February, 1981. A new Source of Heavy Minerals from Canadian Oil Sands Mining

CONTACT INFORMATION

Email us at minerals@sgs.com
WWW.SGS.COM/MINERALS

WHEN YOU NEED TO BE SURE