TECHNICAL PROGRESS REPORT
AWARD NO. DE-FG26-06NT42745
APRIL- JUNE 2008

SOLVENT BASED ENHANCED OIL RECOVERY FOR IN-SITU UPGRADING OF HEAVY OIL

1 PROPRIETARY NOTICE

This document contains trade secret and commercial or financial information that is proprietary to the Applied Research Center at Florida International University. Pursuant to the protection accorded by the Freedom of Information Act [5 USC 552(b) (4)], as amended, and the provisions of 18 USC 1905, it must at all times be treated as privileged and confidential and is not to be duplicated, used, or disclosed, in whole or in part, for any purpose except as specifically authorized by the Applied Research Center in writing.

2 TABLE OF CONTENTS

1 PROPRIETARY NOTICE 1

2 TABLE OF CONTENTS 1

3 ACTIVITIES 1

4 SIGNIFICANT UPCOMING EVENTS 2

3 ACTIVITIES

During this quarter, a significant amount of effort was devoted to the following tasks:

Preparation of a peer-reviewed paper entitled, "A Mathematical Model of CO_2 Injection in Heavy oil Reservoirs", for presentation at the annual COMSOL conference in Boston, October 2008.

The University of Texas, Austin prepared a report on Capacity of Solvent Based Injection Processes to Reduce Unwanted Substances.

4 Significant Upcoming Events

We intend to include the super critical behavior of carbon dioxide in the mathematical model being developed. Additionally, we will continue to develop the experimental setup to evaluate gas dispersion in a porous media via PIV.

5 APPENDIX – A Capacity of Solvent Based Injection Processes to Reduce Unwanted Substances.

APPENDIX – A

BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN

SUPPORT FOR
"SOLVENT BASED ENHANCED OIL RECOVERY FOR IN-SITU UPGRADING OF HEAVY OIL SANDS"

JULY 2008

1 TABLE OF CONTENTS

1 TABLE OF CONTENTS 2

2 ACTIVITY DESCRIPTION 2

3 CAPACITY OF SOLVENT-BASED INJECTION PROCESSES TO REDUCE UNWANTED SUBSTANCES 2

4 ECONOMIC MODELING OF HEAVY OIL EXPLOITATION AND UPGRADING 7

5 CONCLUSIONS 12

6 APPENDIX: SAMPLE CRUDE ASSAY 13

2 ACTIVITY DESCRIPTION

The University of Texas at Austin Bureau of Economic Geology's Center for Energy Economics provided support to Florida International University's Applied Research Center in their DOE funded 3 year project "Solvent Based Enhanced Oil Recovery for In-Situ Upgrading of Heavy Oil Sands". This report presents research results for the support provided, with special focus on tasks 2 (reported on previously) and 3 of the subcontract between both institutions.

Task 2 quantified, based on available bitumen characterization data, the capacity of solvent injection based processes of addressing the need to reduce chlorides, nitrogen and other unwanted substances from upgraded crude. Task 3 dealt with the economic modeling of heavy oil sand exploitation and upgrading and the opportunities for in-situ upgrading.

3 CAPACITY OF SOLVENT-BASED INJECTION PROCESSES TO REDUCE UNWANTED SUBSTANCES

The capacity of solvent based processes of addressing the need to remove certain compounds from the crude/tar was quantified. Solvent based upgrading processes target the removal of

asphaltenes from the crude matrix in addition to some additional heavy components. The process is a consequence of changing the matrix of fluids in which the asphaltenes are suspended (possibly in the form of miscelles). The change in the fluid matrix leads to the precipitation of asphaltenes generating an additional phase. This phenomenon is observed both in heavy as well as in light crude oil (though asphaltene concentrations are much greater in heavier crude). Some heavy resins may be trapped within the asphaltene miscelles and would be trapped in the precipitate. This highly viscous hybrid phase will have a lower mobility than the matrix, which now has an even lower viscosity due to the presence of the solvent. This allows for the treatment of the precipitate as a solid in suspension in the matrix.

Fortunately, the generation of a new phase and the marked difference in mobility can be used to physically separate the two. Given that many of the undesired heavy metals are associated with porfirins and other types of asphaltenes that are present in the precipitate, an upgraded crude can be obtained. In addition, some of the more recalcitrant compounds that have Sulfur and Nitrogen are also in the asphaltene fraction, leaving more easily treatable compounds in the upgraded crude.

We chose to base our estimates on a publicly available assay of tar sand: the Surmont oil sands (or bitumen) of Athabasca though the results can be readily extended to the Schrader Bluff Pool at the Milne Point Unit in Alaska[1]. This Surmont oil sand is representative of the extensive

1 US DOE Report DOE/BC/14864-15 (DE-96006092) 1995. The research project had the purpose of determining the nature of the miscible solvent that would optimize (economically) heavy oil recovery from Schrader Bluff. Given the properties of the 1.5 billion barrels in place (14 to 21 API), the upgrading was limited due to the miscibility of the solvent but the tests showed an increase in productivity and of the estimated recovery factor.

Oil sands deposits in North America. Based on the assay, we estimated the capacity to upgrade the crude and to determine the new contents of the undesired substances. The methodology used to estimate the capacity to upgrade crude and the properties of the upgraded crude can be extended to other crude for which an assay is available.

In order to estimate the properties of the upgraded crude, we first assumed that the solvent process could remove 100% of the asphaltenes present in the crude. This is observed in standard tests using heavier solvents such as pentane. Presented below is a table that shows the properties of the original crude and that of an upgraded crude with 100% removal of asphaltenes which would serve as the upper bound of upgrading using this type of process from the perspective of heavy metal removal.

		Crude	Asphaltenes	Upgraded Crude
V	ppm	221	208.88	12.12
Ni	ppm	78.2	77.64	0.56
Fe	ppm	30.2	26.48	3.72
N	%	0.32	0.05	0.27
S	%	5	0.60	4.40
Acid Number		2.7	0.27	2.43

Of interest is that the removal of the asphaltenes is able to considerably reduce heavy metal content. However, nitrogen, sulfur and acidic compounds are only reduced slightly.

The reason for the lackluster results for the removal of certain substances is that these in particular are present in other components in addition to the asphaltene fraction with similar concentrations. That implies that even with the removal of asphaltenes, the concentration of these substances is only slightly modified. However, as will be seen below, the ability to process the crude is greatly improved.

The main benefit is the reduction in the concentration of heavy metals. Vanadium, nickel and iron are found predominantly in asphaltenes and are mostly not present in the upgraded crude. This fact has an additional very important implication. Compounds such as sulfur and nitrogen are removed in refinery processes using in most cases catalytic processes. The effectiveness of catalysts is reduced with the presence of heavy metals such as V and Ni. Given that these heavy metals have been removed from the matrix, catalytic processes will now be able to remove S and N from the upgraded crude with greater ease and at lower overall costs.

The results presented above are independent of the solvent used since they represent an upper bound for asphaltene removal. Depending on PVT conditions and the properties (affinity) of the solvent, different results can be obtained. Of interest is considering the use of CO_2 as the proposed solvent. CO_2 has been used as an additive in SAGD processes[2] and its effect has been

2 S. Canbolat et al, Asphaltene Deposition Durng SAGD: Effect of Non-Condensable Gases, Petroleum Science and Tehcnology, 24:69-92, 2006.

studied. Increases in CO_2 injection in addition to the steam, where shown, at least modeled, to result in increased asphaltene deposition.

The phase behavior of CO_2/crude oil mixtures[3] presents an interesting property that we believe will determine the design of any CO_2 based heavy oil upgrading process. Given that CO_2 would be handled in its supercritical state, one interesting feature is that the density of CO_2 changes greatly with small changes in pressure. The consequence of this is related to the fact that solvent extraction processes, as mentioned above, are directly tied to the density of the solvent being used. Thus different "solvents" can be achieved with changes in the pressure of the extraction. Higher pressure results in a denser CO_2, and thus a heavier solvent. A heavier solvent is more compatible with heavier non-asphaltene fractions of the crude which are removed from the precipitate. This implies less quality of the upgraded crude. On the other hand, a lower pressure results in a lighter solvent and thus higher quality upgraded crude.

This behavior of CO_2 and crude oil mixtures will need to be addressed in any modeling attempt, especially in reservoir simulators since during production, near well bore pressure reduces rather quickly as distance to the well bore is reduced. This would lead to spatially

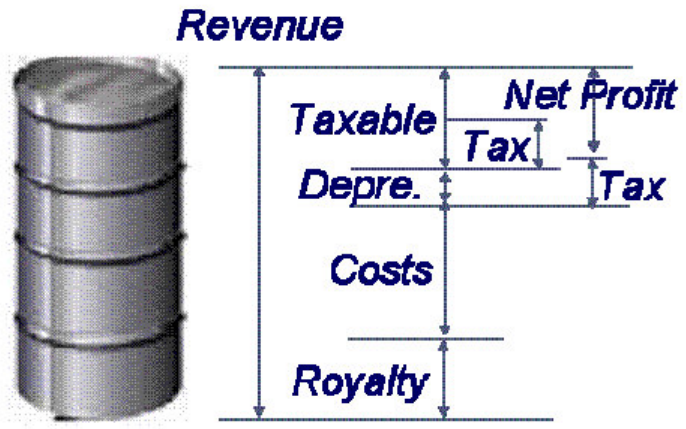
3 J. Hwang et al, Phase Behavior of CO_2/Crude Oil Mixtures in Supercritical Fluid Extraction System: Experimental Data and Modeling, Ind. Eng. Chem. Res. 1995, 34, 1280-1286

varying interactions between the CO_2 solvent and the crude oil. Interestingly, the crude that is near the well bore, or has moved towards the well bore, should have already had contact with the solvent and will already have some level of upgrading. The additional interactions near the well bore will be able to upgrade the crude even more if the mobility ratio between the solvent upgraded crude mixture and the separation of phases are appropriate.

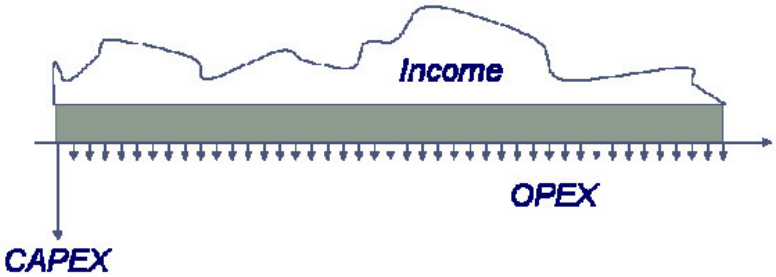
4 ECONOMIC MODELING OF HEAVY OIL EXPLOITATION AND UPGRADING

A set of simplified economic models were developed for the production and upgrading of heavy oil. Firstly, a model for the development of a Greenfield extra-heavy oil project was developed that incorporates the necessary capital expenses for midstream investments such as an export pipeline and an upgrading facility. The model incorporates uncertainty in capital expenditures, operating cost data, well production, in place crude quality, project delays and the obvious price uncertainty. The model serves as the baseline with which to compare the proposed in-situ upgrading process or any other process.

As with most oil production projects, the fiscal regime is of great importance and frames the viability of investment. A simplified tax-royalty fiscal model was implemented in the model for the exploitation of an extra-heavy or tar sand resource. Depreciation of the capital expenditures is also incorporated and allows for scenarios which consider rapid depreciation.



The economic model is a simplified discounted cash flow model. The model categorizes capital expenditures into two groups, large expenditures that are associated with the startup (initial wells, export pipeline, upgrader) and those made during production (additional well, flow stations). In addition to the additional capital expenditures that are made during the life of the project, certain expenses are made related to the operations (OPEX).

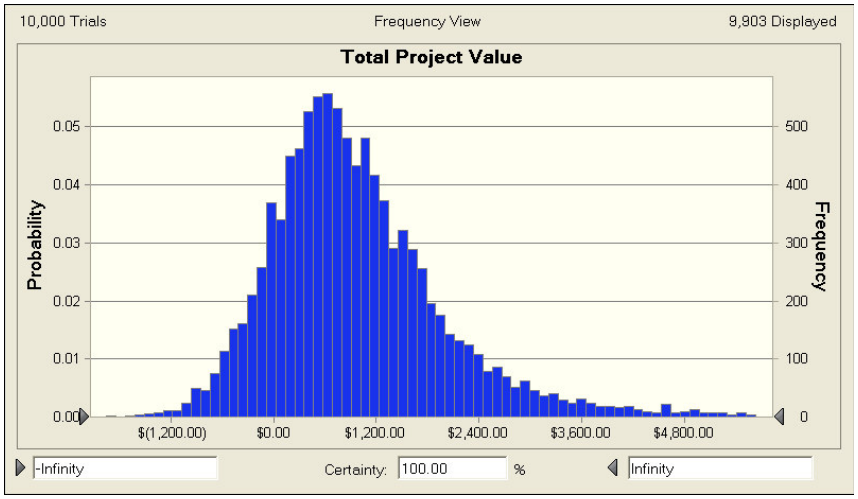


Based on this simplified cash flow model, the discounted net present value can be calculated for the project. In addition, once a fiscal regime is set, then the breakdown of cash flow into the mineral rights owner and the investor can be made. It should be clear that the potential value of the project is independent of the fiscal regime and that the fiscal regime determines the distribution of the project value between the mineral rights owner, the taxation authority and the project developer. In some cases, the mineral rights owner and taxation authority also participates

as an investor in the project (one good example is that of a country in which the National Oil Company participates in the enterprise).

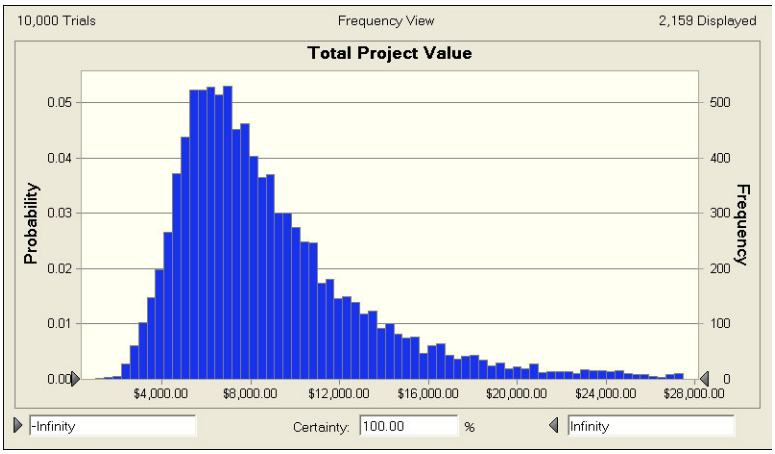
In order to provide an adequate dimension for the model, sample runs were performed to value a project with a target throughput of 100,000 barrels per day of upgraded crude oil. The project value is split between the owner of the mineral rights (royalty payments), the taxing authority and the company that is making the investment. In some cases, the owner of the mineral rights and the taxing authority are one and the same reducing the split into a company take and the government's take.

Model runs were performed for a hypothetical project[4] with a production start date of 1998 (low price expectations). This resulted with in a distribution of net present value as shown below and a NPV(P50) of $815 million.



4 The fiscal regime considered was the regime existing in 1998 in Venezuela for the exploitation of the Faja del Orinoco. Tax-royalty regimes in North America have a similar structure and can be incorporated rather easily. Current increases in royalty and tax rates in Alberta is modifying the viability of similar large scale production/upgrading projects.

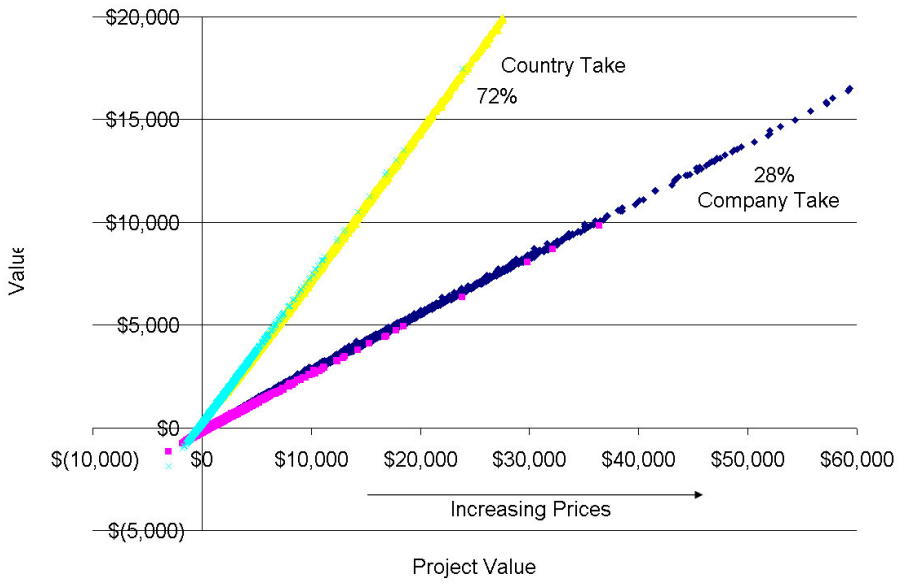
Interestingly, low price expectations were not met, but rather prices rose considerably. The project was then re-evaluated fixing prices between 1998 and 2006 to the real market prices and leaving the rest of the project with current higher price expectations. This results in a project with a NPV distribution as shown below, with a NPV(P50) of $7,786 million.



During the 7 year period, given the increase in oil prices, the expected value of the project increased an order of magnitude. More over, during the first 7 years, the original expected value was achieved leaving 90% of the value for future returns. The plot below shows the cloud of possible values for the project as a function of the price of crude in year 10. The considerable increase in value in the project is a clear consequence of the rise in oil prices during that period.

The value of the project is distributed among the owner of the resource, the taxing authority and the company that makes the necessary investments. In the case considered here, the national oil company is assumed to participate as an equal partner in the venture, increasing the government take by adding to the royalty and tax payments, half of the profits associated with the project.

The distribution of value with the assumed fiscal regime is shown below in which the horizontal axis is the value of the project, and the different takes are shown.

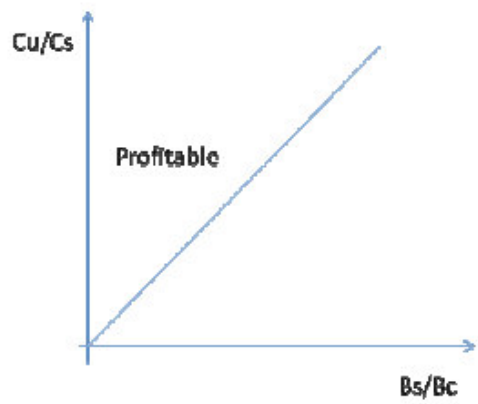


The economics of the solvent based upgrading process as proposed here is a function of many variables. From the perspective of an open system that incorporates all of the internal processes, the variables that determine the economics of the process are: cost of solvent; replacement solvent per cycle; value of original heavy crude oil; cost of upgrading said heavy crude oil to a given quality achievable via solvent based methods; value of solvent based upgraded crude.

The process is deemed to be profitable when compared to the conventional upgrading process it replaces if the ratio of the following two dimensionless quantities is greater than one: the first dimensionless quantity is the ratio of the cost of conventionally upgrading a barrel of heavy crude to the cost of a barrel of solvent; the second dimensionless quantity is the ratio between the

barrels of solvent that need to be replaced per cycle to the barrels of upgraded crude that are produced per cycle.

The most efficient process would have no losses associated with the solvent. This would imply that the solvent based process would be attractive if the cost of conventionally upgrading crude was greater than a barrel of solvent. This can be repeated for different values of the second dimensionless quantity to construct the following plot.



Current estimates for conventionally upgrading heavy crude from 8API to 16API are of the order of $8 per barrel. If that is compared with the cost of a mixture of equal parts propane and butane (cost approximately $2 per gallon or $84 per barrel), the maximum allowable loss of solvent per crude produced per cycle would be slightly less than 10%.

5 CONCLUSIONS

Solvent based processes show the potential to remove undesired substances from heavy crude such as heavy metals. The generation of a new phase within the crude and the differences in mobility between the new crude matrix and the precipitate readily allows for the removal of asphaltenes in-situ and the production of an upgraded crude low in heavy metal content that can be more easily treated to remove additional substances such as Sulfur and Nitrogen.

6 APPENDIX: SAMPLE CRUDE ASSAY

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Crude
Cut Range	C1-C5	C6-166	155	185	210	335	380	450	510	580	635	725	785	830	900	970	1050	1125	
Yield	0	0	0	0	0.26	0.3	1.21	2.16	4.01	3.87	7.4	5.63	4.68	8.33	7.22	7.26	7.01	40.67	100
Gravity	0.5734	0.6827	0.7151	0.7325	0.8268	0.8486	0.8628	0.8814	0.9018	0.9196	0.9494	0.9708	0.9754	0.9856	0.9972	1.0092	1.0238	1.0858	1.0164
API	115.3	75.8	66.4	61.7	39.6	35.2	32.5	29	25.4	22.4	17.5	14.3	13.6	12.1	10.4	8.7	6.7	-1.2	7.7154
S		0.07	0.06	0.053	1.444	1.244	1.224	1.54	1.989	2.438	33.19	3.709	3.739	3.741	3.808	4.046	4.665	6.659	5
Acid Number						0.31	0.2	0.4	0.94	2.19	2.5	2.69	2.97	3.33	3.09	3.09	3.5243	3.01222	2.7
N								0.012	0.016	0.026	0.07	0.11	0.13	0.17	0.21	0.26	0.35	0.55	0.32
Bromine										5	8.7	8.7	9.8	11.4					
V															0.5	3.7	11.2	513.6	221
Ni															0.3	1.6	4.9	190.9	78.2
Asphaltenes																		22.24	9.045
Fe															0.7	1.5	4.4	19.5	30.2