ECONOMIC EVALUATION OF GAS TO LIQUIDS (GTL) PRODUCT TRANSPORTATION THROUGH THE TRANS ALASKA PIPELINE SYSTEM (TAPS)

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A

THESIS

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ABSTRACT

The Alaska North Slope is a potential candidate for the Gas to Liquid (GTL) technology. With over 38 Tcf of natural gas reserves stranded on the Alaska North Slope, the GTL technology is considered as a possible method of harnessing the abundant resources. GTL fuels are environmentally friendly (sulfur free) with better ignition and burning properties than conventional petroleum products from crude oil. Evaluating the options of transporting GTL products through the existing Trans-Alaska Pipeline System (TAPS) together with crude oil either as a blend of crude oil and GTL (commingled) or as alternate slugs of each product (batching) is the main focus of this study. Economic evaluation using Rate of Return analysis to identify the most favorable mode of transportation of the GTL products was performed. Batching, using the modern tracking and sensor techniques was found to be the most economic method yielding the highest return on investment.

TABLE OF CONTENTS

Page #

LIST OF FIGURES

FIG #	LIST OF FIGURES (CONTD)	PAGE #

TABLE #	LIST OF TABLES	PAGE #

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The Alaska North Slope (ANS) holds an estimated 38 Trillion Cubic Feet (TCF) of proven natural gas reserves in the developed and undeveloped fields. About 26 TCF of the ANS gas is estimated to be available for sale. In addition to the known gas resources, published estimates by the U.S. Geological Survey (USGS) puts the technically recoverable gas in the undiscovered fields at about a mean value of 64 TCF (Thomas et al, 1996). Prudhoe Bay and Point Thompson fields contain about 25 TCF of the estimated 26 TCF of recoverable natural gas on the ANS, a significant resource of over 4 billion barrels of oil equivalent. Natural gas hydrates is also another huge potential source of unconventional natural gas. From the discovery of the Prudhoe Bay to the present, the urgency to develop the capability to sell the large, currently unmarketable, ANS gas resources has increased due to the steep decline in the ANS oil production.

Getting ANS natural gas resources to markets requires a thorough assessment of all the options available for harnessing, processing and transporting the gas from ANS to the markets. Options available for utilizing these gas resources include;

1. Build a new natural gas pipeline from ANS to feed an LNG facility in southeast Alaska. This option involves constructing 800-mile gas pipeline, building an LNG facility and shipping the LNG products to the Far East and the Pacific Rim markets. Total world LNG import in 1997 was 81.8 million tons, of which, 61.7 million tons representing about 75% of world LNG imports went to East Asia. Japan and Korea (nearly 60 million tons of imports). LNG imports is expected to rise to 100 million tons in 2005 and an estimated 130 million tons in 2010. Many new potential LNG supply sources competing to fill this growing demand include Qatar, Oman, and Yemen in the Middle East, Malaysia and Indonesia in Asia. The importance of these market situation is to give an insight into the pending competition that any Alaska North Slope gas project is expected to meet in the market place.

2. Transport the gas through a new natural gas pipeline to the markets through Canada to the continental US. This option is confronted with debates on the particular route the gas pipeline would take to ensure maximum benefit to all parties including the pipeline owners, the state of Alaska and its residents while taking advantage of already existing pipeline infrastructure in Canada. The options are either 'the Northern route' which will pass through the Beaufort sea,

down from the Mckenzie delta into the continental US. The other option is to route the pipeline through interior Alaska and Canada to the mid-western states.

3. The other option is to take advantage of the Gas to Liquids (GTL) technology, which is getting increasingly popular. The GTL option involves converting the gas to middle distillate hydrocarbons by the Fischer-Tropsch process and transport the fuels through the existing Trans Alaska Pipeline System (TAPS) alongside the crude oil from the ANS.

The GTL technology is one of most promising options for harnessing and utilizing the natural gas resources on the ANS. The advantage of the technology utilizing ANS gas is that it is possible to transport gas products along with the crude oil produced from the ANS through the existing Trans Alaska Pipeline System (TAPS). The Trans Alaska Pipeline System is originally designed to transport single-phase crude oil. Possible operational challenges that may be potentially posed by transporting these products through the pipeline need to be investigated. GTL products are known to have poor cold flow properties and this is a major concern for transporting GTL through TAPS. Study of solid/asphaltene deposition and wax appearance temperature and pressure when GTL flows alone or with crude oil in the pipeline. Phase behavior of GTL products and Reid Vapor Pressure concerns are all important transportation issues that are critical to any mode of transportation proposed for the GTL products.

Considering the huge investment required to make these high quality fuels, another real challenge is how to transport these products to the markets through TAPS with minimal contamination by the crude oil. The alternative is to simply blend the product with the crude oil and transport it through the TAPS. Each transportation option available has different economic impacts on the overall economics of the project depending on how much investment is made to keep the fuel as clean as possible at the Valdez marine terminal.

Transportation options identified are

i. batching alternate slugs of crude oil and the GTL products.

ii. transport the crude oil and the GTL as commingled fluids through TAPS.

The GTL option is strongly supported by the following points

- The decrease in throughput through the TAPS warrants an urgent need to get additional liquids to be transported through the TAPS

- GTL fuels are environmentally superior to fuels from crude oil containing little or no sulphur.

- The Technology is getting more popular and there are reported breakthroughs in the Fischer-Tropsch synthesis, which is constantly driving the capital cost of GTL plants to economic levels.

1.2 OBJECTIVES AND SCOPE OF STUDY

The overall objective of the study is to make an economic evaluation of all the identified modes of transporting GTL products;

a. Identify all economic parameters that affect each mode of transportation.

b. Investigate the economic impact of the change in the hydraulics and hydrodynamics of fluids in TAPS due to the introduction of GTL.

c. Incorporate the transportation of GTL products through TAPS into the entire GTL project economics to find the most economical method of transportation.

d. Incorporate some flexibility into the developed economic models to answer various 'what-if' questions.

e. Perform sensitivity analyses on all the various parameters that are input to the economic evaluation, to study the effect of any changes in those parameters to the whole project economics in general and the transportation economics in particular.

CHAPTER 2

REVIEW OF LITREATURE

The decision on how to transport GTL products through the TAPS is as important as making the decision of embarking on the GTL project itself. Identifying the various transportation options and the operational challenges facing these transport options becomes a key factor in the ANS gas utilization project. Some key components of the transportation of the GTL study include;

i. Understanding of the GTL conversion process.

ii. Identification of the transportation issues with GTL product through TAPS

2.1 THE GTL CONVERSION PROCESS

Recently, most of the new literature regarding GTL information came from Exxon and Syntroleum, two leading corporations with competing GTL processes. Both processes are based on the Fischer-Tropsch (FT) technology, but each uses a different method to produce the syn-gas used as a feed into the F-T process and different catalysts in the F-T reactor. (Robertson et al, 1999).

Gas to Liquids conversion is essentially a three-step process (Hariharan 2000).

i. Synthesis gas (Syngas) Production

ii Synthetic Crude (Syncrude) Production or Heavy Paraffin Synthesis and

iii. Heavy Paraffin Conversion or Product refining.

Synthesis gas ($CO + H_2$) is produced in the first step from natural gas by steam reforming, partial oxidation or auto thermal reforming of natural gas. Once syngas is produced, it is chemically converted to higher hydrocarbon liquids. Various GTL conversion process are available with the F-T process as the most popular. The Fischer Tropsch synthesis is a polymerization reaction that uses CH_x monomers derived from syngas to form high molecular weight hydrocarbons. It is conducted in F-T reactors, which could be a fixed bed, fluidized bed or slurry bed reactors. The fixed bed reactor is used primarily to produce diesel while the fluidized bed reactor is to produce gasoline. The third step involves upgrading F-T products and is used to improve liquid fuel selectivity and quality of GTL products. The upgrading is achieved by oligomerization of the C_3 to C_6 olefins and hydrocracking of waxes. The total cost of a GTL conversion plant is usually split in the following manner:

i. Syngas Production: 60% of total cost of conversion plant

ii. Syncrude Production: 25 - 30% of total cost

iii. Product upgrading: 10 – 15% of the total cost.

2.2 GTL TRANSPORTION HYDRAULICS

Pertinent energy equations were solved for both batch and commingled flow modes. The solutions to these equations were presented for determining pressure gradient and optimum slug length for batch operations. The Bernoulli equation of pressure for the flow of fluids in pipes was used (Akwukwaegbu 2001). The derived flow equations presented can be modified under specified operating conditions or constraints of the Trans Alaska Pipeline System (TAPS). The results of the sample calculation indicates that the pressure gradient obtained from the batch flow calculations are higher than those obtained from that of commingled flow. The reason being that for batch flow, the pressure gradient is the ratio of the total pressure drop across the slug to the length of the slug, whereas for commingled flow, it is the ratio of the total pressure drop to the length of the pipe segment. Several assumptions were made to solve the equations. Some of the assumptions include:

i. Incompressible fluid flow, steady state fully developed

ii. Constant slug length

iii. The bubble (void) between the slugs is occupied by air

iv. The liquid film has a constant thickness

v. Flow is isothermal with constant fluid properties

vi. There is some degree of mixing between trailing film edge and the head of the slug.

Transporting alternate slugs of refined of petroleum products from the refineries to storage depots through pipeline systems has been a common practice in the US and many parts of the world. However, transporting alternate slugs of these refined products and crude oil is not common. Use of crude oil pipeline to transport refined petroleum products can be successful and cost effective, based on the experience of one Western Canadian pipeline company (Baum et al 1998).

The pipeline regularly transports crude oil and a wide range of products including jet fuel, gasoline (unleaded and premium unleaded), diesel (regular sulfur, low sulfur and low temperature), methyl tertiary butyl ether (MTBE), and crude-oil (light sweet, light sour and heavy). Refined petroleum products move in the pipeline consecutively. Each distinct product is referred to as a "batch" and when several products are placed together in the line, they are called a "batch-train". A typical refined products batch-train consists of a variety of products for different shippers and can be up to 350 Km (220 miles) long. Crude oil is transported between refined product batch-trains. As a batch train moves through the pipeline, adjacent products commingle forming the "interface zone". The extent of commingling or the length of the interface is a function of velocity, density difference between the two products, viscosity, pipe diameter and distance traveled. Accurate interface detection and optimization of batch sizes and configurations are important factors in reducing operating costs. Dynamic modeling also proved useful in optimization and minimization of operating costs.

Of the processes available to remove contaminants picked up by refined products moving through a crude oil line, distillation is the most effective in lowering sulfur content and removing color bodies. If a product has no color specification, caustic treating is more economical than distillation. The pipeline travels approximately 1,260 km and crosses the Rocky and coastal mountain ranges in the arctic region of Western Canada.

The major cost driver for both the GTL and the LNG conversion projects is the initial investment costs. If this variable is successfully lowered or even held at the current assumed value, both projects show acceptable rate of return for the reference crude oil price while providing the Units; Prudhoe Bay Unit (PBU) and Point Thompson Unit (PTU) a reasonable price for their gas. Of even greater significance to the GTL conversion project is plant efficiency. An increase in efficiency not only increases the profit stream by increasing liquid product sales volume, but the increased volume also decreases TAPS transportation cost for all transported liquids, providing a higher ANS oil price without GTL Conversion. (Thomas et al 1996). A target efficiency of 70 to 75% for advanced GTL technology under development may prove out in time to be ready for rapid GTL deployment envisioned and which would improve the GTL base economics. The South African plant with plant conversion efficiency about 57% and the newer shell plant design with 63% conversion efficiency are used as benchmark for the assumed 60% efficiency. The recommendations include a site-specific economics of both the GTL and LNG options with regards to existing infrastructure. This assumes that the GTL conversion plant will be built on the North Slope and the LNG liquefaction plant is built south east of Alaska following the construction of a gas pipeline, more precise and process cost estimates for the GTL option should be developed because of the important sensitivity of the capital cost to the option. A more complete assessment of the effect of the TAPS tariffs, anticipated from the GTL product volumes, on future ANS oil production from all existing fields and potential developments was recommended. The several dollar per barrel reduction could be important in determining how long selected ANS reservoirs might continue to produce, and affect whether non-production reservoirs might be on line. A clear picture should be developed for the cost penalties associated with capital construction and facility operation in the arctic climate and remote locations of the ANS. The potential benefits of each gas commercialization option on the various regions and overall state of Alaska should be stressed in detail to aid decision-making. Such examination might include: an analysis of the types and aggregate of manufacturing and labor components for construction and operation of each gas option and the resulting stimulation and local economic development, direct and indirect local employment to be generated.

Evaluating both the Prudhoe Bay field model and the gas project model is necessary to effectively evaluate the scenarios being considered and are tied together by the natural gas transfer price. The transfer price is calculated with the use of the "net back" term. The "net back" refers to the net fraction of the gas price sold by the gas project (GTL or LNG) that is returned "back" to the Unit operators as payment for the gas. (Robertson et al 1999). The study evaluated the following scenarios:

- No major gas sales scenario consists of continuing with current utilization of the natural gas to maximize oil production. Under this scenario, oil production continues until 2025.
- The Natural Gas Pipeline project scenario takes natural gas from Prudhoe Bay beginning in 2005 and reaches a rate of 2.0 Bcf/D in 2009.
- A fast-paced GTL Development scenario consists of constructing a 300,000 B/D GTL plant (2.5 Bcf/D feed rate) on the ANS to match the timing and volumes proposed in the LNG scenario.
- A slower-paced GTL Development scenario consists of a GTL plant construction schedule designed to take advantage of the learning curve associated with implementation of newer technologies. Located on the ANS, the plant takes gas from Prudhoe Bay at a rate of 0.5 Bcf/D beginning in 2005.
- A 300,000 B/D GTL plant (fast-paced) is located in Valdez, AK. This scenario assumes that the natural gas pipeline is built and a tariff is charged to the gas passing through the pipeline. The assumed gas purchase rate is equal to the LNG scenario. A lower capital-cost factor of 1.2 is applied at the

Valdez location as opposed to the 1.5 capital cost factor associated with a ANS location.

A deterministic evaluation of the economic viability of the scenarios outlined above was accomplished in the study above by discounted cash flow analysis. The results were presented by the net present value of the project. Of the scenarios analyzed, only the slow paced GTL development scenario has a positive incremental combined net present value using a discounted rate of 10%. The gas sales revenues of the slow-paced ANS GTL plant are realized later in the life of this scenario than in the fast-paced GTL scenarios and the LNG scenario, which tends to decrease the net present value of the project. However, savings in the capital costs associated with the "learning curve" that are incorporated into this option outweighs the added discount in revenue caused by delaying gas sales. The study also compared a fast paced GTL plant in southern Alaska (Valdez) to the fast-paced GTL plant on the North Slope. Locating the plant in an ice-free port could potentially become economically attractive compared to a ANS location. This resulted in a reduction of the construction cost from 1.5 to 1.2 times the cost of gulf coast plant due to reduced shipping, labor and material cost. The construction of a new $6 billion pipeline to transport the gas from the slope would potentially add about $0.8/Mcf to the cost of the gas. Sensitivity analysis was performed on several inputs to determine the economic value of each scenario. The objective of the analysis was to determine which input parameters cause the greatest effect on project economics. This information is vital in determining those parameters that offer the greatest potential for increasing or decreasing the economic viability. These parameters require the most attention and are natural targets for further research efforts. From the results, the four most critical variables are the Gulf coast GTL plant cost, the world oil price, the ANS cost factor and the GTL liquids per barrel premium. The Monte Carlo simulation technique, which permits a "probabilistic analysis" of project economics by applying probability distributions to the input as opposed to deterministic results, was done. Applying a 90 percent confidence interval sets the rate of return between 9.8 and 11.9 percent. The median value of 10.8 percent indicates that half of the time, a rate of return calculation would return a value of 10.8 percent or greater. The standard deviation was 0.7 percent, which demonstrates that the results are tightly centered on the average of 10.8 percent.

In their conclusion (Robertson st al 1999), the results indicate that only the slow-paced GTL scenario yielded a rate of return greater than 10 percent. The other scenarios did not show positive net present values under the economic conditions selected for the simulations. Their rank, in order of net present value, is as follows: slow-paced GTL development, no major-gas-sales, fast paced GTL development, fast-paced GTL development in southern Alaska and finally a gas pipeline/LNG project. The slow- paced GTL development would allow cost savings on subsequent expansions. These assumed savings along with lowering of the transportation tariff combine to distinguish this option for marketing the ANS gas from the other scenarios.

2.3 ISSUES WITH TRANSPORTING GTL THROUGH TAPS

Several operational issues need to be addressed when considering transporting GTL through TAPS. Some of the issues identified include;

i. An accurate prediction of the optimal slug length for batching

ii. Prediction of the interface length and timing of their arrival at the terminal in case of batch operations to facilitate timely switching of the product train into the appropriate storage or reception facility.

iii. The interaction of GTL with chemicals such as corrosion inhibitors, drag reducers which are currently used for crude oil transport through TAPS

iv. Impact of GTL batching on local refinery operations and vapor recovery facilities.

v. Determination of GTL gelling temperatures and a complete rheology of the products with their implication on TAPS operations.

vi. Effect of solids precipitation (wax, asphaltenes etc) within the pipeline.

vii. The phase behavior of the GTL products and any vapor pressure concerns

viii. Ability of the facility to handle GTL transportation, which differs from the original design specification of transporting crude between 24 and 32^0 API.

ix. Cost benefit analysis of transporting GTL through TAPS as opposed to building a new pipeline.

x. Provision of storage and handling facilities in case of batch operations to maintain product purity.

xi. Temperature effects on GTL and GTL-Crude mixtures.

xii. Application of new technology in transporting the products through TAPS

The economic implication of the issues identified above to come up with the most cost-effective mode of transportation is the major focus of this study. The recommendations are however subject to the technical feasibility considering TAPS operations and environment.

CHAPTER 3

GTL TRANSPORTAION OPTIONS AND CONSIDERATIONS

3.1 TRANSPORTATION MODES

In transporting GTL products through the Trans Alaskan Pipeline System, two modes of transportation are evaluated in this study. The choice of the mode of transportation to adopt depends on the expected purity of the shipped product and a trade-off between loss in product value due to contamination and cost of keeping the product pure at the terminal.

The first method considered involves blending the ANS crude oil and the GTL products. This method is termed the commingled mode of transportation. The Second method is to pump alternate slugs of the GTL products and crude oil through the TAPS called the batch mode. Batching of the product could be achieved in three different ways namely; the traditional batching technique called the "batch mode A" in this study. This is used as a base case or do nothing case. The second method involves batching with physical barriers such as pigs and some other spacers called "batch mode B", and a third technique which uses modern batching technology called "batch mode C".

3.1.1 Commingled Mode

To discuss this mode of transportation, it is necessary to take a close look at the physical properties of each of the products to be blended. Generally, the crude oil blend from the ANS is a dark brown medium crude with an API gravity of about 32°, viscosity of about 17cp at standard conditions with wax deposition tendencies at standard condition of temperature and pressure. Samples of GTL products from pilot plants show that they are essentially middle distillates found in a typical crude oil. The GTL product has a viscosity of about 1.5cp at standard conditions, typically diesel and naphtha based product with API ranging from about 62° for 354°C distillate to 66° for the 254°C distillate. The blending proportion of crude oil and GTL product on the North Slope is assumed to be a matter of availability of each of the product at any particular time rather than an intended ratio. However, with the commencement of the GTL project, the ratio is expected to continue changing depending on the amount of crude throughput available for blending assuming the GTL production remains constant. From the operational perspective, blends such as 3:1 crude oil to GTL with a resultant API of about 39.9°, 1:1 of crude oil and GTL with a resultant API of about 47° have been studied.

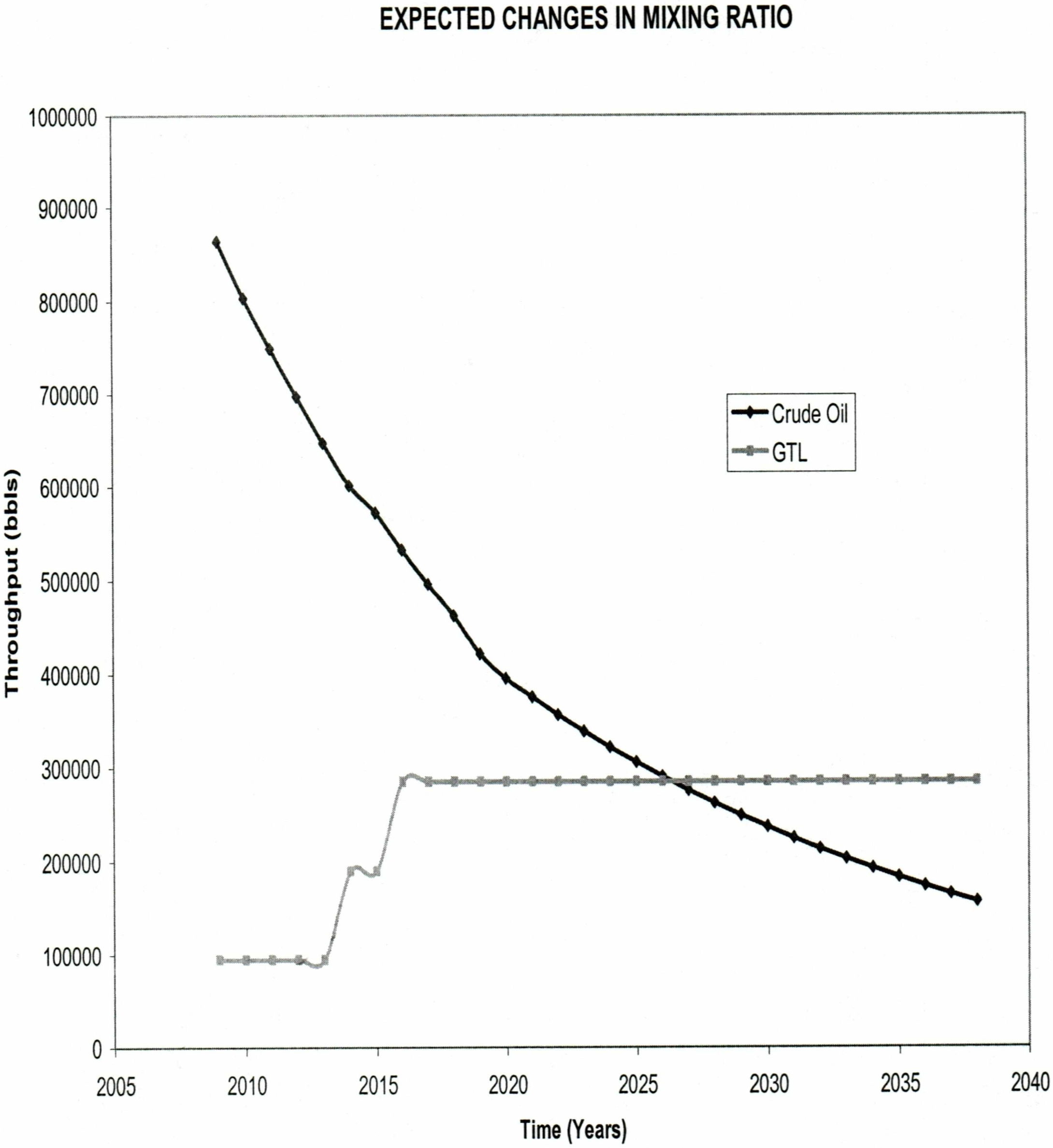


Fig 3.1 Projected throughput of GTL and Crude oil through TAPS

The flexibility of using existing infrastructure to the fullest advantage with minimal addition to capital cost for transportation is the most attractive aspect of this mode of transportation. This includes the use of the present holding tanks at the ANS and storage tanks at the Valdez Marine Terminal, elimination of extra piping to the respective tanks at the Valdez Marine Terminal and minimal logistic concerns. At first glance therefore, it would be intuitive to tag this method as the most cost-effective. In the pump stations, pressure relief tanks are required for emergency operations. They are expected to come in as temporary storage in case of any unforeseen valve or process malfunction to reduce any pressure build up in the pipeline. The commingled mode of transportation does not require this additional facility because the present relief tanks system is capable of handling the crude – GTL blend together. The GTL economic model analyzes the effect of these initial savings on the entire project economics.

Table 3.1 Physical Properties of Pure GTL, Crude Oil and their blends

Sample	Density	API
254GTL	0.71645	66
302GTL	0.7243	63.9
344GTL	0.7302	62.3
Crude	0.86215	32.6

Sample Preparation #1

Sample #	GTL Sample	GTL Density	Crude Density	GTL Portion	Crude Portion	Total Mass	Calculated Density	API
1	254 Dist	0.7165	0.8622	1	1	197.325	0.7893	47.8
2	254 Dist	0.7165	0.8622	1	3	206.431	0.8257	39.9
3	302 Dist	0.7243	0.8622	1	1	198.306	0.7932	46.9
4	302 Dist	0.7243	0.8622	1	3	206.922	0.8277	39.5
5	344 Dist	0.7302	0.8622	1	1	199.044	0.7962	46.2
6	344 Dist	0.7302	0.8622	1	3	207.291	0.8292	39.2

Sample Preparation #2

Sample #	GTL Sample	GTL Density	Crude Density	GTL Portion	Crude Portion	Total Mass	Calculated Density	API
1	254 Dist	0.7165	0.8622	1	0	204.188	0.7165	66
2	254 Dist	0.7165	0.8622	1	1	224.951	0.7893	47.8
3	254 Dist	0.7165	0.8622	1	3	235.332	0.8257	39.9
4	302 Dist	0.7243	0.8622	1	0	206.426	0.7243	63.9
5	302 Dist	0.7243	0.8622	1	1	226.069	0.7932	46.9
6	302 Dist	0.7243	0.8622	1	3	235.891	0.8277	39.5
7	344 Dist	0.7302	0.8622	1	0	208.107	0.7302	62.3
8	344 Dist	0.7302	0.8622	1	1	226.91	0.7962	46.2
9	344 Dist	0.7302	0.8622	1	3	236.311	0.8292	39.2

Results of viscosity measurements carried out at atmospheric pressure and at different temperatures from 20°C (68°F) to 60°C (140°F) are available. The viscosity measurement at any temperature is carried out by noting the lowest shear rate, which will give more than 10% torque reading, then the shear rates are successively increased until the viscosity reading stabilizes and then decreased in the same manner. After the last reading, the motor is turned off for at least 5 minutes followed by viscosity determination at the

lowest speed (Hariharan, 2000). The results are tabulated below;

Table 3.2 Viscosity (cp) Results at Atmospheric Pressure (Hariharan 2001)

Temp °C	**Temp °F**	**100% Crude Oil**	**Crude:GTL 3:1**	**Crude:GTL 1:1**	**Crude: GTL 1:3**	**100% GTL**
20	68	17.3	6.8	4.1	2.3	1.3
30	86	10.8	5.3	3	1.9	1.1
40	104	7.7	4.3	2.3	1.6	0.96
50	122	6.4	3.7	1.9	1.4	0.81
60	140	5.5	3.4	1.7	1.3	0.68

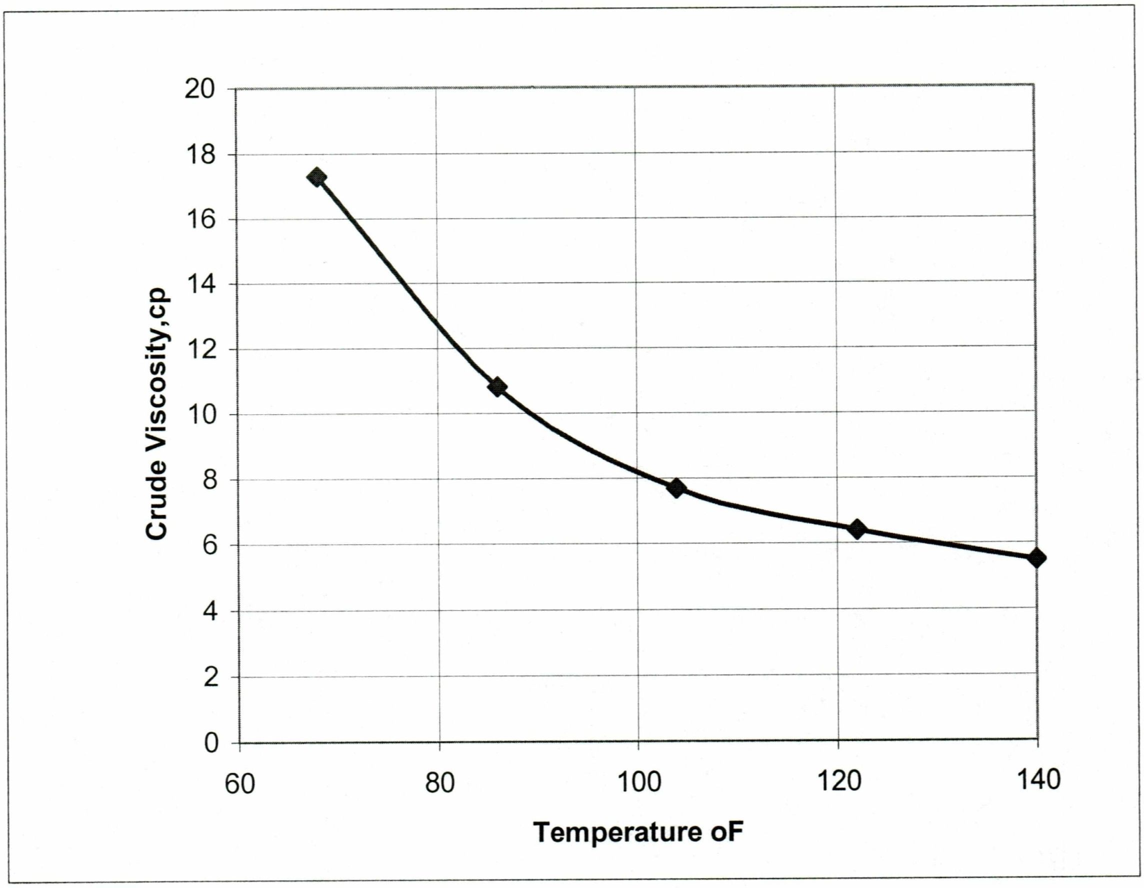


Fig 3.2 Crude Oil Viscosity at Different Temperatures

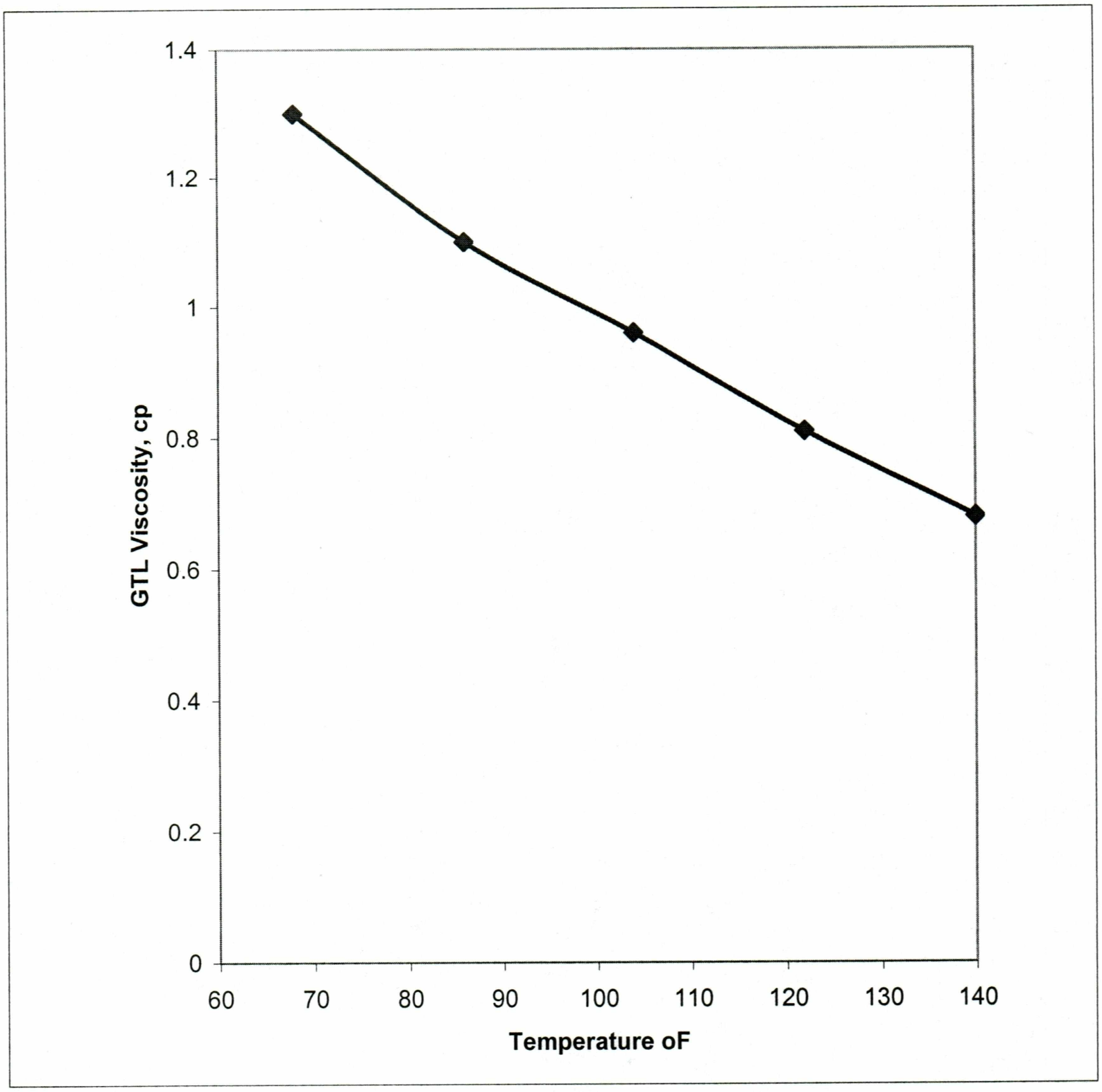


Fig 3.3 GTL Viscosity at Various Temperatures

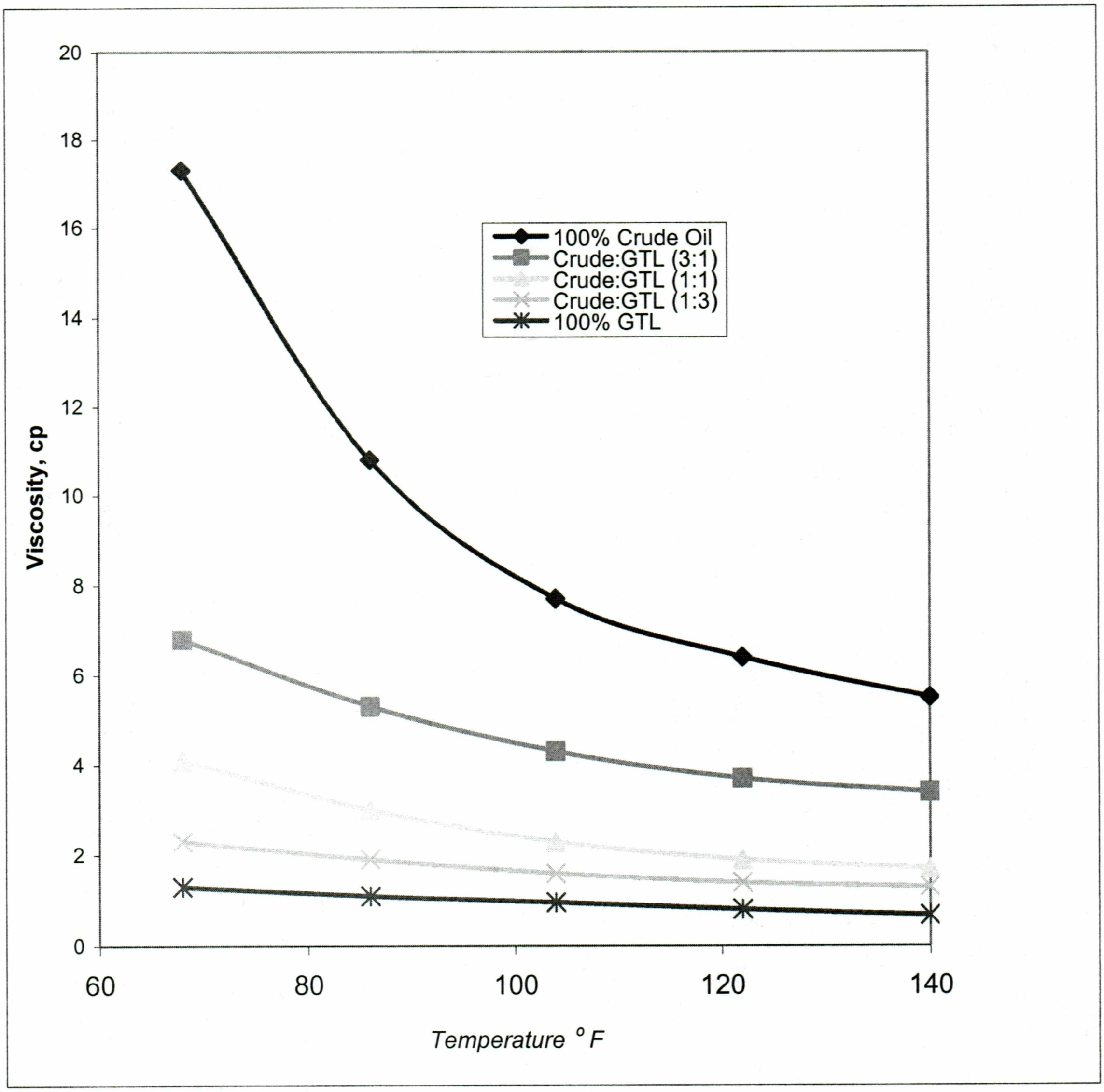


Fig 3.4 Viscosity of Various GTL-Crude Oil Blends

3.1.2 Batch Mode

In the batch mode of transportation, the GTL products could be batched in three different ways:

i. Uncontrolled batching of Products termed batch mode 'A'

ii. Controlled batching using pigs and spacers termed as batch mode 'B'.

iii. Controlled batching using modern batching techniques termed batch mode 'C'.

Currently, there are two storage tanks located at Prudhoe Bay with a working volume of approximately 300,000 barrels. However, this volume is not for batching GTL. If GTL is to be batched next to crude oil, then while GTL is being transported through TAPS, the crude oil must be stored. Conversely, while crude oil is transported through TAPS, GTL must be stored. A necessary requirement for batch operations on the North Slope is availability of storage space to store one product while the other is being transported through the pipeline. For optimum efficiency of operations, up to one day's production of both the crude oil and GTL may be required on the North Slope for storage and flexibility of operations. This puts the storage or holding requirements on the Slope to approximately 300,000 to 400,000 barrels of GTL while crude oil is transported through TAPS and when GTL is transported through TAPS, approximately 700,000 barrels of crude oil will need temporary storage until conveyance. This requirement is necessary for all the types of batching as described in this work (i.e. batch modes A, B, and C).

3.1.2.1 Batch Mode 'A'

The batch mode A or the 'as-is' batching is considered the easiest of the batch modes of transportation. This mode of transportation requires minimal additions to capital and labor costs. Typically, any batch operation requires that there are separate tanks for the GTL at ANS and Valdez marine terminal and clean tankers. Basically, the physics of the flowing liquid products (Crude Oil and GTL) controls the behavior of the products while in the pipeline. This uncontrolled batching technique results in the creation of an interface zone in between the two phases (Crude Oil and GTL mixture). The length of this interface is a function of the viscosity, velocity and density difference between the two products, pipeline diameter and distance. Loss of product value due to contamination of the GTL products is at it's maximum in this mode when compared to other batching techniques. However, this is the common practice for refined products batching in the US. The interface generally gets downgraded to crude oil.

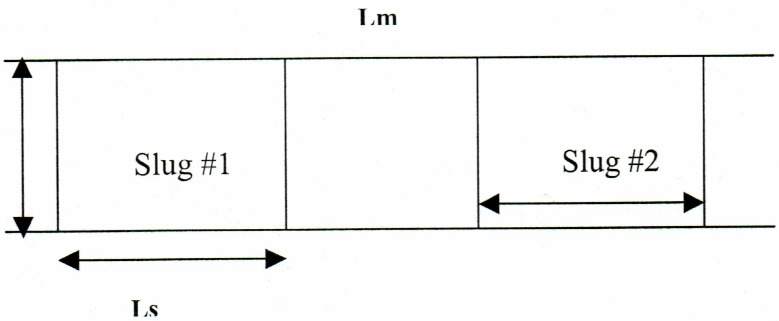


Figure 3.5: Typical Batch

Equations have been derived for calculating the minimum slug length, which can be translated to volumes for effective batching and minimal contamination for large diameter pipes. However, from the economic viewpoint, it is pointed out that as slug length increases, segregated tank requirements also increase. Further discussion on these is included in Chapter 4. In the Batch Mode operations, it is assumed that a special berth will be dedicated to GTL products at the Valdez Marine Terminal and special tankers will be used to carry only GTL products. This ensures that further secondary contamination does not take place beyond the Trans Alaska Pipeline System. This method of transportation is very similar to mode 'C' with the major difference coming from the employment of available technologies in the later to enhance purity of the transported products before, during and after transportation. The economics of this mode therefore forms a base case for the modern batching technique.

3.1.2.2 Batch Mode 'B'

In this method, pipeline pigs are used to achieve the objective of phase or slug separation. It is expected that these pigs will effectively prevent mixing of the alternate slugs of GTL products and crude oil. This method requires the entire basic infrastructure that is used in the base case batch mode plus some additional capital. The GTL products will be stored in separate tanks both at the ANS and in Valdez Marine Terminal. Transporting the products through the TAPS would not be left to fluid dynamics to govern their movement in the pipeline since the pigs would keep the oil and GTL separate. The number of slugs expected to be in the pipeline at any time would determine the number of pigs required. Intelligent pigs with sensors attached to them are commonly available with capabilities of detecting product movement. Detecting product movement can minimize the time needed to divert flow from crude oil storage tanks to GTL storage tanks.

A major operational challenge is that pigs need to be diverted at every pump station along the TAPS where flow is diverted accordingly for the fluid to pass through the pumps. Additional labor is required at each pump station to carry out this task on a continuous basis.

Most operators are of the view that the use of pigs to batch these products would reduce or completely prevent the mixing of the products. Some other operators believe that batching with pigs would not reduce the mixing but rather increase the mixing due to increased turbulence (Baum et al, 1998). This is currently under further study. In this study, the assumption is that the pigs would help maintain product purity. Possibilities exist for improvement in pigging technology. For instance, it is possible to attach sensors to the pigs that would enable automatic diversion of flow at the pump stations. The opening and closing of valves can be fully automated at the pump stations with good instrumentation and controls. Pigs are also available that are specifically designed for batching of petroleum products.

3.1.2.3 Batch Mode 'C'

The modern batching technique, identified here as batch mode 'C' entails pumping alternate slugs of GTL and Crude oil while having fluid movement monitored by interface detection devices to minimize loss of product value. Available interface detection technologies include densitometers, sound-velocity interface detectors, colorimeters, pipeline interface detectors and photo detectors (Baum et al 1998).

A densitometer measures online the specific gravity of the product in the pipeline, and can detect even small changes in product density. In terms of accuracy, they can distinguish between premium and regular gasoline.

The sound velocity interface detector employs changes in the sound velocity rather than changes in density to detect different liquids.

A colorimeter detects color changes in the contents of the pipeline. It measures color quality with a dual wavelength, dual detector optical system. At the receiving terminal, which could be at a refinery or tank farm, a dynamic hydraulic model for optimizing product movement and a Distributed Control System (DCS) can be used to control product movement. A DCS allocates the crude oil and GTL to their respective tanks at the optimal time reducing error in valve opening and closing. This is synchronized with the pumping at the plant end, employing already calculated optimum slug length from batch mode ‘A’, length of interface, the interface and slug velocities. This method would require additional storage tanks and shipping facility to ensure that purity of the products is maintained. Increasing batch size can minimize product reprocessing; the amount of interface product remains constant regardless of the batch size. Consequently, the amount of reprocessing required relative to the product received is important in minimizing cost. The volume of product that can be placed in the pipeline, however, is limited by the tankage available at the receiving location, consumer demand for the product, scheduling requirements for crude oil deliveries. Batching of products in a particular sequence known as “batch configuration” can hold product clean-up to a minimum. Some guidelines for setting up a batch configuration include;

- Avoid placing next to one another products that are not miscible.
- Avoid placing next to one another two products with significant viscosity differences
- Group similar product types sequentially

Interfacial mixing is an inverse logarithmic function. Therefore, the mixing zone or interface develop very rapidly in the early stages of transportation. Once an established interface is formed, routing the products through the pump stations along the pipeline and interrupting the batch movement have relatively little effect on product mixing. Typical volumes for a diesel / gasoline interface would be about 5000 barrels. At the Valdez marine terminal, it is important that the sequencing valves be timed to ensure that the pipeline fluid movement is not restricted. Restricting the pipeline flow could result in creation of a pressure wave that could cause a surge valve to open thereby directing the pipeline contents to a separate tank. As part of the operating procedure in receiving a batch at terminal, an operator is expected to test the switching valves to ensure their operability before a batch arrives. Because of the importance of switch valves, a back-up system provides control of the operation of the valves.

In a crude oil – refined product batch operation, proper sequencing of the product batches and the use of interface-detection equipment can minimize but not eliminate product contamination. In addition to the mixing of products at the interface, refined products pick up elemental sulfur and color bodies from the walls of the pipeline during transit to the receiving terminals. (Baum et al, 1998) Several technologies are currently used in returning refined products to their original quality standards. These include; Distillation, Metal-Oxide treating, Caustic treating and Filtration.

3.2 ECONOMIC PARAMETERS

In order to conduct the economic analysis of GTL transportation through TAPS, the following economic parameters are considered in this study:

- A large-scale GTL project consisting of three trains each having a production capacity of about 100,000 barrels of GTL products per day.
- Pipeline Tariffs obtained from available forecasts and charged based on throughput and is expected to pay for the pipeline, pipeline maintenance and storage cost at the terminal and some return on investment.
- A salvage value of zero.
- Each mode of GTL transportation has an associated capital cost which varies from minimal capital investments for the commingled mode to huge capital costs for the modern batching approach.
- Construction starts in 3 years by 2005, lasts 4 years through 2009 and production begins same year.
- Train 2 construction commences after train one has started production and train 3 commenced two years after train 2 is started to spread out the investment. (Slow-Paced development)
- All transportation costs rely on the existing infrastructure of the oil pipeline operation and maintenance, therefore; only additional capital costs specific to GTL will increase the cost.
- Discount rate of 10% is used for the capital costs

- Depreciation of property is by Modified Accelerated Capital Recovery System (MACRS).

3.2.1 Rate Of Return Analysis

Rate of return analysis was used in evaluating the various transportation modes. To conduct rate of return analysis, an accurate estimate of the capital and operational costs involved in the project was necessary as well as an estimate of expected product price and revenue. The project life was assumed to be twenty years initially. The rate of return was still increasing significantly and the evaluation had to be made for a 30-year project life. Based on construction costs, the construction schedule, the timing of product sales, and the expected revenue a rate of return was estimated. It is assumed that 100% equity financing is used which is typical for oil and gas firms when comparing different projects.

3.3 IDENTIFYING CAPITAL AND OPERATING COSTS

The capital costs include all costs from the GTL plant to the delivery of product to the GTL tankers in Valdez.

The first common cost to all modes of transportation is the contingency plan capital. No production of GTL can begin until this capital is in place. Contingency plan capital refers to the capital that must be set aside to help handle emergency situations that might lead to shutting down the pipeline and ensure quick restart of operations. Laboratory measurements show that in the arctic environment a window of about thirty (30) days is allowed to restore operation in case of any shutdown during the winter season or risk shutting down operation once the crude oil in the pipeline gels due to very cold temperatures. The window for cold restarts in the winter for the pipeline when GTL is in the pipeline for either the commingled mode or the batch mode is estimated to be smaller compared to when only crude oil flows through the pipeline. This is given adequate treatment in the gel strength prediction study for both a fast and slow ramp cooling process (Timmcke 2002).

Another common cost to all modes of transportation is the cost of building a pipeline from the GTL plant to Pump Station 1. It is assumed that the GTL plant would be situated not more than one mile for pump station one.

The piping cost required to transport the gas from the production wells and stations are not included in the GTL project cost. The drilling and completion cost of the gas wells are also not part of the GTL cost here but are assumed to be a part of the gas purchase cost. The GTL plant is assumed to come with a conditioning unit for removal of acid gases such as CO_2 and H_2S and are therefore not considered separately.

On the distinctive capital costs, batch mode 'A' does not incur any extra costs apart from that outlined above. Batch mode B incurs additional capital costs in purchasing pigs and labor to handle the pigs on a continuous basis at different pump stations.

Batch Mode 'C' requires additional investment costs from those outlined above including interface detection devices for minimizing impurities associated with mixing, product movement control devices that use the Distributed Control System (DCS), densitometers, colorimeters, and some complex instrumentation. This technology has been proven effective and has been used extensively by the petroleum products transportation industry in pipelines. Product movement control has two main components. The first is the dynamic hydraulic model and the second is a DCS. This system is complex and expensive.

3.3.1 Plant Capital Expenditure (CAPEX)

The capital cost of a GTL plant is estimated at between $25,000 per daily barrel (DBL) capacity and $35,000/DBL (Thomas et al., 1996). Current industry average for a US Gulf Coast plant puts the capital cost at about $24,000 / DBL. Most of the plants from which these cost estimates were derived are small-scale GTL plants with design capacity of between 30,000 to 50,000 barrels per day (bpd). As technology advances, these costs are expected to come down significantly. Technology will be the main factor that will determine whether there will be economics of scale or not. Coal fired plants for example do not have economics of scale due to increased complexity as the plant size becomes larger. The maintenance cost increases with increase in capacity of those plants. One such significant leap in GTL technology is the reduction in the size of the steam-reforming unit to about forty times less than the conventional size of the steam reformer. This is projected to result in a significant change in the capital cost for GTL plants. This is estimated to put the capital cost at about $20,000/ DBL for a commercial scale plant in the Gulf Coast. This compact reformer technology is currently being tested in a pilot plant in Nikiski, AK by BP Exploration (Alaska) Inc. The reformers come in compact units built to commercial scale. To increase output, additional whole compact reformer units are added to operate in parallel with existing ones and minor modifications made to other units in the plant to increase plant output capacity.

The Alaskan North slope is assumed to have a cost scaling up factor of about 1.3-1.5 times the cost of building the same plant in the Gulf of Mexico. If the compact reformer technology passes the test to commercial status, then the capital cost of the plant on the Alaska North Slope is anticipated to be at about $28,000 /DBL capacity assuming the same plant is built at a cost of about $20,000 /DBL in the Gulf Coast. However, this study evaluated a wide range of capital costs of GTL plants from $35,000 /DBL down to $20,000 /DBL.

Application of the learning curve as presented by Robertson et al (1999) was not employed in this study. Cost improvement based on a learning curve or progress curve plays a crucial role in the competitiveness of the chemical and petrochemical industry. It has been observed that more rapid cost improvement for a product results in expanding market share and profits. Though initial or pilot projects may be economically marginal, expectations of rapid cost improvement based on a learning curve is often the motivator to invest in such projects. As GTL technology unfolds and operators gain experience from building and operating earlier trains, a rapid cost improvement is expected. This is usually represented by a common rule of thumb based on observations from petrochemical plants as;

$$C_n = C_1 n^b$$

Where,

C_n = Cost of the n^{th} unit,

C_1 = Cost of the first unit,

n = number of unit being estimated and

b = exponent equal to the improvement – curve rate divided by the natural log of 2

Cost improvement rate for organic chemical production was found to be 73.8 percent on the average. GTL plant falling under the same industry, would have the 'b' exponent given by:

$$b = \frac{Ln0.738}{Ln2} = -0.4383$$

In the learning curve advantage as presented, one or combinations of factors presented below are expected to play important roles in driving down cost of subsequent trains:

- Learning by plant operators and designers
- Technical improvement
- Economies of scale
- Probable decrease in cost of raw (feedstock) material

The scenarios presented assume that the capital cost remains the same in all the trains and this is the worst case possible since capital cost improvement would be significant in the second and third trains. As noted above, the Prudhoe Bay gas has a high carbon dioxide content and needs to be conditioned before it is fed to the GTL plant. The above cost is expected to cover the gas conditioning.

3.3.2 Storage, Product Separation and Other Costs

For the batch mode of transportation, it is assumed that new holding tanks (APSC 2002) will be built on the North Slope. The holding tanks presently in place on ANS have a holding capacity per foot of 4,400 barrels. For an estimated 300,000 barrels per day of GTL product conversion plant, the footage of temporary storage required would be given by:

$$\frac{300{,}000}{4{,}400} = 68.18\mathit{ft}$$

Maximum allowable height by OCC (Operational Command Center) is approximately 32 ft and an 8ft minimum level maintained, leaving out only 24 ft (APSC April 2002).

$$\frac{68.18\mathit{ft}}{24\mathit{ft}} = 3\mathit{StorageTanks}$$

Each of the tanks is estimated to cost about $65 million. This estimate includes fittings, accessories, piping and refrigerated foundation.

At the Marine Terminal in Valdez, a first case where new tanks are built for storage of GTL is considered first. This represents the worst-case scenario. For a one-week storage capacity, four new tanks are required at the Valdez Marine Terminal where the tanks have holding capacity of 500,000 barrels each. The cost of these four tanks is estimated at approximately $270 million or $65 million each. This cost is expected to cover the fittings and accessories such as; pressure relief valves, emergency relief vents, tank piping, mixers, internal heaters, water draw-off valves, tank instrumentation, tank insulation, thief hatch, corrosion control. Another option is to recondition and reconfigure four of the 18 existing tanks for GTL storage. This is an optimistic assumption. The cost of reconditioning and reconfiguring each of the tanks is put at approximately $5 million dollars so about 20 million dollars is estimated to recondition the four tanks.

Emergency relief tanks for GTL at pump stations 3, 4, 5, 7, 9, and 12 are required. Building these tanks is another major cost in the transportation model. These emergency relief tanks are 55,000-barrel capacity tanks. To maintain GTL product purity, each of the pump stations may require a separate emergency relief tank for GTL products. Each of these tanks is estimated to cost about $16 million bringing the cost for all the pump stations mentioned above to $96 million. In the second and optimistic scenario, it is assumed that the emergency relief tanks will not be required since such emergency operations are only very occasional. The present emergency tanks are therefore assumed sufficient to handle the situations as long as they are kept clean and ready to receive any products in case of emergency.

For batching of products with pigs, the number of pigs required is obtained by applying the optimum length of slug for each batch of the products the cost added to the cost of batching with pigs. Manual labor is required to handle these pigs at the pump stations. This is also accounted for in the economic analysis of this mode of transportation. The pigs also need to be transported back to the North Slope on a continuous basis.

Vapor pressure estimates from the laboratory show that the vapor pressure of GTL products is within the acceptable limits and can be handled by the existing vapor pressure recovery system. Further study of the vapor pressure of GTL products are also in progress at the University of Alaska Fairbanks. The vapor pressures are required for live GTL products from the plants under pipeline conditions of pressure and temperature to obtain the true behavior of the GTL products in pipeline conditions. However, some piping modification will need to be done and together with all other piping jobs to the tanks, an estimate of $10 million dollars might be required.

Table 3.3 Capital Cost Schedule For Various Modes of Transportation ($ millions)

SUMMARY OF CAPITAL COST ESTIMATES FOR DIFFERENT MODES OF TRANSPORTATION						
No	**Item**	**Cost each ($mm)**	**Batch Mode A**	**Batch Mode B**	**Batch Mode C**	**Commingled**
5	**Tanks @ Valdez**	65	325	325	325	0
4	**Tanks @ Slope**	65	260	260	260	0
6	**Pressure Relief Tanks**	16	96	96	96	0
1	**Contigency Plan Capital**	20	20	20	20	20
1	**Additional Piping**	10	10	10	10	10
	Labor Cost/ yr	2.72	0	2.72	0	0
	Cost Of Pigs	5	0	5	0	0
	Cost of DCS and Accessories	20	0	0	20	0
	Total		**711**	**719**	**731**	**30**

3.3.3 Energy Cost

The Products from the North Slope to Valdez pass through several pump stations at the moment. These stations are booster stations and consume fuel for running the pumps and power generators. The first four pump stations are run on gas fuel.

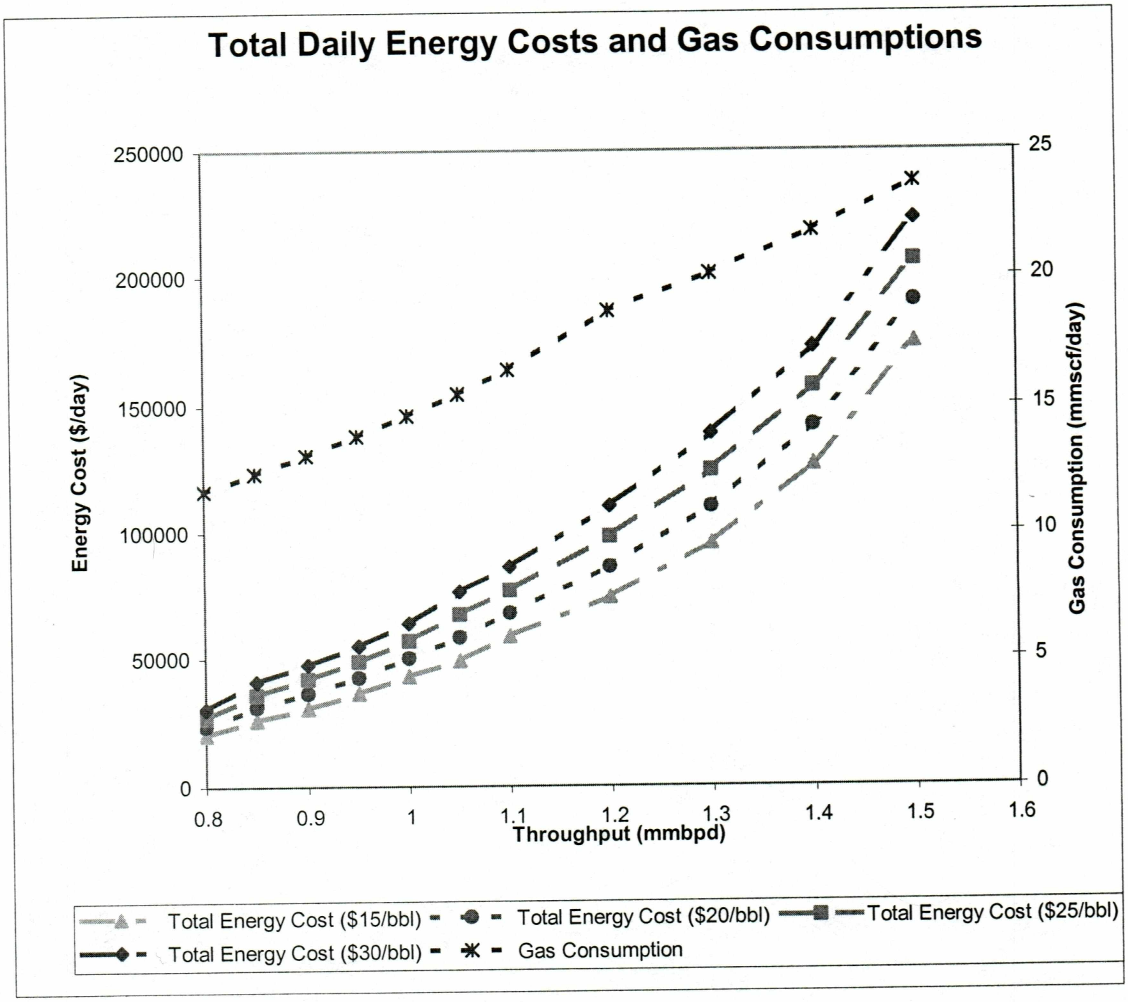


Figure 3.6 Energy cost as a function of throughput. (APSC 2001)

Currently, the gas is supplied to the pump stations at no extra cost from the ANS. The other stations operate on diesel fuel. The fuel cost is a function of throughput of the TAPS. A plot of throughput versus energy cost at various oil prices is presented in Figure 6.2. The gas is assumed to sell at the same price as the gas supplied to the GTL plant and half (for

Simplicity sake) of the calculated cost for running these stations tied to the GTL process.

Equations were fitted through the gas consumption curve to determine what the gas consumption would be at rates that have not been transported through the TAPS and which are anticipated in the future as throughput continues to decline.

3.3.4 Cost of Upstream Natural Gas

Natural gas is expected to be supplied to the GTL plant by the gas producers or owners. The gas owners or operators will fix the price of the feed gas to pay for their costs of extraction and make some profit. There may be other factors that may affect the gas pricing but in this analysis, only the cost of feed gas that will pay for extraction costs and a profit margin is considered.

To determine the amount of gas needed as feedstock to produce a barrel of GTL , it is necessary to relate the energy content of the produced liquid fuel to the gas used in a common energy unit usually in BTU.

The energy content of a typical barrel of oil is estimated to be 5.8 MMBTU. The energy content of GTL is assumed to be the same with that of a typical barrel of oil. For natural gas, the energy content is about 1 MMBTU per MCF. Solving for the gas energy required per barrel below:

$$\text{Gas energy per barrel of GTL} = \frac{5.75\dfrac{MMBTU}{BBL}}{1.15\dfrac{MMBTU}{MCF}} = 5.0\frac{MCF}{BBL}$$

At 60% conversion efficiency, the feedstock needed to produce a barrel of GTL is:

$$\text{Gas to GTL conversion} = \frac{5.0}{0.6} = 8.33\frac{MCF}{BBL}$$

$$\text{North Slope gas price} = \frac{\text{(North Slope GTL Price)}}{\text{Gas to GTL Conversion}} \times \text{(gas Product net back)}$$

The expected daily gas consumption is approximately 2.5 bcf or approximately 29 years supply of gas. Where the North Slope GTL price is also known as the wellhead price.

The North Slope gas price is often known also as the gas transfer price and is the cost of the gas feed stock to the buyers which in this case is the GTL operator. The term gas product 'net back' refers to the net fraction of the gas sales as GTL that goes to the owner of the gas. It is usually determined based on agreement on a return on investment expected by the gas owners. As an example, if the price of GTL is $26.25 and a net back of 10% is used, then the gas transfer price would be approximately $0.44 per MCF.

3.3.5 The TAPS Tariff

The TAPS tariff is the most significant cost item in the economics of the transportation of the GTL products through the pipeline. Six independent companies own the Trans Alaska Pipeline System (TAPS). Each of the owners charges their own tariff per barrel of product transported through the pipeline. The tariff is expected to cover the cost of operation and maintenance of the pipeline, the cost of storage, cost of dismantling and demobilizing the TAPS at the end of its operations and in addition to the above yield some return on investment for the owner companies. Operating the pump stations with GTL and Crude oil passing through the TAPS will require an increase in the cost of

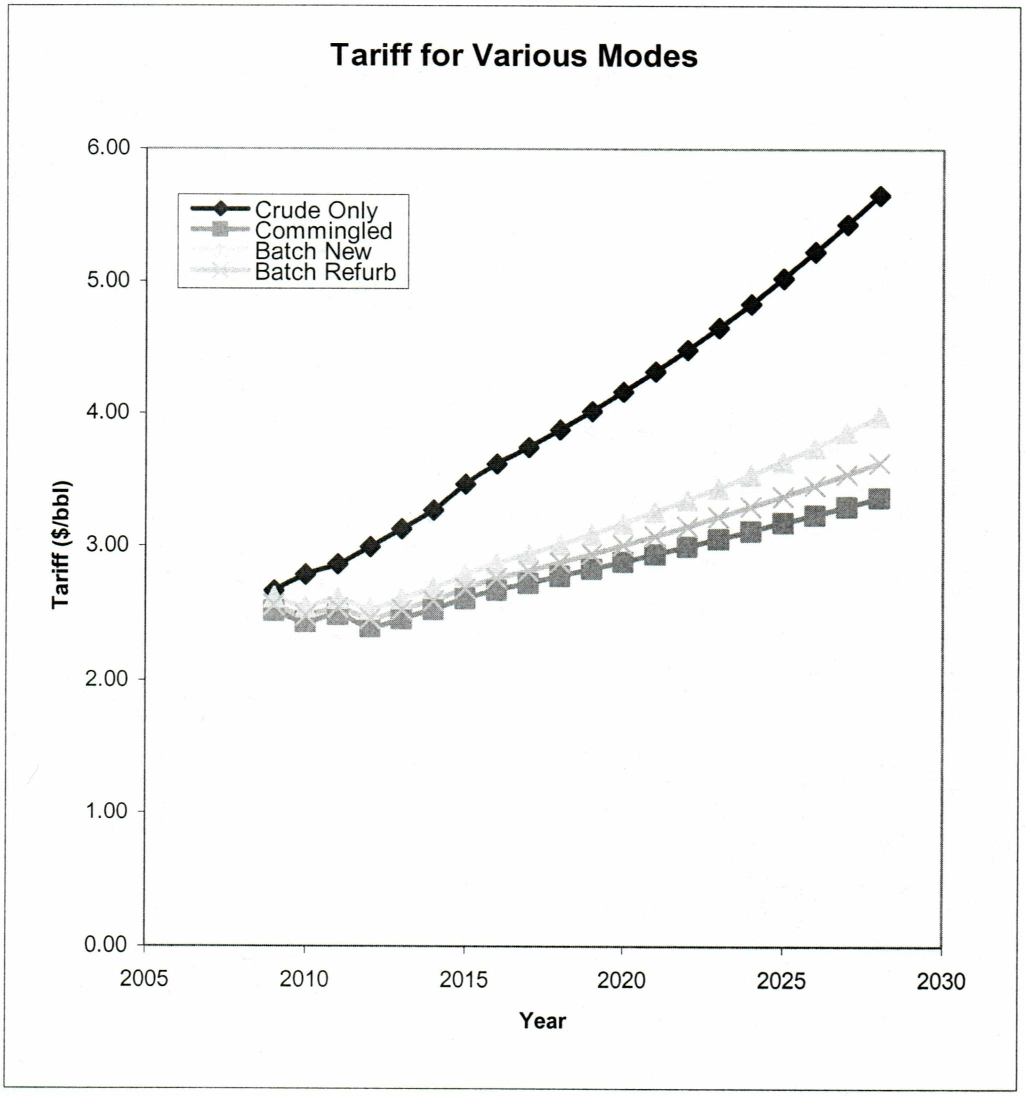


Figure 3.7 Tariff estimate for different scenarios TAPS throughput

Table 3.4 TAPS Tariff Estimate for Various Modes

TAPS TARIFF ESTIMATE FOR DIFFERENT MODES							
No of Periods				20			
Discount Rate				10%			
Capital Inv				731000000		335000000	
Period	Year	Crude Only	Commingled	Batch New ($/bbl)		Batch Refurb ($/bbl)	
1	2009	2.66	2.51	$0.12	$2.63	$0.06	$2.57
2	2010	2.78	2.43	$0.13	$2.57	$0.06	$2.49
3	2011	2.86	2.48	$0.15	$2.63	$0.07	$2.55
4	2012	2.99	2.40	$0.16	$2.56	$0.07	$2.47
5	2013	3.12	2.46	$0.18	$2.64	$0.08	$2.54
6	2014	3.26	2.52	$0.20	$2.72	$0.09	$2.61
7	2015	3.46	2.61	$0.22	$2.82	$0.10	$2.70
8	2016	3.62	2.67	$0.24	$2.91	$0.11	$2.78
9	2017	3.74	2.72	$0.26	$2.98	$0.12	$2.84
10	2018	3.88	2.77	$0.29	$3.06	$0.13	$2.90
11	2019	4.02	2.83	$0.32	$3.14	$0.15	$2.97
12	2020	4.16	2.88	$0.35	$3.23	$0.16	$3.04
13	2021	4.32	2.94	$0.39	$3.32	$0.18	$3.11
14	2022	4.48	2.99	$0.42	$3.42	$0.19	$3.19
15	2023	4.65	3.05	$0.47	$3.52	$0.21	$3.27
16	2024	4.83	3.11	$0.51	$3.62	$0.23	$3.35
17	2025	5.02	3.17	$0.56	$3.74	$0.26	$3.43
18	2026	5.22	3.23	$0.62	$3.85	$0.28	$3.52
19	2027	5.43	3.30	$0.68	$3.98	$0.31	$3.61
20	2028	5.65	3.36	$0.75	$4.11	$0.34	$3.70

diesel fuel to run the pump stations. This energy cost is a function of both the throughput and the world spot oil price (Figure 3.6). Presently, the first four pump stations have gas turbines and the gas is supplied at no cost to the pipeline company. When the GTL project commences, the gas is expected to attract extra cost. This is because the gas for the pump stations operations will be an added cost, purchased at the going price of natural gas on the North Slope. The amount of gas required to run the pump stations is also a function of the TAPS throughput. A plot of the amount of gas required to run stations versus throughput is also presented in figure 3.6.

The TAPS tariff as noted above incorporates some return on investments for the owners of the pipeline after the operation and maintenance cost. The six owners of the pipeline charge different rates for their ‘space’ in the pipeline. Therefore, it is not very correct to generalize and assume one particular discount rate for all the companies though they all fall within a range. The discount rate charged by each company depends on the company’s view of rate of return and its perception of ‘risk’.

The tariff estimates for the next two decades are obtained from the Alaska Department of Revenue (Table 3.4). The estimates give separate numbers for a case where GTL is transported through the TAPS with the crude oil and if crude oil alone continues to be transported through the pipeline. The tariff for the crude oil and GTL represents the commingled mode, which does not account for the extra capital investment required for batching of the products. For the batch modes, the huge capital costs required to keep the products as clean as possible is factored into the tariff. The tariff for the batch modes is therefore different for the various modes of transportation (Figure 3.6). This illustrates one of the arguments for GTL, that it provides added liquid fill for the pipeline as crude oil production decreases. That is, it gives a longer life and makes it economic to transport lower volumes of crude oil. This is because it will get so expensive on a per barrel basis that crude oil transportation would have to be shut down if it not for GTL. For the batch modes, the additional capital investment is allocated on a per barrel basis and a 10% discount rate.

3.3.6 Taxes

3.3.6.1 Property Tax (Ad Valorem)

Each of the three trains is depreciated depending on the number years it is expected to operate within in the 30-year period. Train one, is depreciated over thirty years, train two is depreciated over a 25-year period and train three is depreciated over a 23-year period. The tax base is computed and the property tax derived. The property tax rate is 2%.

3.3.6.2. State Corporate Income Tax

The state corporate income tax is given by; (income before State and Federal taxes – State Income Tax depreciation) x State Income Tax Rate.

The income tax depreciation is calculated using the MACRS depreciation method. The State Income tax rate used is 9.40 % based on recent values from the State Department of Revenue (DOR).

3.3.6.3 Severance Tax

The State gas severance tax and royalty is assumed to be zero for the GTL project. This assumption is based on the Alaska Department of Revenue tax model for the gas projects and would serve as some tax relief to encourage the take off of the gas utilization project. Further studies may investigate the effect of these taxes on rate of return.

3.3.6.4 Federal Corporate Income Tax

This is calculated using the income before state and federal income taxes, less the depreciation and multiplied by the Federal Income Tax rate. The Federal Income Tax rate used here is 35% based on current values of this tax.

3.4 GTL PRODUCT PREMIUM

GTL products are expected to receive some price premium compared to conventional crude oil products to reflect their high quality and environmental attractiveness as a fossil fuel. It is expected to follow the world crude oil and oil product pricing system closely. An important crude oil marker grade is the Brent crude oil produced in the North Sea. It is traded internationally on the Internal Petroleum

Exchange (IPE) and the futures market, a rapidly growing trend in world crude oil marketing. The price of crude oils have continued to fluctuate over the past decade and this makes future trends difficult to predict. For example, at low point, Brent sold for $10 per barrel in 1998, but rose to about $33 per barrel in September 2000. In the last decade, the average Brent price was about $19 per barrel and projections put the average at over $22 per barrel in the next five years. Typical GTL yield assessment like 20% naphtha and 80% diesel is assumed reasonable. The GTL diesel is superior to the conventional crude oil refined diesel with regards to sulphur, cetane number, aromatic content and density. However it has relatively poor cold flow properties. Typical GTL diesel has a cetane number greater than 70, compared to a usual diesel product end specification of 50. This means that opportunities exist for utilizing GTL diesel as a blend stock to upgrade refinery middle distillates products. The zero aromatics content of GTL diesel gives it another advantage for blending with conventional distillates where aromatic content specification becomes a limiting factor. Various numbers have been advanced for GTL product premium. Generally, the GTL diesel product is predicted to have between $2 and $2.5 per barrel premium over conventional diesel. In the model used, a premium of 1.25 times the world crude oil spot price is used. The choice of relating the product premium and price, as a function of the world crude oil price is an obvious one taking into account that the price of refined products consistently follows the trend of crude oil prices.

CHAPTER 4

RESULTS OF ECONOMIC ANALYSIS

To perform the economic evaluation of the different transportation modes, a GTL scenario is assumed where the facility is built on the ANS. A 300,000 barrels per day plant was assumed. By the current standards, this is a very large scale GTL plant. Taking into account that one of the numerous benefits expected from the GTL option is the provision of additional liquid fill to keep the pipeline operations running. This therefore requires a huge GTL facility that can provide enough liquids to significantly improve the economics of the TAPS. Another reason is that 38 Tcf is a substantial resource concentrated in one area and only a GTL plant of that magnitude can successfully utilize that resource. Initial analysis considered a project life of twenty years. This was later found to be inadequate to give enough time for the last train of the GTL facility to payout and yield some return on investment. Therefore, the life of the project was finally assumed to be thirty years. The operating efficiency for the plant is assumed to be 95%. The state and federal income taxes are estimated based on their current values in other oil and gas projects in the state of Alaska. Table 4.1 gives a summary of the economic parameters or assumptions that were made to perform proper economic evaluation of the transportation options.

Table 4.1 Economic Assumptions

ECONOMIC ASSUMPTIONS	
Conversion @ 60% efficiency	8.33 MScf / Bbl
Plant Uptime Efficiency	95%
Project Life	30 years
Plant Capacity	300 MBPD
Taxes	
State Income Tax	9.4%
Federal CIT	35.0%
Property Tax	2%
Depreciation	Modified Accelerated Capital Recovery Scheme

Other important model parameters were estimated based on current industry estimates on GTL and petrochemical-type facilities. The other parameters used in the analysis and the range of possible changes in those parameters that were studied are presented in Table 4.2 .

Table 4.2 Model Parameters

MODEL PARAMETERS FOR ROR
Cost Estimates
Plant Cost ranging from $20,000/BPD to $35,000
Gas Cost based on net back of 10%
Annual Operating and Maintenance cost of 5.6% of Plant Cost
Transportation and storage estimated with Tariff estimates. Capital investment are amortized over the project life and worked out per barrel of product.
Revenue Estimates
ROR calculation based on $21.00 per barrel crude price.
GTL products given a premium of 1.25 times Spot Oil price
Batch Transportation efficiency of 95%

4.1 METHOD OF EVALUATION

Rate of return analysis was performed incorporating the capital cost of transportation for the batch and commingled mode. The capital investment required for transportation of GTL products was amortized and will be paid back through the thirty years of the project life at a discount rate of 10%. The yearly amortization was divided by the throughput to arrive at the extra cost in $/bbl of batching GTL product either by purchase of new infrastructure or refurbishing of existing infrastructure.

4.2 INVESTMENT PATTERN

Construction is assumed to start in year 2005 and last till 2008 for the first train. The capital cost is varied between $20,000 /DBL and $35,000 / DBL invested equally between the four years. The second train is assumed to commence immediately the first is completed and put on production, construction of the third after two years of commencing of the construction train 2. Operating and maintenance cost for each of the trains commences in the same year with production for each of the three trains. The learning curve associated with the above approach to investment was not incorporated as noted above.

The property tax is calculated from a tax base obtained after depreciating the capital cost using the MACRS. The taxation formula obtained from the state's department of revenue was used to calculate property tax base and finally obtain the tax, which is 2% of the tax base. A cash flow model was set up to analyze the same. For the different modes of transportation, the associated capital cost was included under the tariff and comes as cost per year. The cost of gas both as raw material for the GTL plant and the cost of gas for running the first four pump stations are all included in the cost section. The revenue was obtained as a product of the expected product sale price and the total product transported. The taxation was then applied appropriately to calculate net revenue and profit. Another factor introduced in the analysis is the batch efficiency, which accounts for product downgrade at the interface formed between crude oil and GTL. Equations to calculate the expected interface between two liquid slugs are available. As the experience of some operators show, this can be about 5000 barrels when batching diesel and gasoline through more than 1000 km of pipeline. Since the size of the interface is not really a function of the length of the slug, it therefore means that providing the required tankage at the North Slope to store GTL and crude oil separately is crucial to achieving good results. This is because it will reduce the number of slugs thereby reducing the amount of interface, which leads to product downgrade, and loss of product premium.

4.3 RESULTS AND DISCUSSION

The result of the analysis performed on each mode of transportation is presented below. The world oil spot price was assumed to average $21 per barrel.

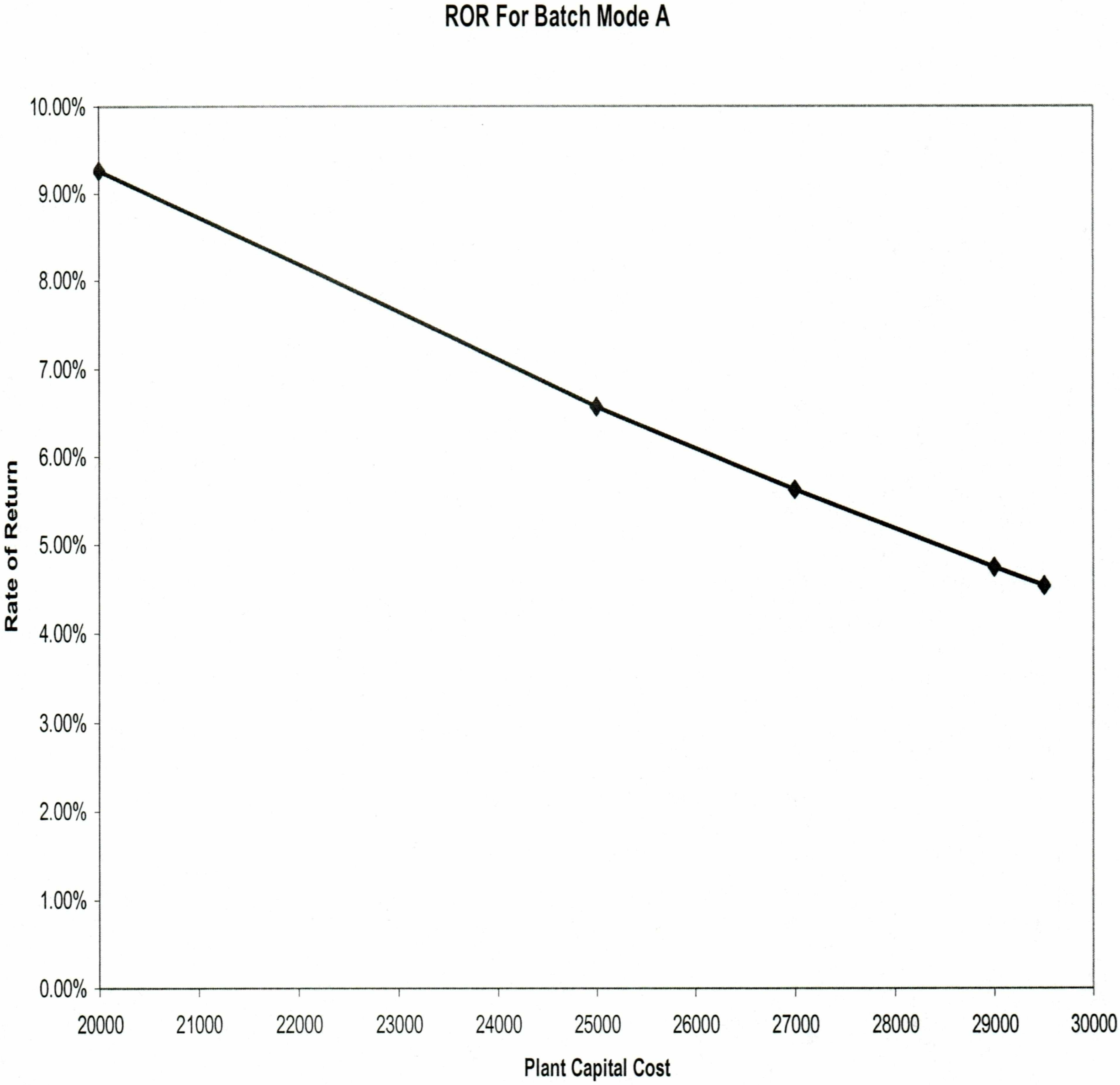


Fig 4.1 Rate of Return Analysis for Batch Mode A

The rate of return analysis for mode A presented above shows the effect of low batching efficiency by letting the physics of the fluid control flow and not employing new technology.

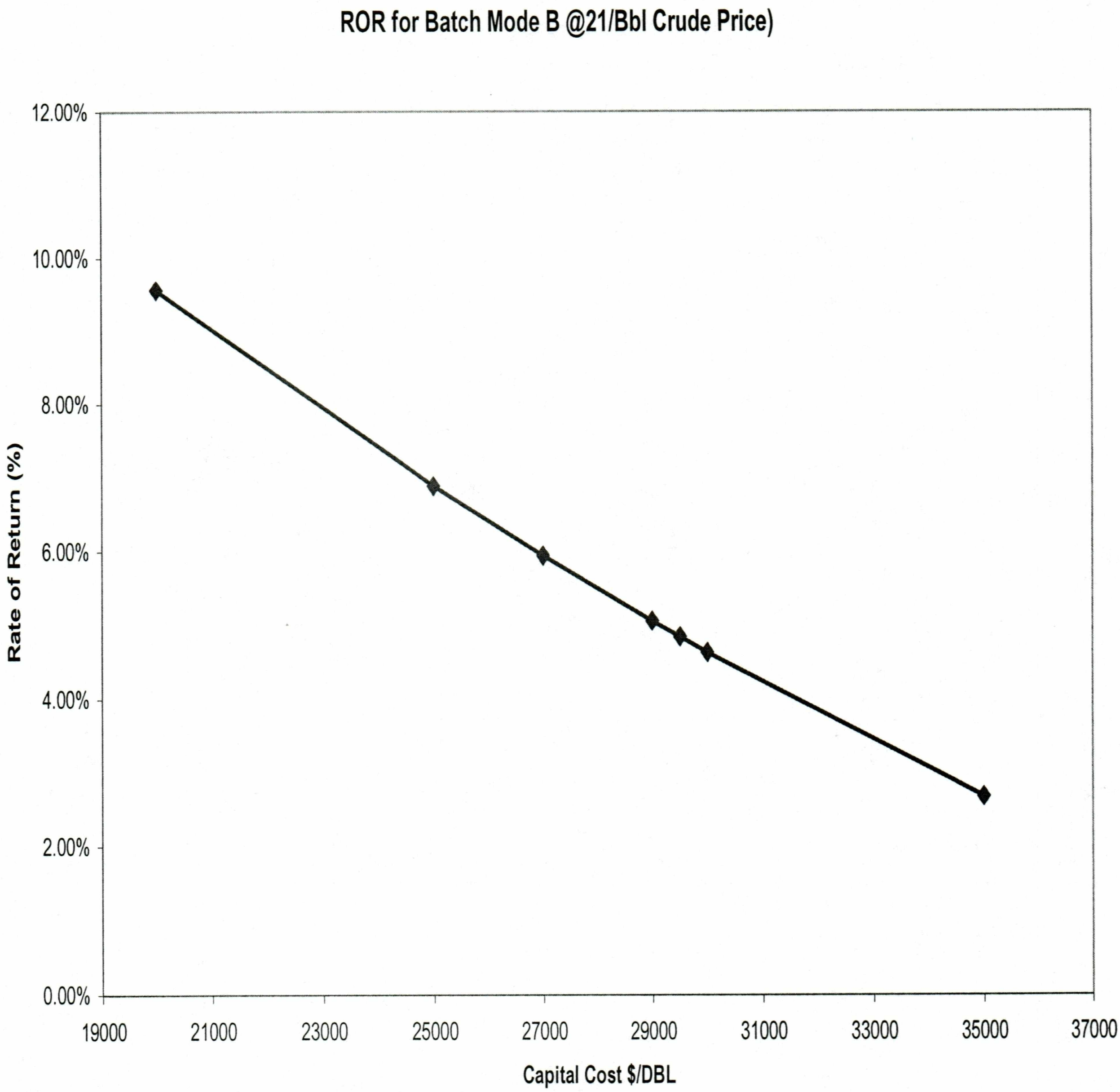


Figure 4.2 Rate of Return for Batch Mode B

Maximum separation efficiency by the pigs is assumed here. However, added costs of labor and the cost of pigs reduces the attractiveness of this option.

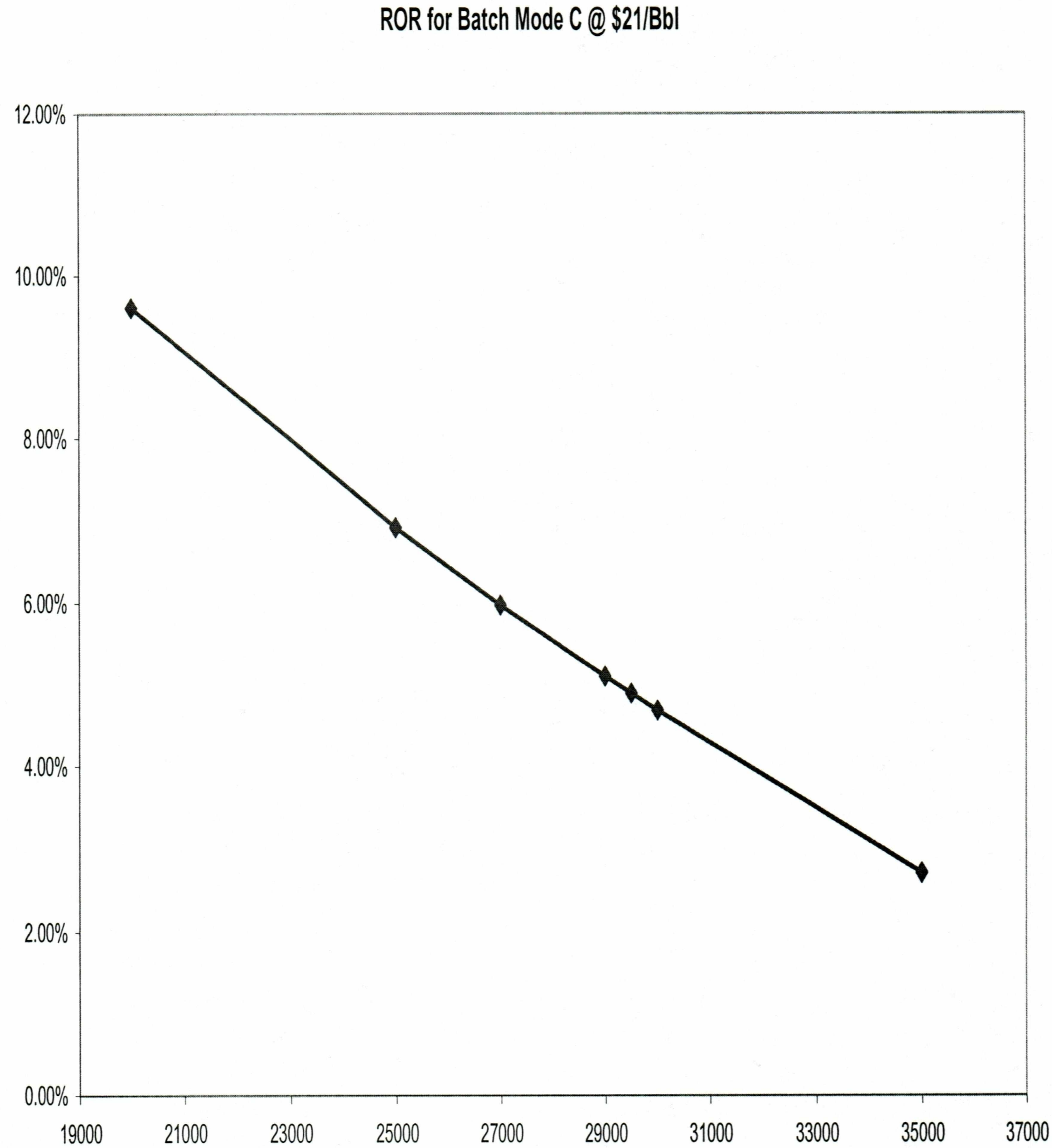


Figure 4.3 Rate of Return for Batch Mode C

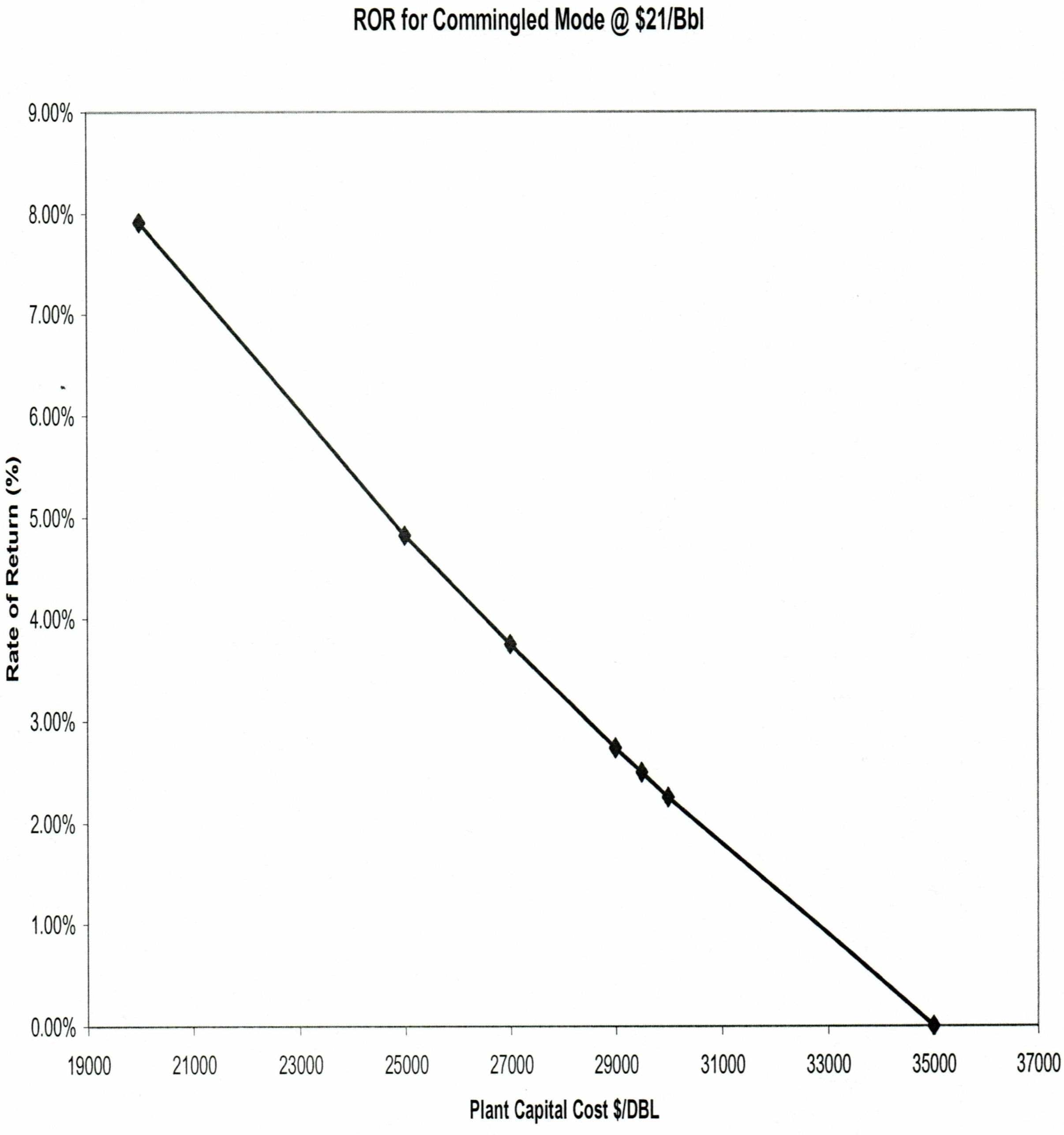


Figure 4.4 Rate of Return for Commingled Mode

Table 4.3 Summary of Rate of Return for all Modes of Transport

CAPEX Per Daily Barrel	Batch A	Batch B	Batch C	Commingled
35000	2.33%	2.68%	2.72%	0.00%
33000	3.10%	3.44%	3.48%	0.00%
30000	4.32%	4.64%	4.68%	2.26%
29500	4.53%	4.85%	4.89%	2.50%
29000	4.74%	5.06%	5.10%	2.74%
27000	5.63%	5.94%	5.98%	3.75%
25000	6.57%	6.88%	6.92%	4.82%
23000	7.58%	7.89%	7.93%	5.97%
20000	9.21%	9.57%	9.61%	7.91%

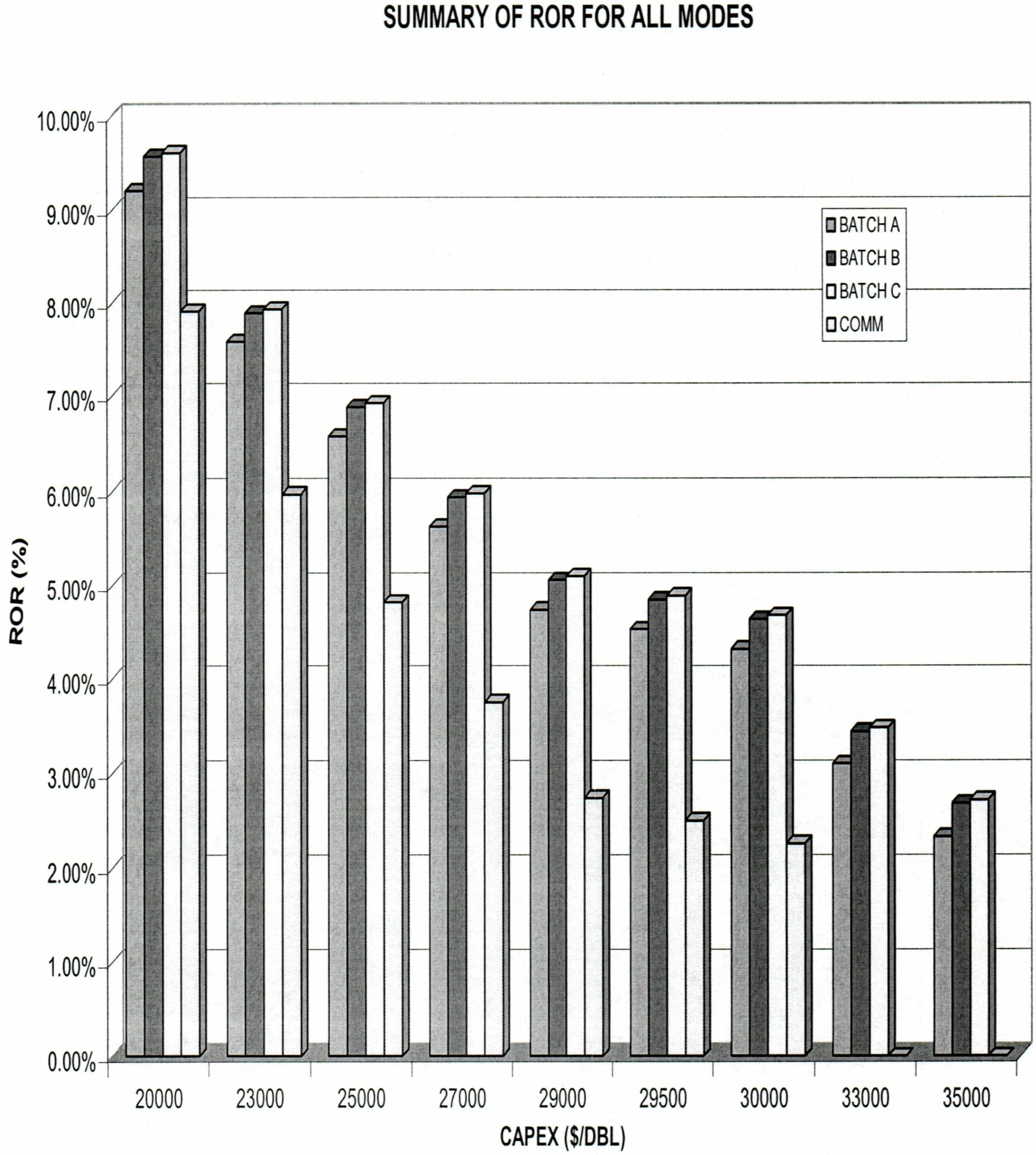


Figure 4.5 Summary of ROR analysis for all modes

4.3.1 Sensitivity Analyses

Key parameters in the rate of return analysis were modified to identify those with the greatest influence on the results. The parameters include:

- Capital Expenditure was varied between $20,000 per daily barrel and $35,000 per daily barrel to accommodate speculated range of plant costs and possible North Slope scale up factor.
- The crude oil price was varied between $21.00 per barrel and $35.00 per barrel
- For the batching operation, installing new storage and relief tanks at the terminal and pump stations respectively versus refurbishing some old tanks GTL production and storage. The results of the analysis are presented below;

Table 4.4 Summary of Sensitivity Using Batch Mode C

Summary of Sensitivity Using Batch Mode C				
Crude Price/ Capex $/DBL	35000	30000	25000	20000
21	2.72%	4.68%	6.92%	9.61%
23	4.15%	6.08%	8.32%	11.04%
25	5.42%	7.34%	9.60%	12.37%
27	6.57%	8.50%	10.79%	13.62%
30	8.15%	10.11%	12.45%	15.37%
35	10.48%	12.51%	14.96%	18.03%

The results of this price variation was performed on batch mode C alone. The reason for this choice was that Mode C gave the highest return on investment and is used for all further investigations. The shaded portion in the table represents all scenarios that cross the 10% rate of return benchmark.. As can be seen from the table, at crude price of $21 per barrel all the capital expenditures considered did not meet the 10% cut off point. The mark is only reached at $35 per barrel of crude oil price if the capital expenditure were to be $35,000 per daily barrel of liquid produced. A 15% Minimum Attractive Rate of Return (MARR) will be difficult to achieve considering the fact that only two scenarios of $20,000 per daily barrel with crude price averaging $30 per barrel will qualify. The second scenario that will qualify is for a higher crude price of $35 per barrel and the same capital cost as scenario 1. This is presented in a three dimensional bar chart shown below.

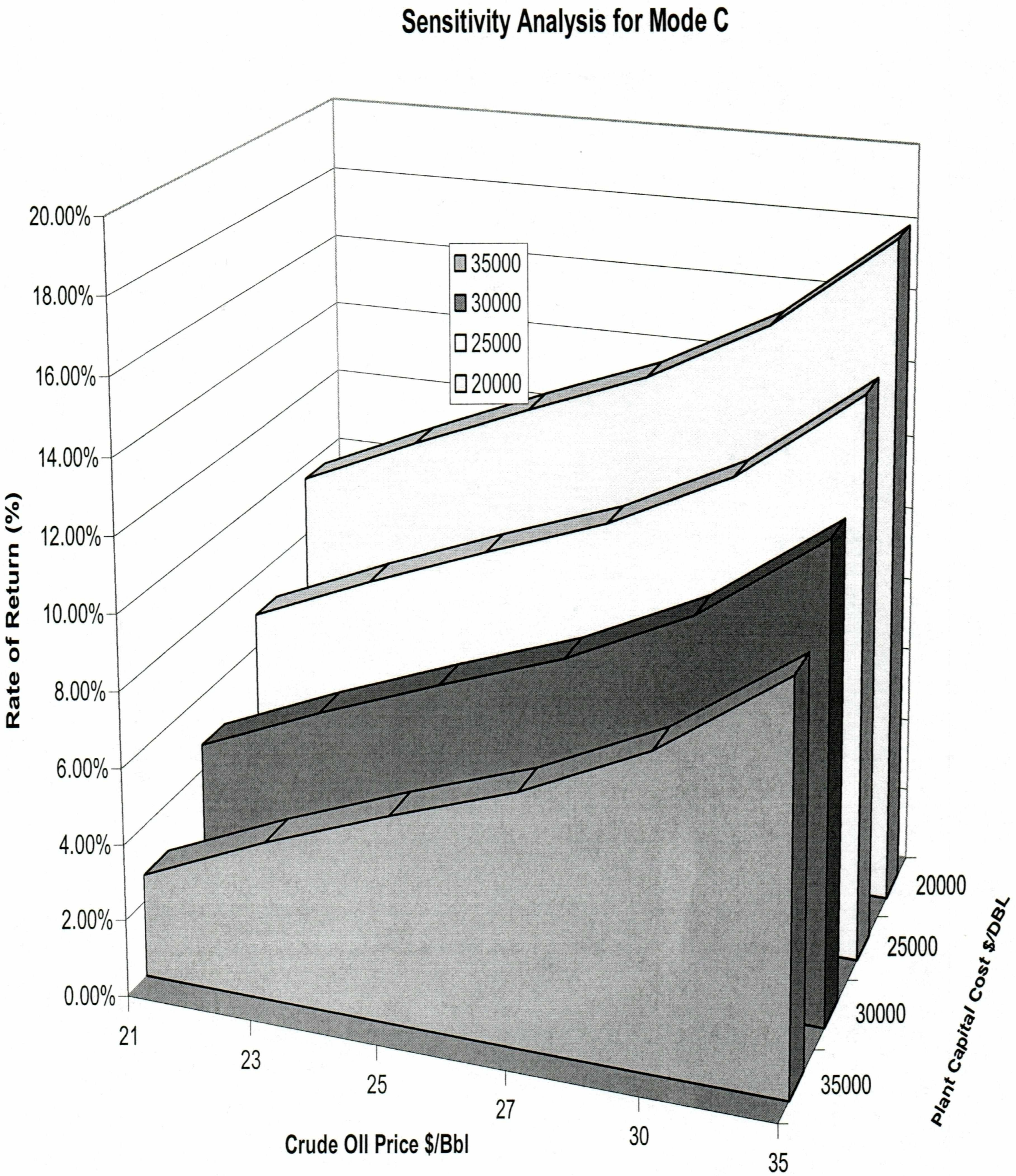


Figure 4.6 ROR for batch mode C at various crude oil prices

Batch mode C had the highest return on investment among all the transportation modes and for all plant capital investments scenarios studied. The recovery efficiency of pure GTL product here was put at 95%. This assumes that 5% of the GTL mixes with the lead and tail crude to form an interface and is expected to clean the pipeline for the pure GTL product as the middle fluid followed by another interface of GTL crude oil mixture. As noted earlier, experience of operators that carry out similar operations show that typically, the length of the interface does not depend on the volume pumped but rather on the difference in the physical properties such as density and viscosity of the leading and tailing product as well as the velocity of the fluids in the pipeline. This implies that holding capacity at the ANS may play a significant role in the optimization process to help minimize the number of slugs to be pumped through in a day.

The GTL premium used in this calculation is 1.25 times the world spot oil price. To arrive at this number, a survey carried out showed that conventional diesel products over the years sold for about 1.42 times the price of crude on the average. A typical GTL plant in this study assumed a product with an 80% yield of Fischer Tropsch (FT) diesel and 20% yield of Naphtha products. Naphtha was given a number of about 1.19 times the price of oil from the historical survey. Combining these two in their ratio of yield and price will give the combined GTL product a value of about 1.37 times the price of crude oil. However, to adopt a conservative approach, 1.25 times the world spot oil price was taken to perform the evaluation. Many authors in the subject are also of the opinion that the GTL diesel should sell at a higher price than the conventional diesel product from typical crude oil distillation process considering its environmental superiority as discussed above. This edge for the GTL diesel was not taken into account in the study.

Advocates of commingling the crude oil and the GTL are usually concerned about the pricing of the GTL products. Another issue also constantly raised is that there might just be a possibility that the value of the commingled product is underrated. To clear this discrepancy in this analysis, another set of sensitivity analysis was carried out to find out reasonable points at which commingling of the products and batching the products give equal return on investment. This set of analysis was carried out keeping the capital expenditure and the world spot oil price constant. The results of the analysis are presented below;

Case 1

This represents a scenario where the commingled product has a price premium of $1 per barrel above world spot oil price. It is important to recognize the fact that as the GTL premium increases, the cost of natural gas is expected to increase due to the net back method of pricing the gas.

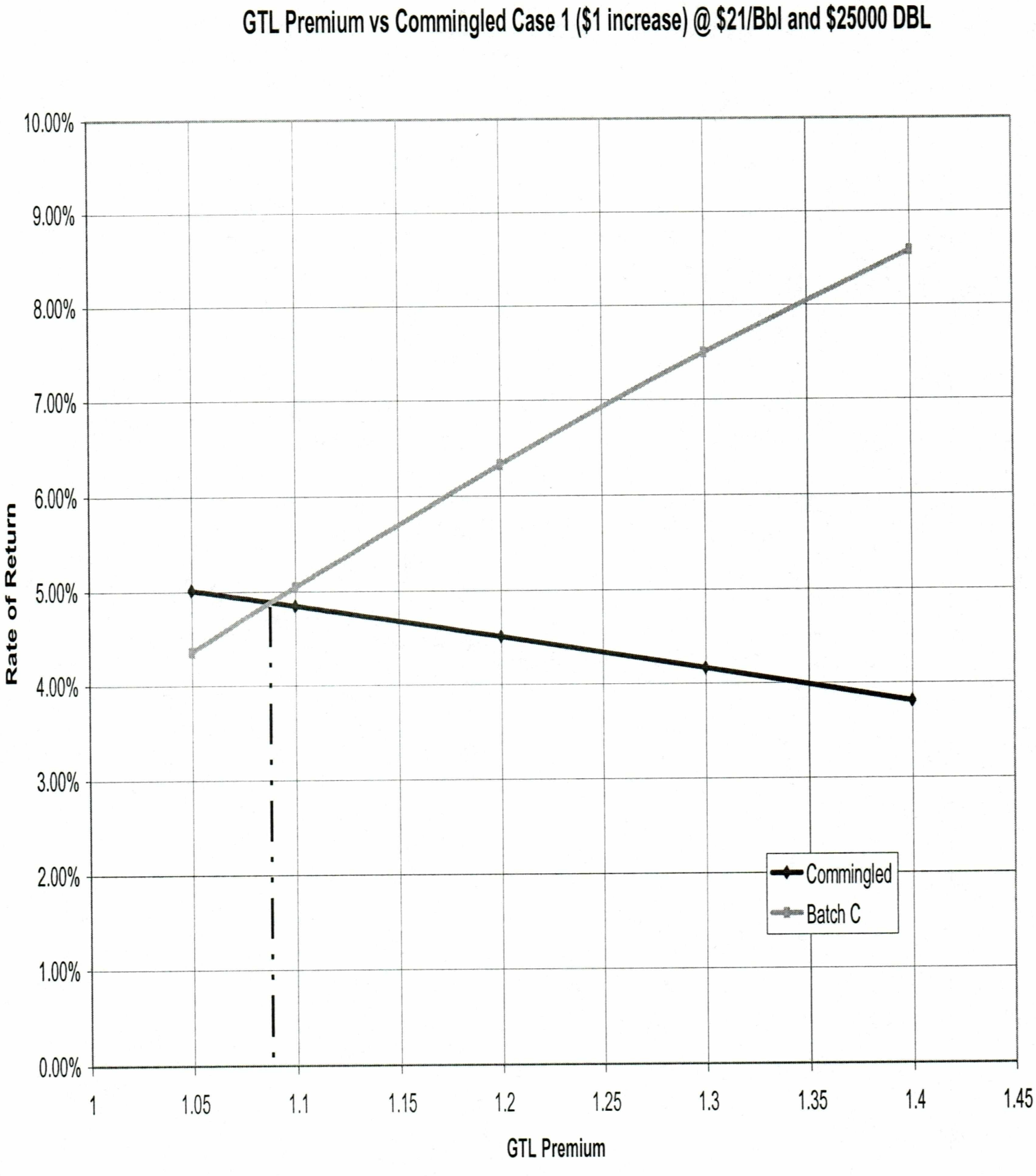


Fig 4.7 GTL premium vs Commingled Case 1 ($1 Increase)

Case 2

This is a scenario where the commingled product has a price premium of $2per barrel above world spot oil price.

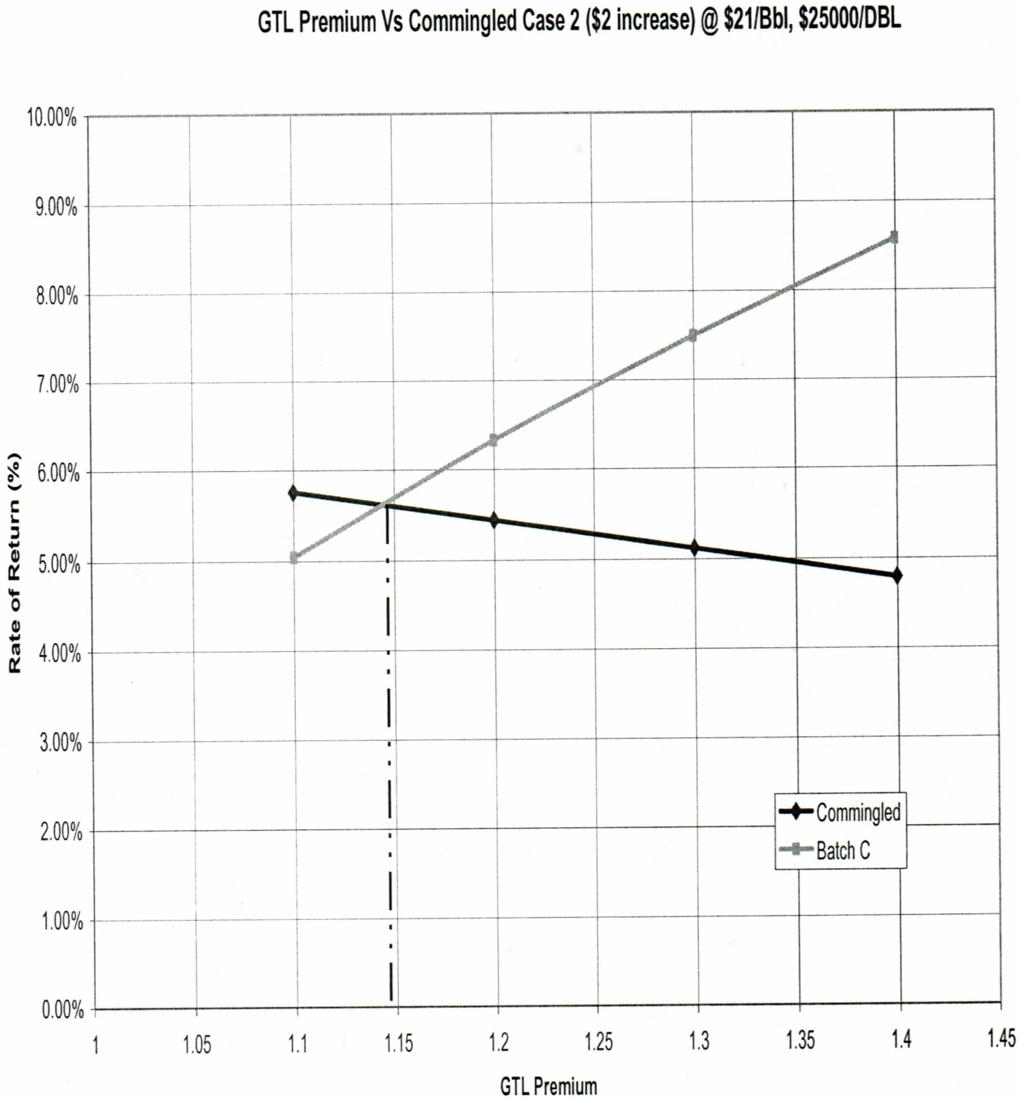


Fig 4.8 GTL Premium vs commingled case 2 ($2 increase)

Case 3

This represents a scenario where the commingled product has a price premium of $3 per barrel above world spot oil price.

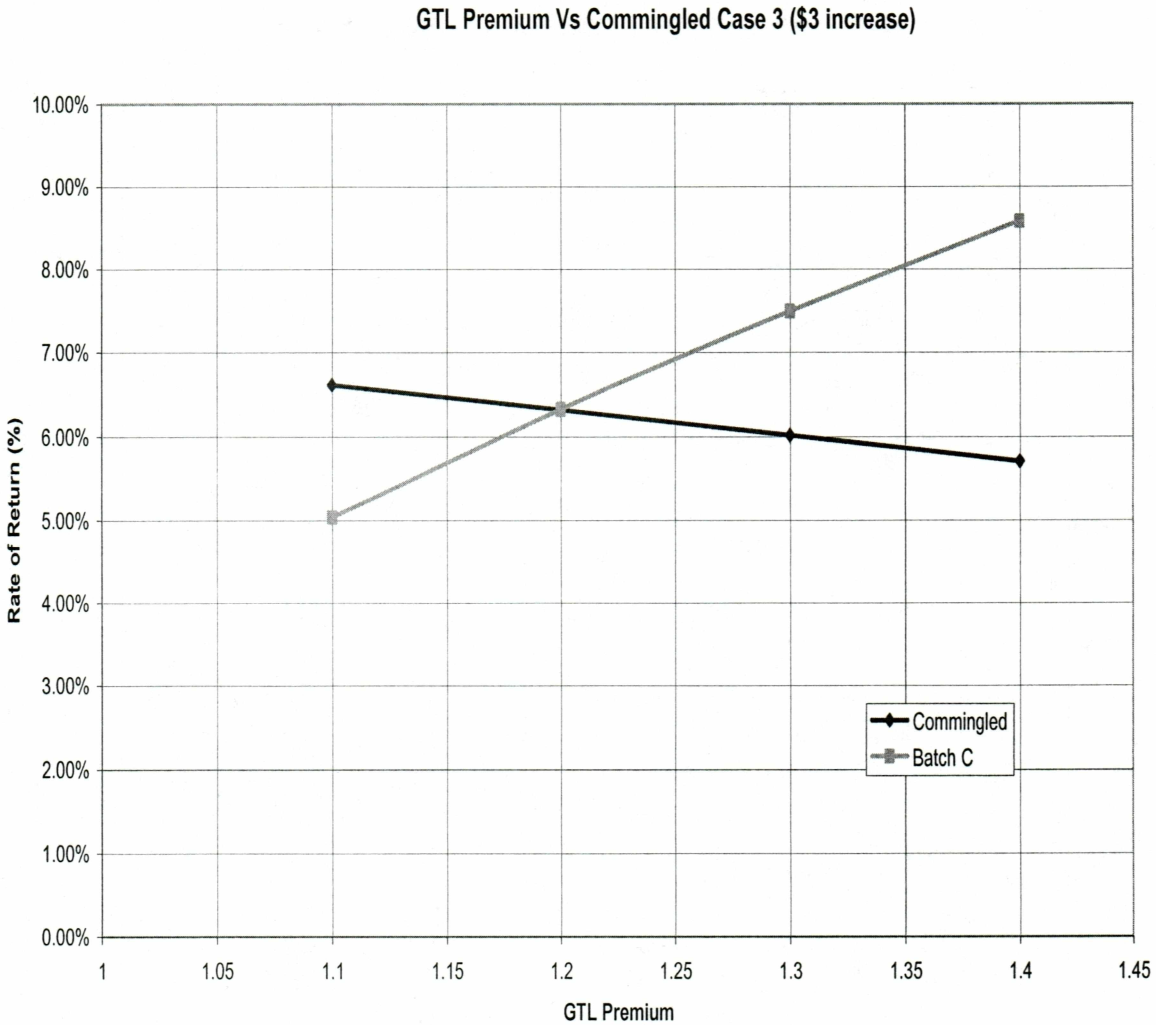


Figure 4.9 GTL premium vs Commingled Case 3 ($3 Increase)

Case 4

This is the most likely scenario. The commingled product has a price premium of $1.5 per barrel over the spot oil price.

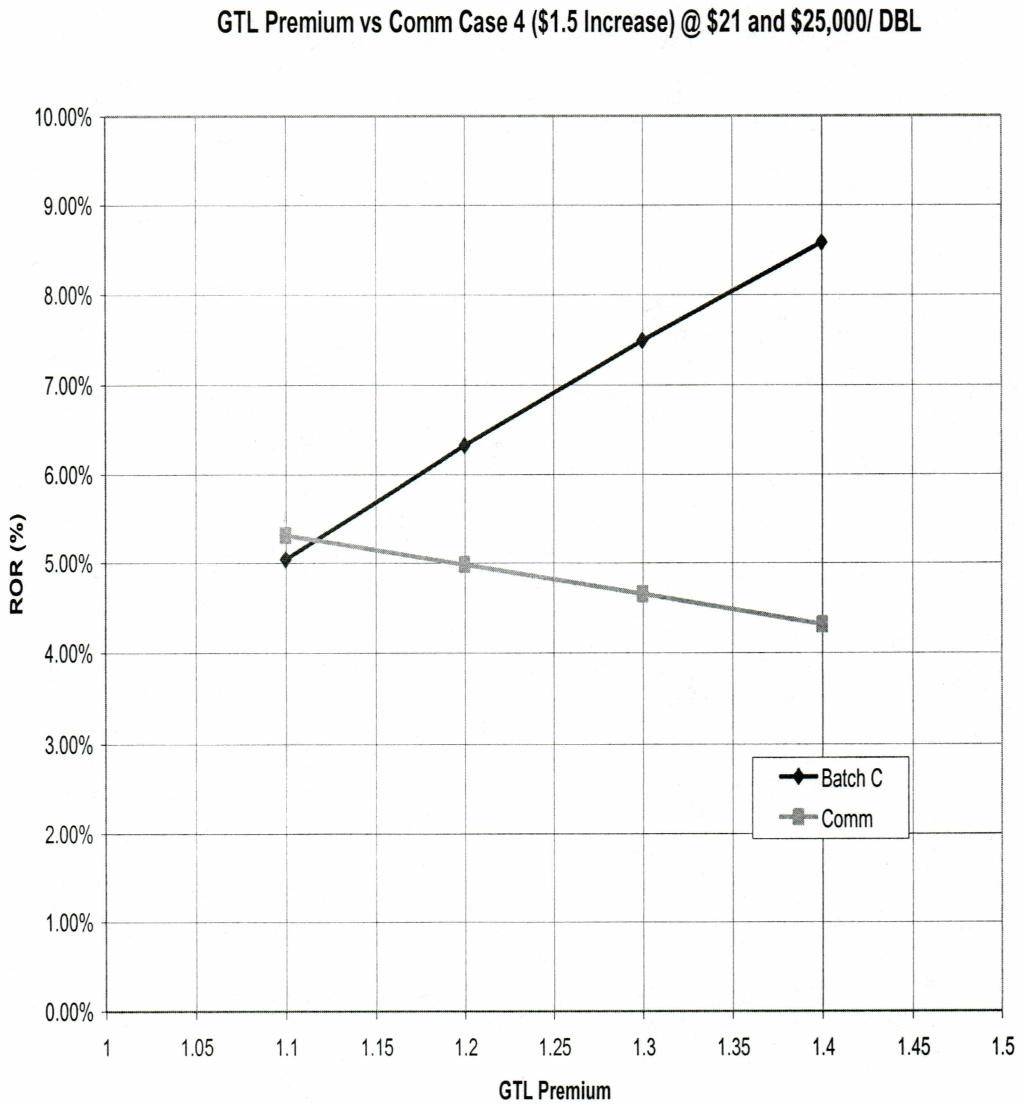


Figure 4.10 GTL premium vs Commingled Case 4 ($1.5 Increase)

The four different cases show the relationship between the premium of the commingled mode and the overall result. Case 1 assumes that the premium is $1. The implication of this is that if the GTL product cannot guarantee a premium of over 1.08 times crude price at $21 per barrel then commingling is better. This translates to $22.68 per barrel or a premium of $1.68 over crude oil price. Case 2 assumes $2 premium for the commingled product. Here, the equilibrium price for the pure GTL product below which batching is not an option is 1.145 times crude price which translates to $24.05 per barrel or a premium of $3.05 over crude oil price. For this case, the commingled product is priced at $23 per barrel. Case 3 assumes a $3 dollar premium for the commingled product. Here, the pure GTL must have a premium of over 1.2 times the crude price to be chosen as the option for transportation. This translates to a GTL price of $25.20 per barrel or a price premium of $4.20 over crude oil. The most realistic case appears to be case 4, which assumes a premium of $1.5 per barrel for the commingled mode and an equilibrium price of 1.12 times crude price. This means that if the GTL can sell for more than $23.52 or a price premium of $2.52 per barrel, then batching is the preferred option.

Another set of sensitivity analysis addressed possible concern what size of interface (mixing zone) between adjacent slugs or simply the batching efficiency can change the choice of the transportation method. In the original analysis, the interface was assumed to be 5% of the entire slug length. There is a minimum length for a successful batch operation (Akwukwaegbu 2001). Equations have been derived by

Scott et all (1986) for calculating the minimum slug length for large diameter pipes, which can be translated to volumes for effective batching and minimal contamination for large diameter pipes given by

$Ln\ (L_s) = -25.4144 + 28.4948\ (Ln(D))^{0.1}$ ------------------------(1)

By using a momentum balance equation over a slug unit, the minimum average fluid velocity V_m is obtained as:

$$V_m = \frac{Q_1 + Q_2}{A} \quad \text{---(2)}$$

The transitional velocity, defined as the velocity of the leading edge of the slug is given as

$$V_t = C_o V_s + V_d \quad \text{---(3)}$$

Where C_o is 2.0 for laminar flow and 1.2 for turbulent flow, V_s is the average slug velocity and V_d is the propagation or drift velocity and is defined as (Kokal et al 1989);

$$V_d = 0.345\sqrt{\frac{Dg(\rho_{l1} - \rho_{l2})}{\rho l1}} \quad \text{-----------------------------------(4)}$$

Due to the difference in phase properties, (density and / or viscosity), one of the fluids usually the less dense phase, tends to flow at a higher in situ velocity than does the other. This results in slipping of one phase past the other, also known as hold-up.

Abdul – Majeed's equation (1996) is a good tool for determining liquid hold-up in the slug.

$$(E_{ls})_{theoretical} = exp(-9304919+0.5285852R-9.219634X10^{-2}R^{2}+9.02418X \quad 10^{-4}R^{4}) - _{Turbulent\ flow} \text{---} (5)$$

$$(E_{ls})_{theoretical} = exp(-1.09924+0.6788495R-0.1232191 \ X \ 10^{-2} \ R + -1.798653 \ X \ 10^{-3} \ R^{3} + 1.626819 \ X \ 10^{-3}R^{4}) - _{Laminar\ flow} \text{-------} (6)$$

$$\text{Where } R = \ln(X) \text{--} (7)$$

$$X = \left[\frac{[V_{s2}\rho_{l2}\upsilon_{l1}]}{[V_{s1}\rho_{l1}\upsilon_{l2}]}\right]^{m} \frac{\rho_{l1}V_{s1}^{2}}{\rho_{l2}V_{s2}^{2}} \text{-----------------------------} (8)$$

m = 0.2 for turbulent flow and m=1 for laminar. A correction is made to the value of the liquid hold-up obtained from both equations

$$(E_{ls})_{actual} = C(E_{ls})_{theoretical} \text{---------------------------------------} (9)$$

$$\text{Where } C = 0.528 \ (V_{s2}V_{s1})^{-0.215121} \text{----------------------------} (10)$$

Another important parameter of big economic importance in the transportation study is the length of the mixing zone. Duckler and Hubbard (1975) presented the following model

$$L_m = \frac{0.15\,(V_m - V_f)^2}{G} \text{---}(11)$$

V_f is the film velocity. It is observed that for large values of V_m, the above equation largely over predicts L_m. Andreussi et al (1993) made the corrections

$L_m = K_m\,(1 - E_{ls})D$---(12)

Where K_m is a factor for the length of the mixing zone and it is approximately equal to 30.

The length of the interface was varied to reflect the effect of distance and possible agitation at the pump stations on the final products that will arrive at the terminal. The results are presented below.

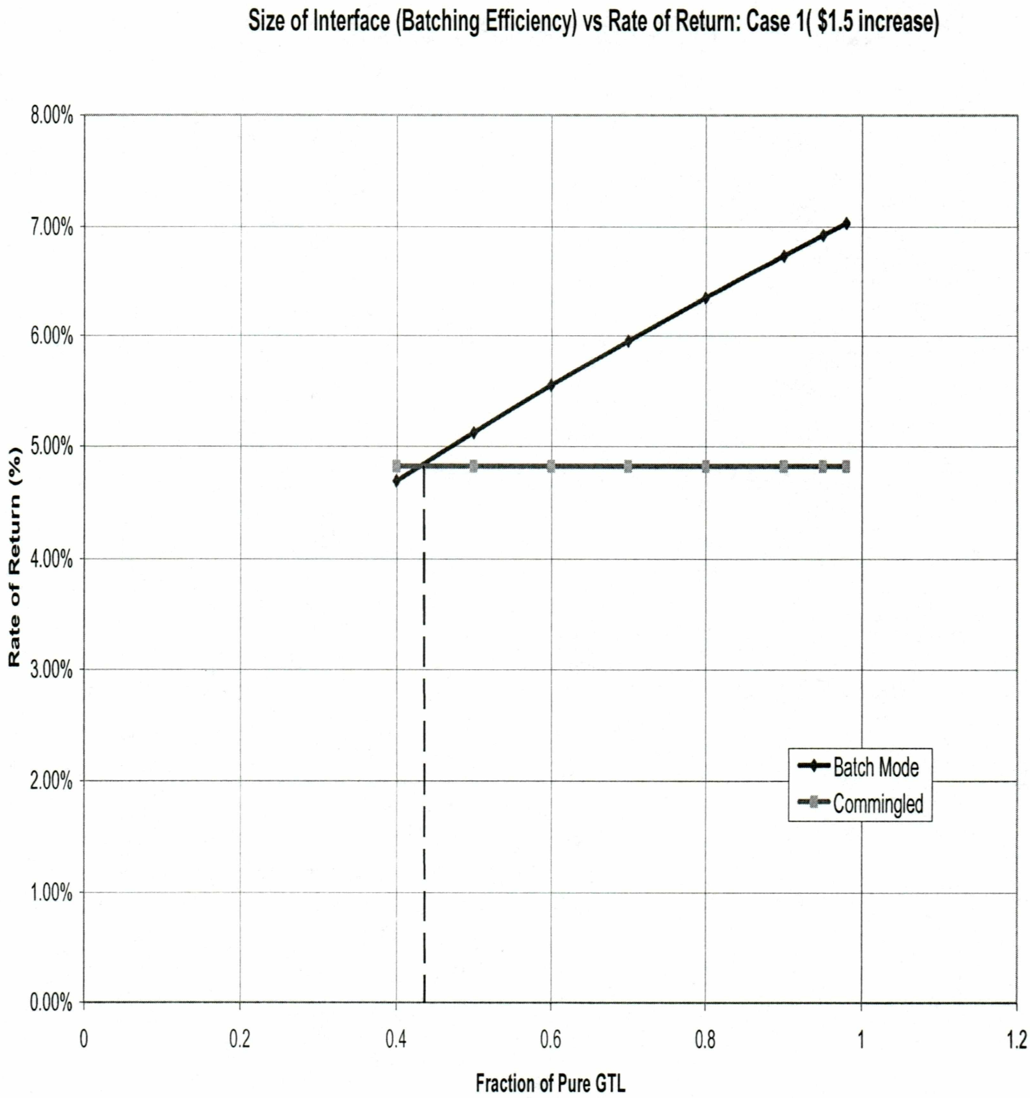


Fig 4.11 Batching Efficiency Case 1

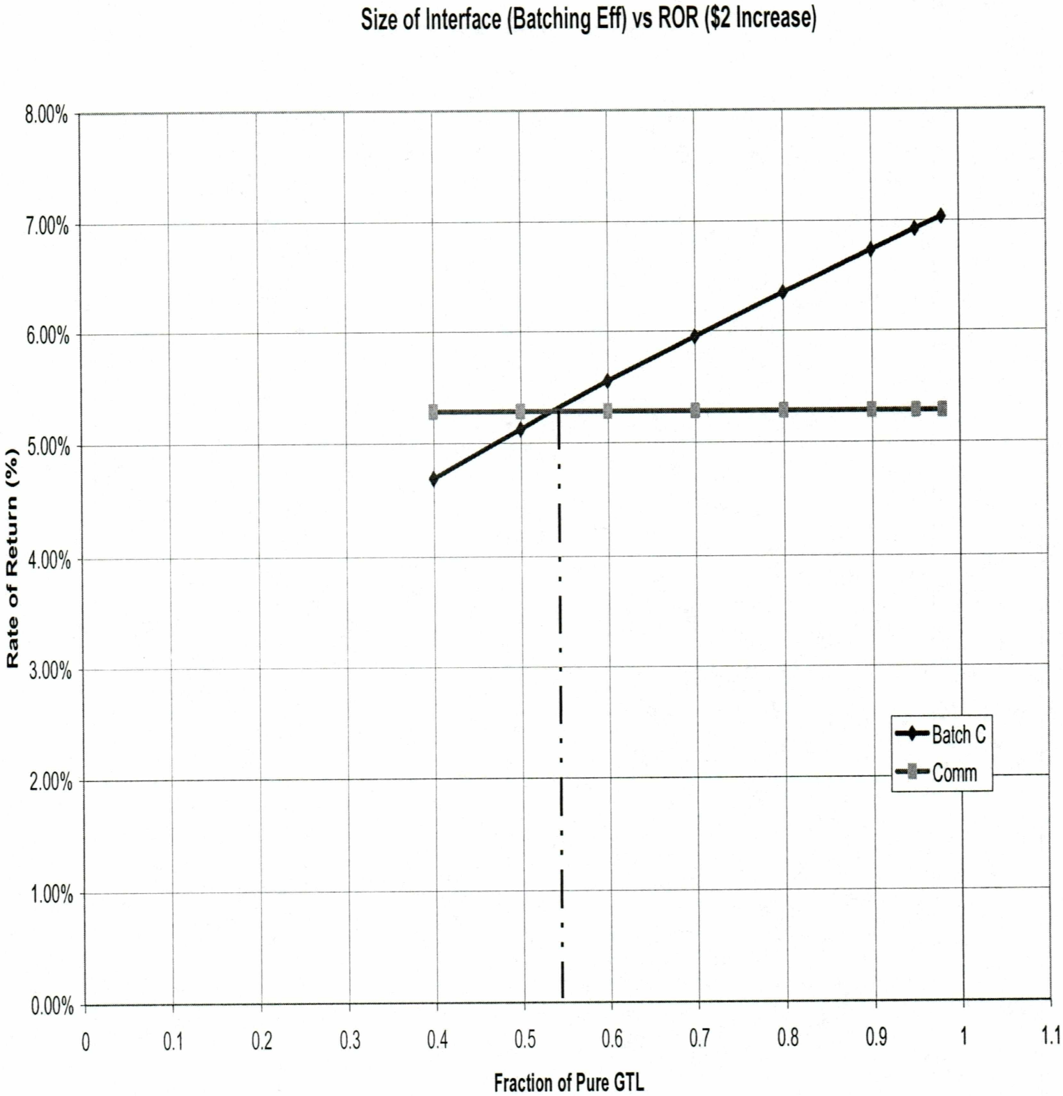


Fig 4.12 Batching Efficiency Case 2

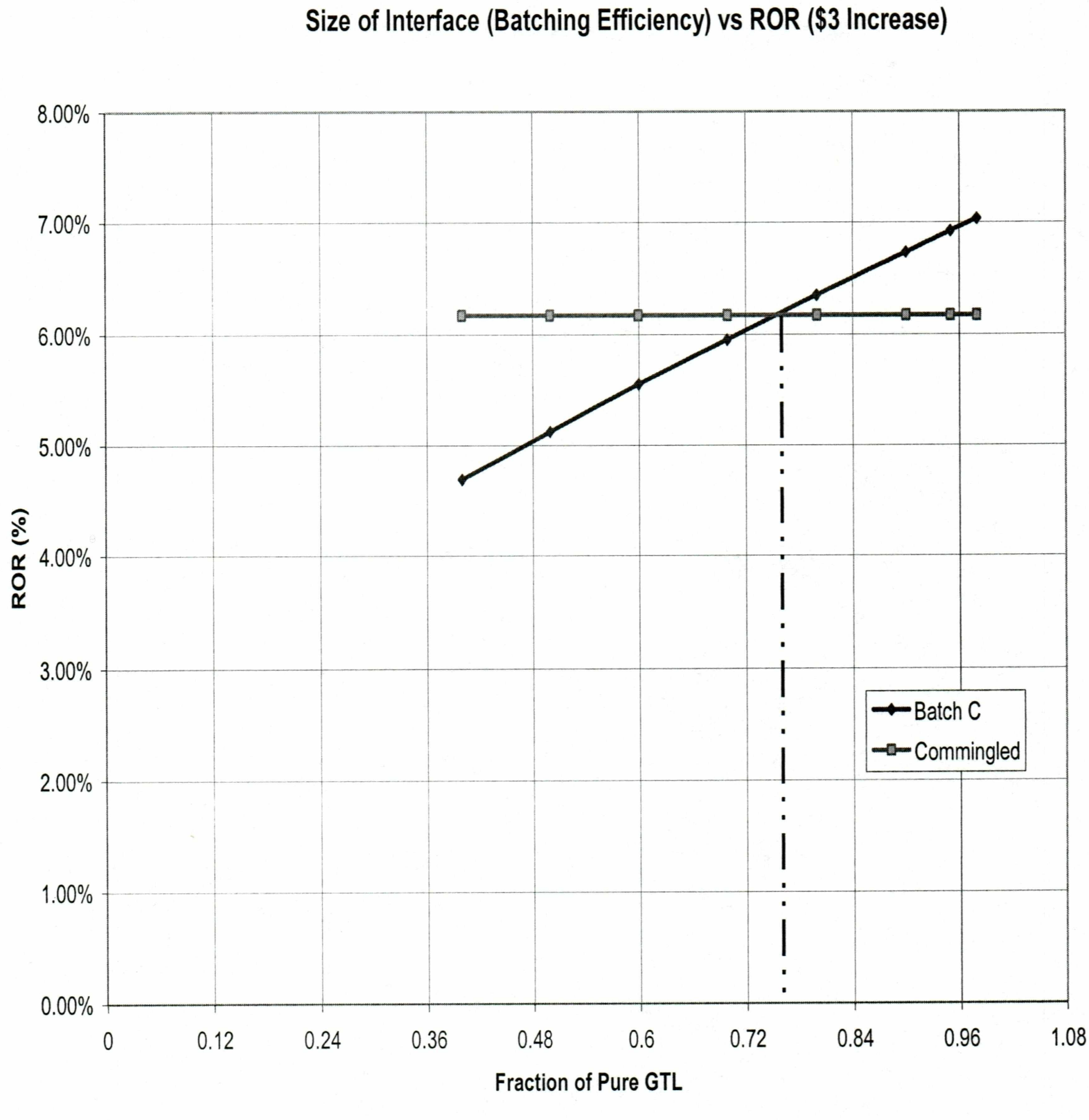


Fig 4.13 Batching Efficiency Case 3

From the above results, case 1 represents a case of $1.5 premium for the commingled product. The figure shows that the interface has to be more than 55% of the entire slug length for both the commingled and batch mode to give the same return on investment. For case 2, for a two-dollar premium on the commingled product, the interface for batch transportation will have to be about 45% of the entire slug length to give equilibrium ROR. A three-dollar premium for the commingled product will be equaled by about 26% interface. In summary therefore, it can be concluded that since the interface is not expected to be more than 10-15% under all operating conditions, the commingled mode will not match the ROR for the batch mode for a three hundred thousand barrel per day GTL facility built on the slope

As mentioned earlier, the main benefit of transporting GTL through the Trans Alaska Pipeline system is the utilization of existing infrastructure. The additional cost of constructing additional equipment and storage facilities for the batch operation is the main consideration in favor of commingling the products. However, in the analysis performed above, the assumption was that new facilities were put in place for ensuring product purity. However, there exists some potential for utilizing the current facilities by reconditioning and refurbishing them to store GTL. Each of the tanks both on the slope and at the terminal cost an estimated $65 million. Estimate for reconditioning the tanks to store GTL was $5 million. The effect of this saving on the final rate of return was quite significant.

Table 4.5 Effect of Reconfiguring versus Building New Tanks

CAPEX ($/DBL)	Build New Tanks	Reconfigure Old Tanks
20,000	9.61%	10.33%
25000	6.92%	7.38%
30000	4.68%	4.99%
35000	2.72%	2.93%

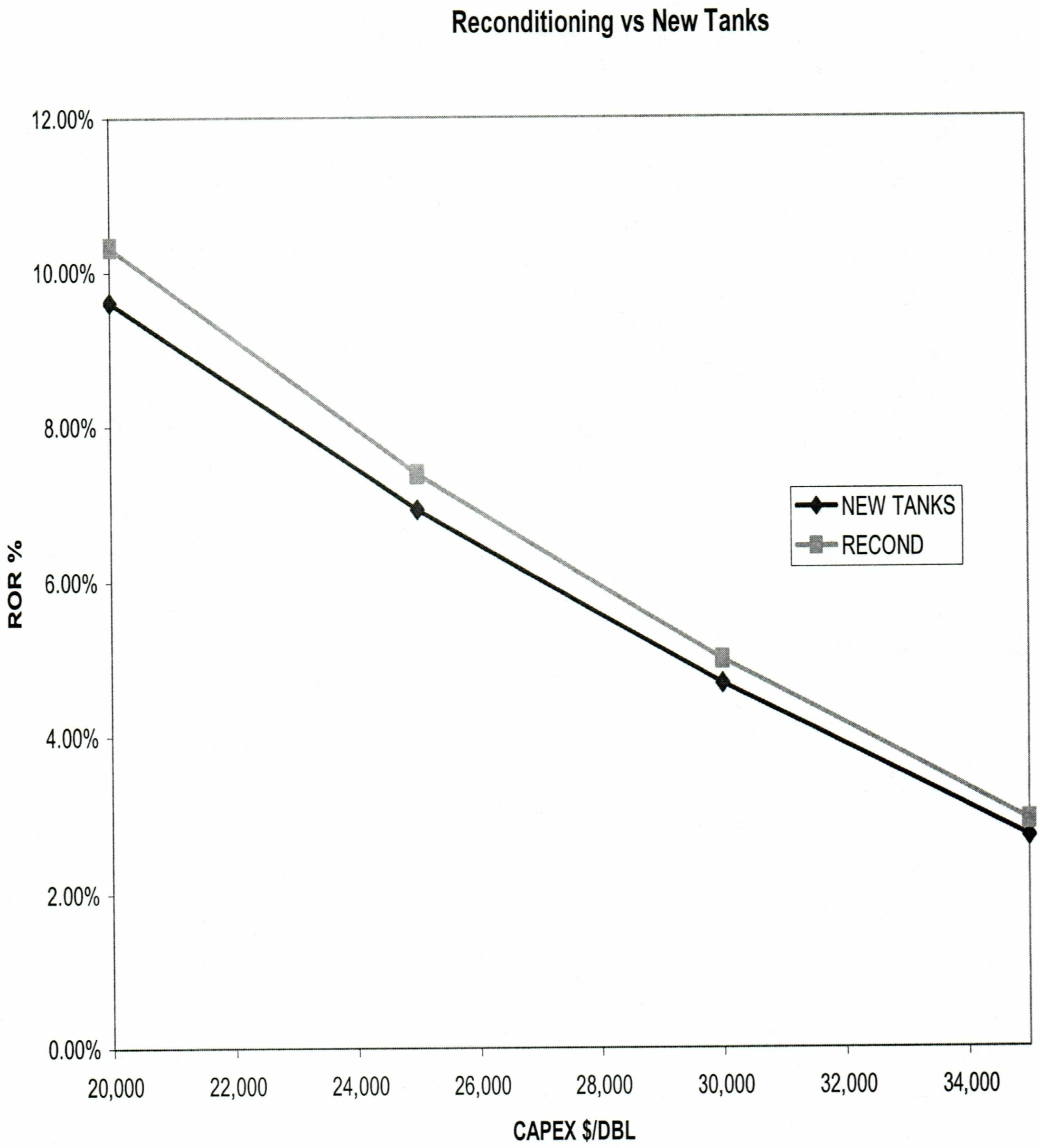


Figure 4.14 Effect of Building new Tanks versus Reconfiguring

As the capital expenditure reduces, the difference between the rate of return for the batch mode and the commingled mode becomes smaller. One theory that supports the commingled mode is to build a low grade GTL plant on the North Slope that will significantly be cheaper than the conventional GTL plant. Another theory is that the commingled product will yield a high amount of middle distillates after refining. The next analysis investigates the capital cost at which both the batch mode and the commingled mode will deliver the same returns and below which it will be better to commingle. The difficulty with this analysis is that the GTL premium for the low grade GTL facility on the Slope will be different from that used in the foregoing analysis. For simplicity, we assume the premium remains 1.25 times world oil price. For average world oil price of $21 per barrel and assuming a commingled product premium of $1.5 per barrel, the result is presented in figure 4.15 below..

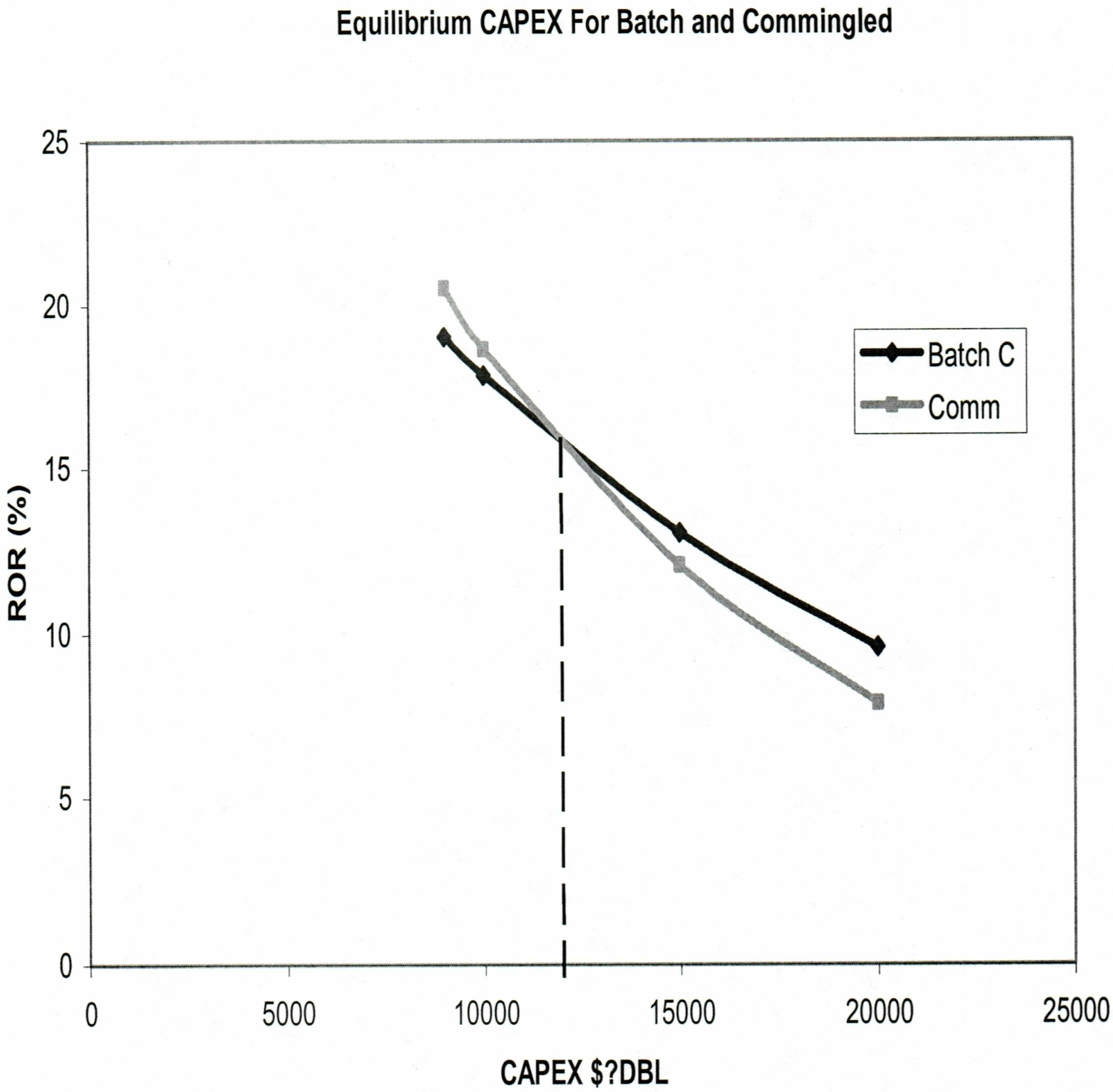


Fig 4.15 Equilibrium CAPEX for Batch and Commingled Modes

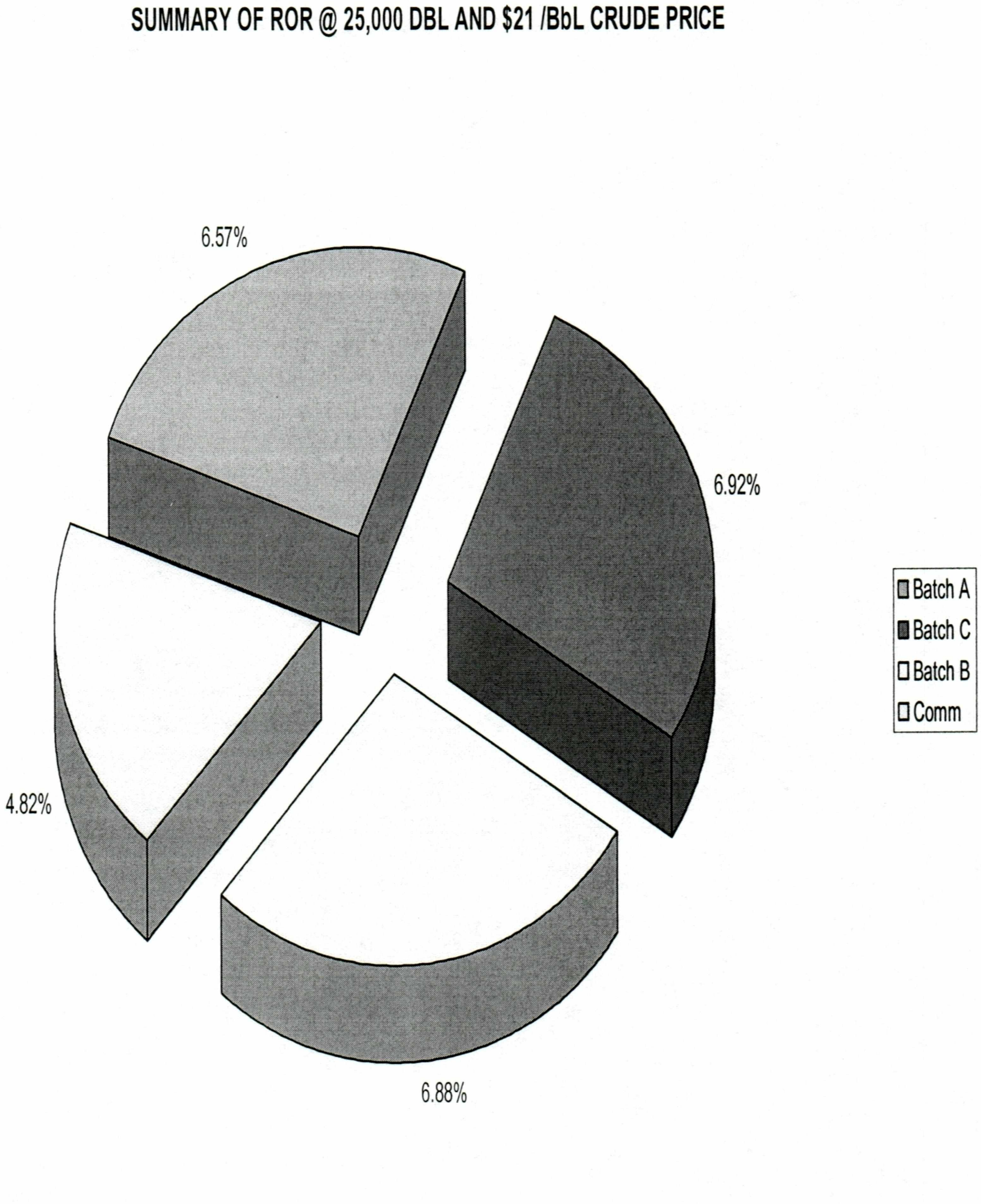


Figure 4.16 Summary of ROR For all Modes of Transportation

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

A comparative study of the different methods of transporting GTL products was performed to evaluate the best available means of transporting these products. However, due to the various possible scenarios that are possible depending on the capital investment available, this study tried to accommodate a lot of cases. The many cases also helped to answer a lot of 'what if' questions expected to arise. From the analysis above, the following conclusions are made and are not exhaustive as there are many other possible cases;

1. The modern batching approach consistently gave the highest return on investment and is recommended for transporting the Gas-To-Liquid products from the North Slope of Alaska to Valdez. This conclusion assumes a $25,000 DBL CAPEX and a GTL premium of about $5.25 per bbl, a commingled product price premium of $1.5 per bbl and world spot of price averaging $21 per bbl.

2. The length of the interface required for the above result to change, i.e. commingled as the choice of transportation is over 50%. Typically, a more

realistic value of the length of the interface is between 5% and 15%. This analysis was conducted for other scenarios too.

3. Reconditioning the tanks at the terminal and utilizing the same relief tanks for both GTL and crude oil even during batching operations has very significant benefit especially for the lower CAPEX range.

4. For a CAPEX of $25,000 DBL, and assuming the commingled product has a price premium of $1.5, the minimum GTL premium required for batching to still remain the preferred option is 1.12 times the world oil price estimated at $21 per barrel. This gives a price premium of $2.5 per barrel.

5. A 10 to 15% minimum attractive rate of return (MARR) will be difficult to achieve considering the CAPEX and world oil price that this is achievable.

The payout time for the project is expected to be about 13 years for the optimum transportation technique and a CAPEX of $25,000 DBL and world oil price averaging $21 per barrel throughout the entire project life.

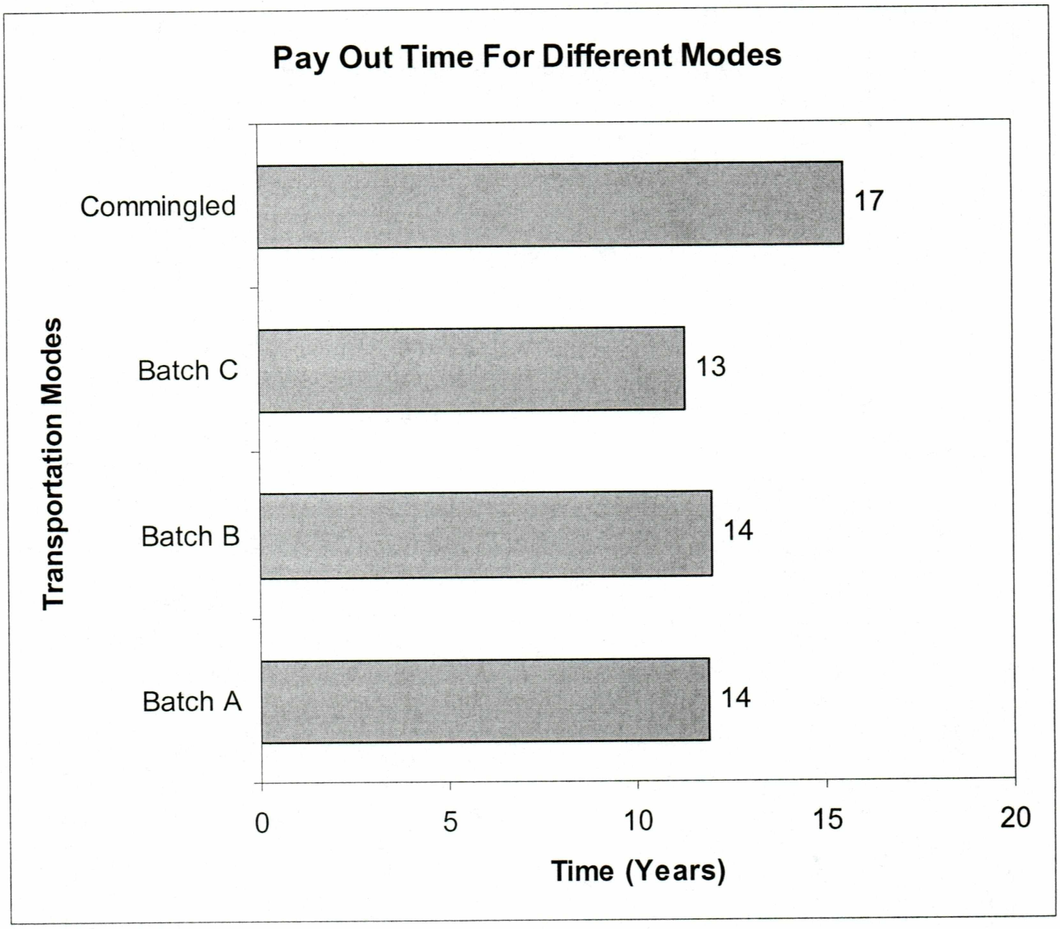


Figure 5.1 Summary of Payout time for Capex $25,000 / DBL and Crude price of $21/bbl

5.2 RECOMMENDATIONS

The major concern with batching is the length of the mixing zone or interface and the purity of the GTL products as they arrive the Marine Terminal in Valdez. Since experience shows that the length of this interface is independent on volume pumped, the following are some recommendations from this study;

1. The key to success in the batch operations is optimization to find the optimum holding capacity on the North Slope that can give the minimum number of batches at any given production period. The optimum fluid velocity should be determined with reasonable accuracy based on the density and viscosity difference of the two products to be transported to ensure minimum interface.

2. A dynamic model that will predict how the interface is expected to behave with distance along the Trans Alaska pipeline System will help reduce the uncertainties in the economic model.

3. A probabilistic economic modeling using monte carlo simulation technique to complement the deterministic model presented in this work.

4. Further studies can generate the ROR results above for a wide range of efficiencies and product premiums.

NOMENCLATURE

ANS	Alaska North Slope
APSC	Alyeska Pipeline Service Company
DBL	Daily Barrel Liquid
DCS	Distributed Control System
DOE	Department of Energy
EIA	Energy Information Administration
GTL	Gas-to-Liquids
LNG	Liquefied Natural Gas
ROR	Rate of return
TAPS	Trans-Alaska Pipeline System
CAPEX	Capital Expenditure
L_m	Length of Mixing Zone, m [ft]
L_s	Slug Length, m [ft]

REFERENCES

Robertson, E.P. "Options for Gas-To-Liquids Technology in Alaska". Contract: DE-AC07-99ID3727, 1999.

Thomas, C.P., T.C. Doughty, J.H. Hackworth, W.B. North, and E.P. Robertson. "Economics of Alaska North Slope Gas Utilization Options". Contract: DE-AC07-94ID13223, 1996.

Department of Oil and Gas, Sate of Alaska. www.state.ak.us.

Akwukwaegbu, Chinedu Franklin. "Evaluation of the Modes of Transporting GTL product s Through The Trans Alaska Pipeline System (TAPS)", MS Thesis, University of Alaska Fairbanks, 2001.

Hariharan Ramakrishnan "Experimental And Economic Evaluation of GTL Fluid Flow Properties and Effect on TAPS" MS Thesis, University of Alaska Fairbanks, 2000.

Scot, S. L.; O. Shoham; and J.P. Brill: " Prediction of Slug length in horizontal large diameter pipes", *Soc. Of Pet. Eng. Jour.*, 1986, pp. 105 – 110.Acoyy

Kokal, S. L. and J.F. Stanislav: "An experimental study of two-phase flow in slightly inclined pipes II. Liquid holdup and pressure drop", *Chem. Eng. Science*, 1989, Vol. 44, no. 3, pp. 681 – 693.

Abdul-Majeed, D.H.: "Liquid holdup in horizontal two-phase gas-liquid flow", *Jour. Of Pet. Sci. and Eng.*,(1996), Vol. 15, pp. 271 – 280.

Duckler, A.E. and M.G. Hubbard: " A model for gas-liquid slug flow in horizontal and near horizontal tubes", *Ind. Chem. Eng. Fundamentals*, (1975), Vol. 14, pp. 337 – 347.

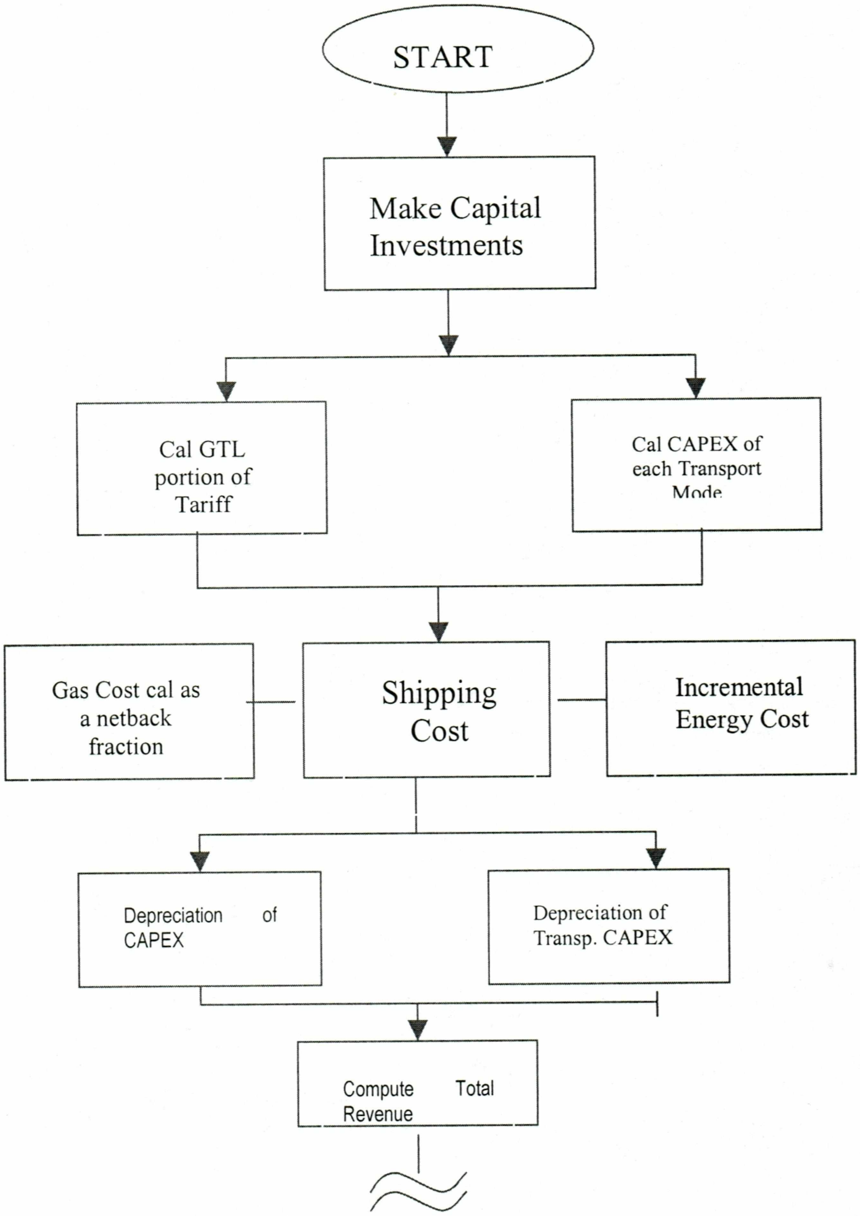
Baum, J.S., Marzocco, K. E.., Hansen, L. I., and Brown, C. A. : " Batching , Treating Keys to Moving Refined Products in Crude-Oil Pipeline", *Oil and Gas Journal*, Oct. 5, 1998

Gaffney, Cline & Associates, "Economics Of GTL" DISR GTL Task Force Report http://www.industry.gov.au/

Kamath, V. A., Khataniar, S., Chukwu, G. A.: "Research Proposal: Study of Transportation of GTL Products from Alaska North Slope (ANS) to Markets" April 1998.

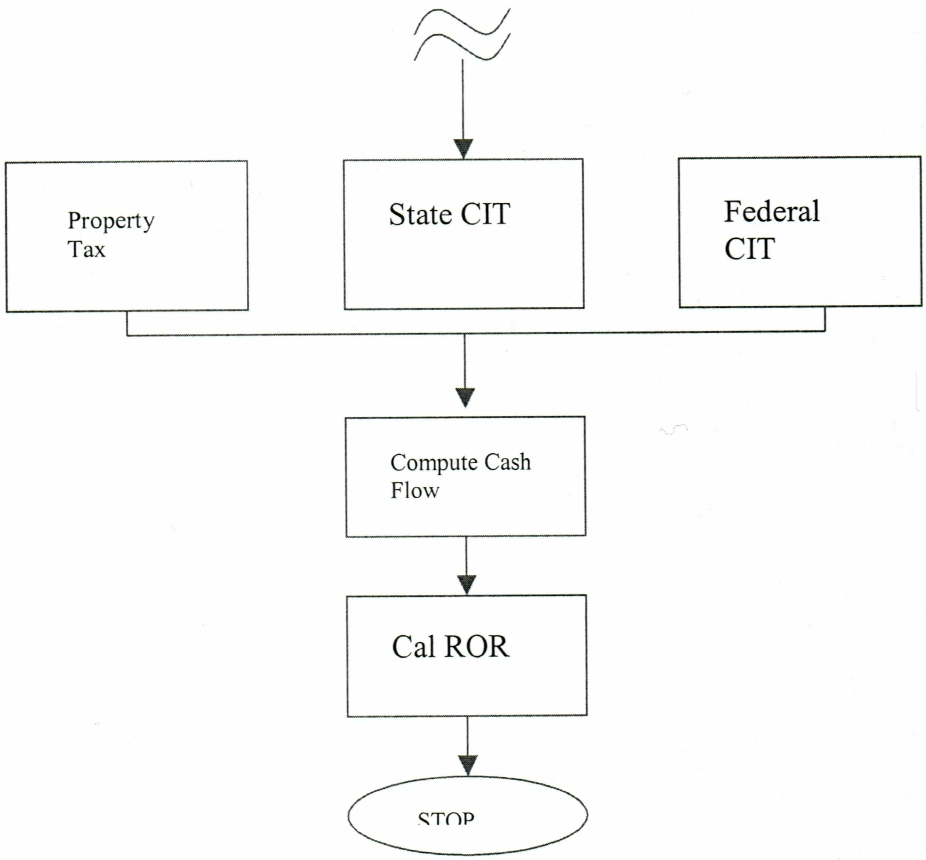
Liu, C.: "Evaluation of Gas-To- Liquids (GTL) Technology and its Application to Transportation of Alaska North Slope (ANS) Natural Gas as GTL products", M.S. Thesis, University of Alaska Fairbanks (Dec., 1999)

APPENDIX A



Appendix A Method of Analysis

APPENDIX A (Continued)



Appendix A Method of Analysis Continued