Alternative Octane Enhancers for 10 ppm Sulfur Gasoline in China

HARTENERGY

July 2013

July 2013

Hart Energy provides specialized data/information products and member-only services and consulting to targeted audiences worldwide and ranks among the leading providers of news, data, and analysis for the global energy industry. Its core publishing and consulting expertise has been extended to online products (databases, maps) and services (websites, market information) as well as industry conferences and exhibitions. Hart Energy clients derive from the energy industry, the financial and investment community, engineering and automotive industries, utilities, leading NGOs, and the world's major governments.

MAIN AUTHOR
Terrence Higgins
Executive Director, Refining and Special Studies

Hart Energy Consulting
A service of Hart Energy Publishing, LLLP
616 S. Voss Rd. Suite 1000
Houston, TX 77057 USA

www.hartenergy.com

This report was prepared for the International Council on Clean Transportation (ICCT), and the views expressed do not necessarily represent those of the ICCT.

Table of Contents

List of Tables and Figures

Executive Summary

Since December 2009, the national gasoline standard reduced the gasoline sulfur limit in China from 500 ppm to 150 ppm maximum, whereas the city/provincial standards currently set the following sulfur limits:

- 10 ppm maximum in Beijing,
- 50 ppm in other major cities: Shanghai, Hangzhou, Ningbo (Zhejiang province), Nanjing, Zhenjiang, Changzhou, Wuxi, Suzhou, Yangzhou, Taizhou, and Nantong (Jiangsu province), and the Pearl River Delta region.

China intends to continue progress with sulfur reduction with eventual 10 ppm implemented nationwide.

Gasoline sulfur reduction is accomplished primarily by desulfurization of refinery gasoline blend streams, primarily the relatively high sulfur catalytic-cracked gasoline stream. The desulfurization process in turn results in a reduction in octane characteristics of the desulfurized gasoline stream. The octane reduction is particularly pronounced for China where a large portion of the catalytic-cracked gasoline stream is included in most of the country’s gasoline pool.

China currently utilizes the metallic additive MMT to provide some incremental octane increases. Initiatives are also under discussion to reduce or remove MMT. The combination of MMT removal and gasoline sulfur reduction will create the need to find alternative octane sources for future gasoline in China.

The International Council on Clean Transportation (ICCT) commissioned a study to assess the impacts of gasoline sulfur reduction and MMT removal on China’s gasoline production. This study builds on a previous study by Hart Energy and MathPro for the ICCT that estimated the overall cost of fuel sulfur reduction in China.

The objectives of the study were to characterize octane production in China, quantify sulfur reduction and MMT removal impacts on octane, identify octane alternatives other than MMT, and quantify the cost of replacing sulfur reduction and MMT removal losses with the identified alternatives. Note that both the previous sulfur study and the current study include the cost of replacing octane loss due to sulfur removal.

This report presents the results of the assessment. The octane loss from sulfur removal was estimated to be 0.4 and the loss from removal of MMT was 0.9 for a total loss of 1.3 octane. Costs for replacing the lost octane with and without additional MTBE are summarized below.

Investment and Gasoline Cost: MTBE and Refinery Processing

	Group A	Group B	Group C	Group D	Group E	Total China
Gasoline Production, K b/d	553	241	261	534	161	1750
Base MMT, mg/l	8	8	8	8	8	8
With Removal, mg/l	nil	Nil	nil	nil	nil	nil
Investment, $MM	**302**	**76**	**34**	**175**	**89**	**676**
Increased refining Cost $MM/yr	**196**	**77**	**76**	**172**	**60**	**571**
Capital Charge and Fixed Cost	57	14	7	33	17	128
Operating Cost	139	63	69	139	43	443
Per Liter Gasoline Cost, (¢/liter)	**0.61**	**0.56**	**0.50**	**0.56**	**0.64**	**0.57**

Investment and Gasoline Cost: Refinery Processing Only – No Incremental MTBE

	Group A	Group B	Group C	Group D	Group E	Total China
Gasoline Production, K b/d	553	241	261	534	161	1750
Base MMT, mg/l	8	8	8	8	8	8
With Removal, mg/l	nil	Nil	nil	nil	nil	nil
Investment, $MM	**318**	**76**	**199**	**302**	**141**	**1036**
Increased refining Cost $MM/yr	**207**	**81**	**110**	**196**	**71**	**665**
Capital Charge and Fixed Cost	60	15	38	57	27	197
Operating Cost	147	66	72	139	44	468
Per Liter Gasoline Cost, (¢/liter)	**0.65**	**0.58**	**0.73**	**0.63**	**0.76**	**0.66**

Section I: Overview of Gasoline and Octane Production in China

A. Background and Introduction

Since December 2009, the national gasoline standard reduced the gasoline sulfur limit in China from 500 ppm to 150 ppm maximum, whereas the city/provincial standards currently set the following sulfur limits:

- 10 ppm maximum in Beijing,
- 50 ppm in other major cities: Shanghai, Hangzhou, Ningbo (Zhejiang province), Nanjing, Zhenjiang, Changzhou, Wuxi, Suzhou, Yangzhou, Taizhou, and Nantong (Jiangsu province), and the Pearl River Delta region.

China intends to continue progress with sulfur reduction with eventual 10 ppm implemented nationwide.

In 2011/2012 the International Council on Clean Transportation (ICCT) commissioned a technical and economic analysis[1] of the transition to low sulfur gasoline and diesel for a number of developing countries. The analysis included an overview and characterization of China's refining industry. The final report provides estimates of investment requirements and capital/operating costs of producing 50 ppm and 10 ppm sulfur gasoline. Refining requirements and costs were determined by classifying the refining industry into five configuration groups (the five groups are defined in Section II) and using refinery linear program models to simulate supply, demand and refining solutions at varying gasoline sulfur levels.

The refinery simulation models used for the ICCT gasoline sulfur analysis determined the desulfurization requirements for 50 ppm and 10 ppm gasoline for each refinery group. The model also computed octane loss associated with desulfurization operations and estimated the combination of investment requirements and operating changes necessary to maintain other (non-sulfur) quality requirements, including gasoline octane. The octane replacement costs were included in the overall cost of reducing gasoline sulfur.

For the gasoline sulfur analysis, non-refinery sources of octane (MMT and oxygenates) were held constant between the initial gasoline sulfur cases and the 50 ppm and 10 ppm sulfur cases. Outside octane sources were not used as part of the sulfur reduction strategy, nor did the study explore a reduction in non-refinery octane sources.

B. Gasoline Production, Sulfur, and Sources of Octane

The ICCT low sulfur gasoline and diesel analysis provided a 2010 refined product supply and demand balance. The analysis projected refinery product output for 2015 from existing refineries, refinery expansions, and new refineries anticipated to be in operation for 2015. The same 2015

---

[1] Technical and Economic Analysis of the Transition to Ultra-Low Sulfur Fuels in Brazil, China, India and Mexico, prepared for ICCT by Hart Energy and MathPro, Inc, October 2012.

refinery configurations and supply/demand were used for this supplemental octane analysis. **Table I.1** shows for the existing (2010) refinery groups the overall refinery input and output, refinery gasoline production, gasoline sulfur, and refinery octane for the refinery Reference Case (higher sulfur) and the 10 ppm sulfur case. The table also shows the investment, refinery operating and per liter costs for producing 10 ppm gasoline. The sulfur reduction costs include any investment and refinery operating cost for maintaining gasoline octane.

Table I.1: Refinery Groups: Input/Output, Gasoline Production and Low Sulfur Cost

	Group A		Group B		Group C	
	Reference	10 ppm	Reference	10 ppm	Reference	10 ppm
Crude Input (K b/d)	2759	2766	839	842	1661	1661
Other Input (K b/d)	44	44	19	19	30	30
Refined Product Output[1] (K b/d)	2957	2960	873	876	1685	1684
Gasoline Production (K b/d)	553	553	241	241	261	261
Gasoline Sulfur (ppm)	110	10	150	10	11	10
Gasoline Octane (RON)	90.3	90.3	90.3	90.3	90.3	90.3
Low Sulfur Investment ($MM)		429		333		7
Capital/Fixed Cost ($MM/y)		82		63		1
Refinery Operations ($MM/y)		43		21		0
Per liter Gasoline Cost (¢/liter)		0.4		0.6		<0.1

	Group D		Group E		Total	
	Reference	10 ppm	Reference	10 ppm	Reference	10 ppm
Crude Input (K b/d)	1985	1993	918	916	8162	8178
Other Input (K b/d)	44	44	470	470	607	607
Refined Product Output[1] (K b/d)	2077	2073	1401	1391	8993	8984
Gasoline Production (K b/d)	534	534	161	161	1750	1750
Gasoline Sulfur (ppm)	150	10	150	10	117	10
Gasoline Octane (RON)	90.3	90.3	90.3	90.3	90.3	90.3
Low Sulfur Investment ($MM)		1004		424		2197
Capital/Fixed Cost ($MM/y)		191		81		417
Refinery Operations ($MM/y)		129		53		246
Per liter Gasoline Cost (¢/liter)		1.0		1.4		0.7

Note: (1) Excludes coke, sulfur, and refinery streams used for fuel or hydrogen production.

Source: Technical and Economic Analysis of the Transition to Ultra-Low Sulfur Fuels in Brazil, China, India and Mexico

The previous sulfur study assumed a gasoline pool octane of 90.3 RON, based on available data. Since then, Hart has developed additional data sources and adjusted its estimate of China gasoline octane. The China gasoline pool is now estimated to consist of RON grades of 90/93/97 with a distribution of 40%/50%/10%. The pool octane is estimated at 92.2 RON.

China relies on oxygenate to provide a large portion of gasoline volume and octane. China also uses MMT to supplement octane. MMT use varies by region, but aggregate 2012 usage was estimated at 11.5 mg/liter. MMT use has been reduced in certain areas and will be reduced to 8 mg/liter by the end of 2013.

For the current octane assessment, the reference case assumes MMT use at 8 mg/liter. The base case assumption for oxygenate use was also increased from that used in the sulfur analysis based on updated market information. The higher base case oxygenate use (and its contribution to gasoline octane) is also consistent with the lower assumption for base case MMT use.

Table I.2 shows the refinery group gasoline production, assumed oxygenate and MMT use and estimated octane contribution of oxygenates and MMT.

Table I.2: Refinery Groups: Input/Output, Gasoline Production and Low Sulfur Cost

	Group A	Group B	Group C	Group D	Group E
Gasoline Production (K b/d)	553	241	261	534	161
Gasoline Octane (RON)	92.2	92.2	92.2	92.2	92.2
Methanol (K b/d)	20	8	18	17	12
Ethanol (K b/d)	11	3	9	12	3
MTBE (K B/d)	37	14	8	35	6
Oxygenate (RON) Contribution[1]	1.3	.7	.7	1.1	1.2
MMT (mg/Liter)	8	8	8	8	8
MMT RON Contribution	.9	.9	.9	.9	.9

Source: Compiled by Hart Energy Consulting (2010)

Source: Technical and Economic Analysis of the Transition to Ultra-Low Sulfur Fuels in Brazil, China, India and Mexico

C. Refinery Octane Improvement Processing Capacity

The refinery configuration in China is unique in that the refineries employ a large portion of conversion capacity (primarily catalytic cracking and coking) with less light oil processing facilities. In terms of octane, China refineries have low capacity for gasoline reforming, isomerization and alkylation as compared to typical high gasoline production refining systems. China light oil processing capacity is less than 8% of crude capacity as compared to 25% in the U.S. and 20% in both Europe and Japan. Refineries can increase the severity of gasoline reforming operations, thereby increasing the octane level of the reformer gasoline stream and in turn the refinery gasoline pool (see discussion in Section II.B). China has less capability to adjust octane given the limited reforming capacity. Table 1.3 shows China light oil processing capacity for the five refinery groups.

Table I.3: China Refining and Light Oil Capacity

(K b/d)

	Group A	Group B	Group C	Group D	Group E
Crude Distillation	3090	870	2140	2350	2250
Gasoline Reforming	260	70	170	277	18
Isomerization	0	0	0	0	0
Alkylation	15	3	0	8	0

Source: Hart Energy and U.S. Energy Information Administration

Section II: Gasoline Desulfurization Strategy and Impact on Octane

A. Gasoline Sulfur Reduction and Octane Impacts in Chinese Refineries

The ICCT low sulfur gasoline study indicates that most of the gasoline production capacity in China resides in China's large conversion refineries. The study defined five groups of such refineries, with each group having a unique combination of conversion units: coking, catalytic cracking (FCC), and hydrocracking (**Table II.1**).

Table II.1: China Capabilities by Refinery Group

Conversion Process	Refinery Group					Refinery Blendstock Produced
	A	B	C	D	E	
Coking	●	●	●		●	Coker Naphtha
Catalytic Cracking	●	●		●	●	FCC Naphtha
Hydrocracking	●		●	●	●	Hydrocrackate

The primary task in producing ULSG (< 50 ppm sulfur) is desulfurizing the gasoline blendstocks produced by the conversion processes – primarily coking and FCC.

In refineries that have an FCC unit (e.g., refineries in Groups A, B, D and E), FCC naphtha is the primary source of sulfur in gasoline by virtue of its high sulfur content and its high volume share in the gasoline pool. FCC naphtha contributes up to 95% of the sulfur in gasoline, prior to processing for sulfur control. Consequently, production of ULSG requires severe desulfurization of FCC naphtha, accomplished primarily via dedicated hydrotreating units called FCC naphtha hydrotreaters or FCC post-treaters

In refineries that have a coker (e.g., refineries in Groups A, B, C and E), production of ULSG also requires desulfurization of coker naphtha. In some refineries, coker naphtha is desulfurized in the FCC post-treater and sent (with treated FCC naphtha) to gasoline blending. More commonly, coker naphtha is desulfurized in the refinery's naphtha hydrotreater unit (which desulfurizes the feed to the catalytic reformer to ≈ 1 ppm) and sent to the reformer.

In refineries that have a hydrocracker (e.g., refineries in Groups A, C, D and E), light and medium hydrocracked naphtha (which have low sulfur content) can be blended directly to gasoline or, more commonly, sent to the naphtha hydrotreater and then the catalytic reformer.

Finally, meeting the most stringent sulfur standards (e.g., 10 ppm sulfur) also requires desulfurization of gasoline blendstocks containing small amounts of sulfur, primarily straight run naphtha and natural gas liquids. This desulfurization can be accomplished in an existing or new naphtha hydrotreater.

FCC naphtha contains a large proportion of olefinic compounds (olefins), which have high octane (comparable to that of U.S. regular grade gasoline). In FCC naphtha hydrotreaters, olefins react with hydrogen to form paraffins (a reaction known as olefin saturation), in a side reaction to the desired desulfurization. Paraffins in general have lower octane than olefins, so that olefin saturation, to the extent that it occurs, reduces the octane of the FCC naphtha. This unwanted side-reaction is the primary cause of the octane loss associated with gasoline sulfur control. (FCC naphtha hydrotreating catalysts are designed to limit olefin saturation, but they do not eliminate it altogether.)

In general, the octane loss increases with (i) increasing sulfur content of the raw FCC naphtha and (ii) decreasing sulfur content of the treated FCC naphtha, as indicated in the **Table II.2** below.

Table II.2: Approximate Octane Loss in FCC Naphtha Hydrotreating

Unfinished FCC Naphtha	Finished FCC Naphtha	
	50 ppm	5 ppm
120	0.9	1.3
500	1.3	1.8
1500	1.8	2.2
2500	2.2	2.5

Assuming that FCC naphtha constitutes about 40 percent of the gasoline pool volume, desulfurizing FCC naphtha to 50 ppm and 7 ppm can support gasoline sulfur standards of 30–50 ppm and 10 ppm, respectively. (Depending on their sulfur content, other gasoline blendstocks, such as straight run naphtha and natural gas liquids, also may require desulfurization to meet these gasoline sulfur standards.)

Again assuming that FCC naphtha constitutes about 40 percent of the gasoline pool volume, the octane losses incurred by the gasoline pool would be about 40 percent of those shown in the table (e.g., about 0.7 octane for desulfurizing FCC naphtha from 500 ppm to 5 ppm.)

In addition to the octane loss, FCC naphtha hydrotreating incurs a small yield loss, in the range of 1 vol% of the FCC naphtha.

Both the octane loss and the yield loss must be replaced to maintain the octane and the volume of the desulfurized finished gasoline pool.

B. Available Options for Replacing Lost Octane

MTBE

In the absence of refining investment, China can increase MTBE use up to a maximum oxygen content of 2.7 wt%. China currently blends MTBE, ethanol and methanol into gasoline in varying concentrations. Based on the current volume of oxygenates blended, the gasoline pool can only accommodate an additional 30 K b/d of MTBE before reaching the 2.7 wt% oxygen maximum. The 30 K b/d of MTBE will increase the China gasoline pool octane by about 0.4 RON. China has recently expanded MTBE production facilities significantly and has actually reduced dependence on imports. The 30 K b/d incremental MTBE volume should be available in the Asia market.

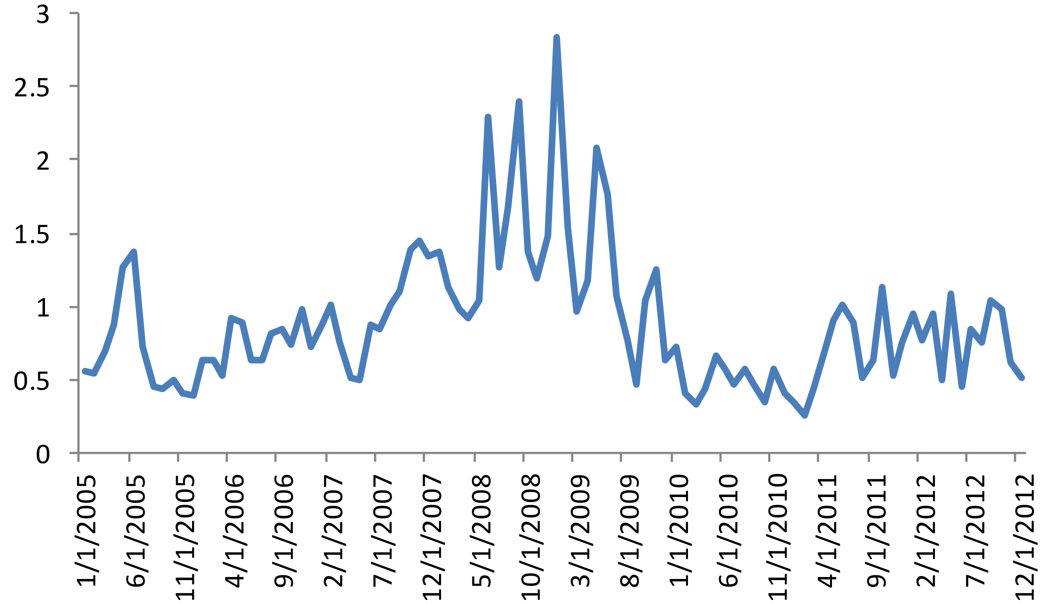
In the U.S., refiners voluntarily chose to discontinue MTBE blending once the oxygen content requirement for reformulated gasoline ended in 2006 and was replaced with a renewable fuels standard. Although about 24 individual states took action to either limit or ban MTBE content in their gasoline due to public concern over contamination of groundwater, the federal government has taken no such action. Because of the litigious nature in the U.S., refiners determined that nuisance litigation risk was not worth continued blending of MTBE, coupled with the renewable fuel mandate.

The United States has a legacy of deteriorating single walled fuel storage tanks prone to leakage, which facilitated the contamination of groundwater. This may not be an issue for countries like China, where rapid installation of new fueling infrastructure creates opportunities for investments in double walled fuel storage tanks that are less prone to leakage. While the widespread availability of ethanol enabled the United States to rapidly transition away from MTBE, this is not an option for China in the near-term. Over the long term, China may wish to work towards solutions beyond MTBE.

Purchase of higher octane gasoline

There is also some octane production capability available in the Asia market to supply incremental octane. China could take advantage of this market by purchasing high octane components, purchasing high octane gasoline, and/or exporting low octane gasoline or blending components. The amount of octane available is difficult to quantify, but a review of available octane values in the Asia market indicates that octane capability is not overly constrained and some incremental octane should be available via this option. **Figure II.1** tracks octane values for Singapore gasoline from 2007 through 2012. Octane values are based on the difference between regular and premium grade gasoline. The octane values are well below peak 2008 values (when refining capacity was constrained) and are not far from historic trends. These values do not indicate any octane constraint in the region, and indicate that some incremental octane supply capability exists.

Figure II.1: Singapore Octane Cost
(cents per liter per octane)



The octane analysis for this study does not include the option of supplement requirements with gasoline purchases in the Asia market. Any assumption on how much octane would be available would be somewhat speculative. We instead assume the availability of octane in the market would serve as an additional resource and margin to cover volatility and uncertainties in the market. The cost of this source would reflect incremental octane cost in the Asian market and therefore should not be significantly different than incremental costs in China. The cost will also typically be in parity with incremental MTBE octane values, which will provide some of the incremental octane for this analysis.

Refinery Operational Adjustments

An additional increment of octane will be available within the refinery by increasing octane on existing gasoline reforming and through optimization of existing operations. This is typically the first option utilized by refiners and for the most part will serve to supply some of the octane lost with gasoline desulfurization.

Increased Reformer Severity

Catalytic gasoline reforming (or, simply, "reforming") is a core refining process and is the most widely used process for improving the octane of the gasoline pool. Reforming is the only refining process in which product octane is subject to control by manipulation of operating conditions. Minor adjustments in operating conditions allow reformers to operate at different "severities", to produce reformate octanes anywhere in the range of 85 to 100 RON. Hence, reforming is both the primary refinery source of incremental octane for gasoline and the primary means of regulating the octane of the gasoline pool.

Increasing reformer severity to enhance octane incurs some loss of reformate yield. This yield loss is in addition to the yield loss incurred in FCC naphtha hydrotreating. Both yield losses must be replaced in order to maintain gasoline volume.

The most direct way to replace the lost gasoline yield is to increase the volume of crude oil processed by the refinery, which leads to corresponding increases in the through-puts of the various refining processes that produce gasoline blendstocks.

Reformer Investment

The remaining octane option is increased refinery processing capacity with investment in new capacity. Reforming expansion and alkylation will be the two primary options. Alkylation will be limited by feedstock availability.

Section III: China Gasoline Sulfur Reduction and MMT Removal Octane Loss

The estimated octane loss due to desulfurization of Chinese gasoline to 10 ppm will for the most part be a function of the FCC gasoline sulfur and the fraction of FCC gasoline in the gasoline pool. The octane loss associated with sulfur reduction and MMT removal for the China refinery groups is shown in **Table III.1**. For MMT, all the refinery groupings have been assumed to use 8 mg/liter MMT so the estimated octane loss is the same for all refinery groups. The average octane loss for all five groups is 1.3 octane.

Table III.1: Octane Loss Due to Sulfur reduction and MMT Removal

	Group A	Group B	Group C	Group D	Group E
Gasoline Production (K b/d)	553	241	261	534	161
Sulfur Reduction Octane Loss (RON)	0.3	0.5	0.0	0.6	0.3
MMT Removal Octane Loss (RON)	0.9	0.9	0.9	0.9	0.9
Refinery Options for Sulfur Reduction Replacement :					
MTBE and Refinery Operational Adjustments	●	●	●	●	●
Increased Reformer Severity	●	●		●	●
Reformer investment				●	●

Source: Compiled by Hart Energy Consulting (2010)

Table III.1 also shows the options used to replace the octane related to sulfur reduction. The options shown are different than the initial sulfur reduction cases. In the updated analysis, the starting octane requirements have been increased. As a result, a greater portion of available reformer octane capacity is utilized in the reference case. Lower sulfur cases must rely more on new refinery reforming investment than in the original sulfur study.

Section IV: Cost of Replacing China Gasoline Octane

The investment, operating and per liter cost of replacing octane lost with MMT removal are shown in **Table IV.1**. The *investment cost* is the total value of investment in new refining facilities required to provide the replacement octane. In this analysis, the new facility investment included is gasoline reformer capacity. The *capital charge* is the annualized capital charges and fixed costs associated with the investments, and the *operating costs* are direct costs associated with net crude oil purchases (to make up yield loss, etc), fuel, and miscellaneous catalyst and chemical costs. MMT purchases are deducted from the operating cost.

Table IV.1: Investment and Gasoline Cost: MTBE and Refinery Processing

	Group A	Group B	Group C	Group D	Group E	Total China
Gasoline Production, K b/d	553	241	261	534	161	1750
Base MMT, mg/l	8	8	8	8	8	8
With Removal, mg/l	nil	Nil	nil	nil	nil	nil
Investment, $MM	**302**	**76**	**34**	**175**	**89**	**676**
Increased refining Cost $MM/yr	**196**	**77**	**76**	**172**	**60**	**571**
Capital Charge and Fixed Cost	57	14	7	33	17	128
Operating Cost	139	63	69	139	43	443
Per Liter Gasoline Cost, (¢/liter)	**0.61**	**0.56**	**0.50**	**0.56**	**0.64**	**0.57**

Table IV.2 shows the investment, operating and per liter costs for replacing octane lost from MMT removal without increasing MTBE blending. For this case, all the incremental octane not supplied by MTBE requires investment in reforming facilities, increasing investment requirements by more than 50%. The total per liter cost of octane replacement is 16% higher without the option of increasing MTBE blending.

Table IV.2: Investment and Gasoline Cost: Refinery Processing Only – No Incremental MTBE

	Group A	Group B	Group C	Group D	Group E	Total China
Gasoline Production, K b/d	553	241	261	534	161	1750
Base MMT, mg/l	8	8	8	8	8	8
With Removal, mg/l	nil	Nil	nil	nil	nil	nil
Investment, $MM	**318**	**76**	**199**	**302**	**141**	**1036**
Increased refining Cost $MM/yr	**207**	**81**	**110**	**196**	**71**	**665**
Capital Charge and Fixed Cost	60	15	38	57	27	197
Operating Cost	147	66	72	139	44	468
Per Liter Gasoline Cost, (¢/liter)	**0.65**	**0.58**	**0.73**	**0.63**	**0.76**	**0.66**

The octane replacement costs in **Tables IV.1** and **IV.2** are in addition to octane costs associated with replacing octane lost due to sulfur reduction processing (see Section 2.A). The cost of replacing octane due to sulfur reduction is included as part of the overall sulfur reduction cost in Table I.1.

Section V: Optimal Cost of Replacing Octane in China

The optimal cost of replacing octane lost from sulfur reduction and MMT removal will be a combination of least cost options available to refiners. As can be seen by comparison of **Tables IV.1** and **IV.2**, MTBE represents the least cost option when comparing between MTBE and refinery processing/investment. But since incremental MTBE blending is limited by the maximum oxygen limit, the ability to achieve lower costs via this route is limited.

The only other option available to refiners is to purchase higher octane gasoline. The amount of octane available under this option is difficult to quantify and has thus not been included in the analysis for which results have been presented in **Tables IV.1** and **IV.2**.

Considering the average Singapore octane costs shown in **Figure II.1**, the higher octane purchase option has potential to lower costs further. The cost of octane in Singapore is greater than the cost of increasing octane via MTBE, but is lower than the cost of refinery investment.

To illustrate the potential change in the optimal octane cost, a scenario has been analyzed where Chinese refiners are assumed to have the option of exchanging 50 K b/d of 90 RON gasoline for 95 RON gasoline in the Asian market. This level of octane requirement from the Asia market is not expected to increase Singapore octane costs significantly. The resulting per liter costs of this case are compared with the previous cases in **Table V.1.** The per liter cost declines from 0.57 cents per liter to 0.56 cents per liter, or a little less than 2%.

Table V.1: Optimal Replacement – Case Cost Comparison
(cents per liter)

	Group A	Group B	Group C	Group D	Group E	Total China
MTBE and Refinery Processing	0.61	0.56	0.50	0.56	0.64	0.57
Refinery Processing Only	0.65	0.58	0.73	0.63	0.76	0.66
MTBE, Processing and Octane Purchase	0.61	0.54	0.49	0.54	0.62	0.56