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**Integration of Gasification with  
Thermal Residue Conversion in refineries**

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## SUMMARY

Refineries worldwide are facing increasing pressures from the environmental legislation, depressed margins, and changing product demand patterns. To cope with the pressure, refiners are forced to look for alternative conversion of the heavy residues. The integration of the thermal residue conversion with the gasification is an excellent solution.

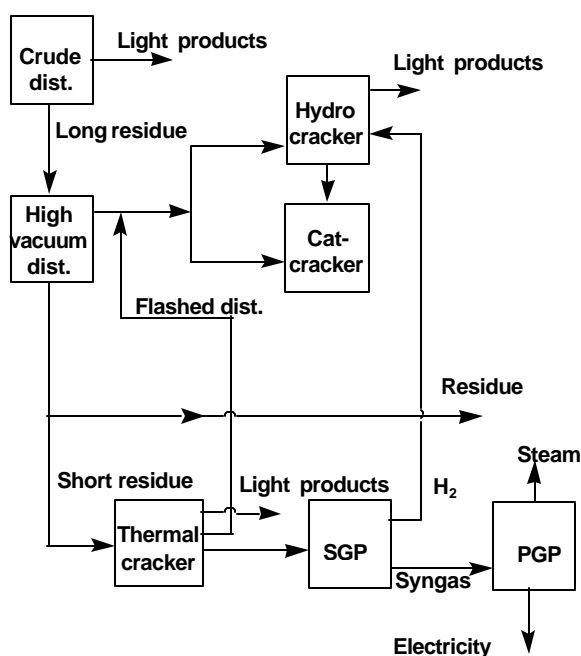
This paper demonstrates the economic benefits of integration of thermal conversion and gasification in refineries. The Shell Gasification Process (SGP) and the Shell Thermal Residue Conversion technologies are described briefly. The synergetic effects of the integration are explained. Two cases are presented to illustrate economic benefits quantitatively. In the first case, the syngas from the residue gasifier is used partly for manufacturing hydrogen for a hydrocracker and partly for an IGCC power generation in a Shell Refinery. The second case highlights the integration of the Shell Deep Thermal Conversion (DTC) process with the Shell Gasification Process, which upgrades “liquid coke” to hydrogen and electricity. The successful development and commercial operation of the Soot Ash Removal Unit is a key to the latter gasification application. When the Deep Thermal Conversion is integrated with the SGP, a maximum value will be added to the refinery residue streams. This configuration takes full advantages of integration of both technologies. It is a recommended route to consider in the refinery residue upgrading.

## INTRODUCTION

Refineries worldwide are facing increasing pressures from the environmental legislation, depressed margins, and changing product demand patterns.

The environmental pressure on the left-over of the bottom of the barrel, or the residue, is mainly driven by sulfur. The sulfur content in the residual fuel oil for inland use is being pushed slowly but steadily from levels of 3 wt % to 1 wt % and even further. It is becoming more and more unacceptable to burn inland Heavy Fuel Oil without expensive flue gas treatment in view of environmental standards. Solutions are, for example, to process sweet crudes with less sulfur. This leads to higher crude costs and reduced flexibility of the refinery. Therefore, refineries are forced to look for alternative conversion of the heavy residues.

Upgrading the residue to lighter products has been a major route to improve the refinery margin. In addition, the increased demand for distillates, i.e., transportation fuels, and the reduced demand for heavy fuel oil would result in an unbalance between demand and supply. This is another driving force for refineries to convert heavy residue oils to lighter products.



**Figure 1. Simplified block diagram of a refinery configuration**

Various technologies are available for residue processing. This paper will concentrate on the Thermal Residue Conversion. These processes produce light products like gasoil, but also make even heavier residual products. And the more lighter products are produced, the heavier is the residue product. One example is the Deep Thermal Conversion (DTC) technology of Shell, which upgrades more than 50 % of the feed residue to lighter products. Simultaneously, the remaining bottom is so heavy that it becomes a “Liquid Coke”. Whereas traditional usage of the residues and liquid coke is becoming unfeasible or

uneconomic, Shell Gasification Process (SGP) technology is an outstanding alternative that upgrades the heavy residues to valuable clean synthesis gas (syngas). The integration of the thermal residue conversion with the gasification is an ideal solution that meets the refinery's needs in many aspects. As an illustration of the commercial application of integration of the thermal conversion and gasification, Figure 1 shows a typical line up of a heavy-end upgrading refinery in which the syngas from an SGP unit is used partly for manufacturing hydrogen for a hydrocracker and partly for the IGCC power block.

This paper will demonstrate the benefits of integration of thermal conversion and gasification processes in refineries. The Shell Gasification Process and the Shell Thermal Residue Conversion technologies are described briefly. The synergetic effects of the integration are explained. The economic benefits are emphasized. Simple gross margins for processing plants are used as a parameter which offers a straight-forward measure of the economic benefit of the plant. Two cases are presented to illustrate the economic benefit quantitatively. In the first case, the syngas from the thermal conversion residue gasifier is used partly for manufacturing hydrogen for a hydrocracker and partly for the IGCC power generation. The second case highlights the integration of the Shell Deep Thermal Conversion and Shell Gasification Process which upgrades "liquid coke" to high-value products.

## ADDING VALUES THROUGH INTEGRATION

### *Value Addition to Refinery Streams*

Integration of the Shell Gasification Process and the Shell Thermal Residue Conversion to upgrade the refinery residue streams results in significant economic benefits. These are illustrated in Figure 2, which shows the simple gross margins of four routes of the residue upgrading. Gross margin is defined here as the value difference between the products and feedstocks of one or more processing unit(s). Applying the Shell Soaker Visbreaking technology (VBU) would bring a straight gross margin of 28 US\$ per ton of intake residue. Integrating the SGP to the VBU would precisely triple this gross margin to 84 US\$. Here the margin for SGP includes also margins of the hydrogen plant and power generation unit. The high conversion of the residue to lighter oil products and upgrading of the thermal conversion residue to electricity and other products for the refinery, like hydrogen, supplement each other and create a large synergetic effect.

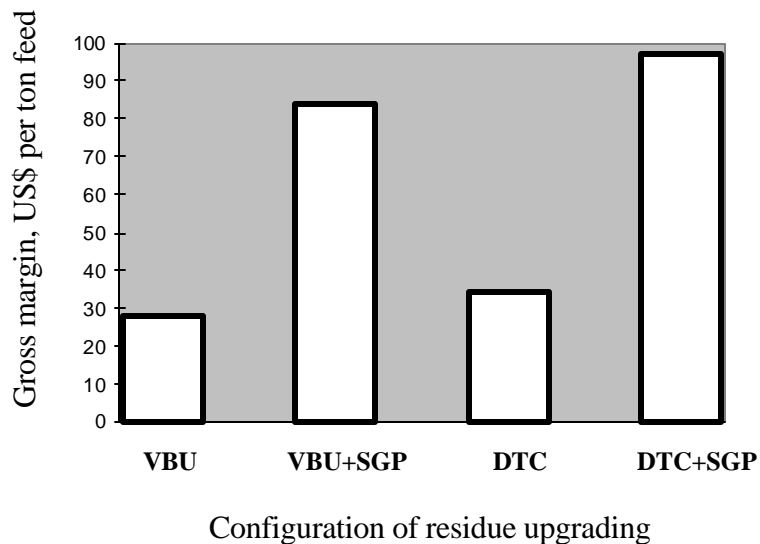
The Deep Thermal Conversion technology improves the gross margin with respect to the VBU from 28 US\$ to 34 US\$. When the DTC is integrated with the SGP, a maximum value will be added to the refinery residue streams. In this configuration, a gross margin of 97 US\$ per ton of residue intake to the thermal conversion unit will be realized, taking full advantages of integration of both technologies. It is a recommended route to consider in the refinery residue upgrading.

Figure 2 is composed of the gross margins from Tables 1 and 5. Details of the calculations which lead to the data in the figure will be explained later in this paper.

### *Upgrading by Thermal Conversion*

The continuous search for more yields of lighter products results in increasing conversion of the thermal conversion process. The Shell Deep Thermal Conversion process has been developed on basis

of the many years of experience with the Shell Soaker Visbreaking process. The process yields a maximum of distillates by applying high conversions of the vacuum residue feed and by vacuum flashing of the cracked residue. High distillate yields are obtained, while still producing a stable liquid residual product, referred to as liquid coke.



**Figure 2. Comparison of benefit of four residue upgrading routes.**

The economic benefit of applying the DTC process comes from the increased yields of lighter products. Table 1 shows a simple increase of the gross margin by applying the DTC technology, as is compared with the conventional visbreaking with a vacuum flasher. The feed is a vacuum residue with properties of API of 5.7, CCR of 22 and a viscosity of 770 cSt@100°C from a Middle East crude. It is clear that the economics are enhanced by applying the DTC technology.

**Table 1 Performance of Deep Thermal Conversion Process**

Type of unit	VBU	DTC
<b>Yields, % w</b>		
Gas (C4-)	2.3	3.8
Naphtha (ECP 165°C)	4.7	8.2
Gasoil (ECP 350°C)	14.0	18.1
Waxy (ECP 520°C)	20.0	22.5
VF Cracked Residue	59.0	47.4
<b>Economics, US\$/ton feed</b>		
Gross margin	28	34

The liquid coke produced in the DTC unit is characterized by its high density, viscosity, carbon content, and sulfur content, as are illustrated by an example in Table 2. The liquid coke is not suitable for blending to commercial fuel oil, and thus has a reduced value. On the other hand, the calorific value of the residue stock drops only slightly with the increase of conversions of the thermal unit. Clearly, a process that can fully utilize the calorific value of the liquid coke irrespective of its other properties will be a key in the overall economic picture.

**Table 2 An example of yields and properties of "liquid coke"**

<b>Charge properties</b>	
API	4.0
Viscosity, cSt @ 150°C	300
CCR, % w	25
Sulphur, % w	4.5
Hydrogen, % w	10.8
<b>"Liquid coke" product</b>	
Yield, % w	50
API	-17
Viscosity, cSt @ 200°C	1500
CCR, % w	51
Sulphur, % w	6.0
Hydrogen, % w	7.0

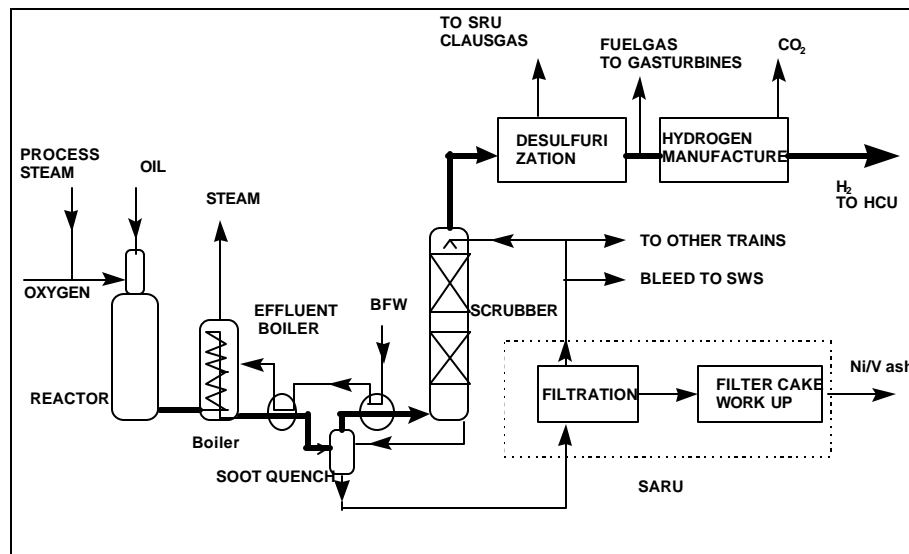
### ***Value Addition by SGP***

Shell Gasification Process (SGP) is the technology that can upgrade the inferior liquid coke to clean, high-value syngas. The performance of SGP is dependent of the calorific value of the feedstock, while it is rather insensitive to the quality of the feedstock, being thermal cracked vacuum flashed residue or asphalt, or the liquid coke as in the present case. The successful development and commercial operation of the Soot Ash Removal Unit (SARU) is essential for this service. In the SARU, the soot and ash are filtered out completely and worked up carefully, so that no soot recirculation in the process is necessary. Therefore, the SGP is a process that can capitalize the calorific value of the liquid coke. This makes the integration of SGP with DTC a particularly attractive solution to the refiners. In fact, the synergetic effect is maximized when liquid coke is involved, as Figure 2 indicates.

### **SHELL GASIFICATION PROCESS (SGP)**

Figure 3 shows a simplified process flow diagram of a typical SGP unit which processes vacuum visbreaker residue. The process features gasification, syngas cooling through a boiler, and carbon handling systems.

The gasifier is equipped with a specially designed burner. The oxidant is preheated to minimize oxygen consumption and mixed with steam as moderator prior to feeding to the burner. The burner and reactor are tuned such that this mixture is intimately mixed with the preheated feedstock within the reactor confinement.



**Figure 3. Simplified Process Flow Diagram of an SGP Unit**

The sensible heat in the product raw synthesis gas at a temperature of about 1300 C is recovered in a Waste Heat Exchanger (WHE) generating high-pressure steam. This syngas cooling concept results in a much higher overall energy efficiency of the gasification process, as is compared to an alternative direct quench design. The design of the WHE has been developed specifically for these operating conditions and is already used in some 135 installations worldwide. Residues originating from all crudes can be gasified in SGP without resulting in serious fouling. The steam from the WHE can be used partly for power generation in steam turbines. A secondary heat recovery takes place in a boiler feed water economizer. The free carbon (soot) particles produced during the gasification are removed from the gas together with the ash.

The commercial application of the SGP process has kept up with the industry trend in the past decades. The continuous endeavour of refineries to get more light products out of the bottom of the barrel goes together with the ever more inferior feeds to SGP which are heavier, more viscous, and with higher levels of sulfur and heavy metals. Initially developed in the 1950s, SGP used fuel oil and bunker C-oil as feedstock. In the 1970s vacuum (short) residue had become the standard feed and in the eighties vacuum residues were even further concentrated by visbreaking or deasphalting. Typically, the current SGP integration is to process vacuum flashed cracked residues. At present, SGP is able to process economically all heavy oils that are known to Shell. Asphalt and liquid coke are two examples of such heavy oils. This is made possible by means of the development and commercialization of the SARU technology.

The challenges of processing more difficult feedstocks have been met through constant efforts of

improving the SGP technology. The reactor pressure has been increased from 20 to 65 bar. Burner development resulted in an integrated heat-up and an increased burner life of more than 8000 hours, while the capacity of the units has been scaled up considerably. Removal and work-up of soot and ash has been improved with a quantum leap by the successful development and commercial operation of the Soot Ash Removal Unit.

Gasification is rather insensitive to the viscosity of the residual feed, so that unlike conventional combustion, even very viscous heavy residues can be gasified. Since these fuels maintain basically their heating value as they get heavier, gasifying the heavy, high viscosity residues for the production of  $H_2$  or power offers the technology which can capitalize the additional economic incentives.

Presently 82 SGP reactors are producing about 62 million Nm<sup>3</sup> syngas per day in 26 plants worldwide. This is equivalent to 23,000 tons of residue per day or nearly 8 million tons of residue per year. The availability of a single SGP string has increased to 98 %. Unplanned shut down is typically 2 days/year.

## **SHELL THERMAL RESIDUE CONVERSION PROCESSES**

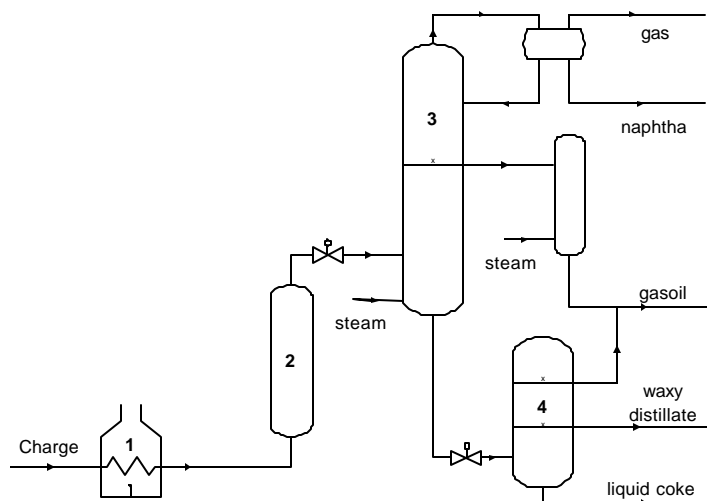
Shell has a long history in Thermal Conversion of residues and distillates. Its first unit, using Dubbs technology was put in operation already in 1921. Over the last 35 years Shell has obtained a leading position in Thermal Conversion, the world's most utilized residue conversion technology. More than 80% of the world wide installed residue conversion capacity is based on a form of Thermal Conversion technology. About 50% of this Thermal Conversion capacity consists of Visbreaking Units and Thermal Gas-oil Units, while the remainder consists of coking technologies (Delayed Coking , Fluid-Coking and Flexicoking).

Shell's experience on operation of own design units goes back more than 35 years. Presently the Royal Dutch / Shell Group alone operates outside the United States 11 visbreaking units and 8 Thermal Gasoil Units. Also one delayed coking unit is operated. This asset base represents a total residue conversion capacity of about 75.000 t/sd. 12 of these units are equipped with downstream vacuum flashers, making use of Shell's proprietary Vacuum Flasher Technology. On top of this Shell has designed and licensed to third parties over 50 visbreaking units representing a capacity of more than 210.000 t/sd. This makes the Shell Soaker Visbreaking the most successfully licensed technology among thermal conversion processes that do not produce solid carbon.

On this extensive basis of design and operational experience, coupled with a continued research and development effort on process and engineering aspects, Shell is continuously improving its portfolio of Thermal Conversion technologies. The unique combination of being a technology licensor and technology operator provides here the leading edge.

The Shell Deep Thermal Conversion process significantly narrows the gap between visbreaking and coking. It has been developed on basis of the many years of experience with the Shell Soaker Visbreaking process. The process yields a maximum of distillates by applying deep thermal conversion of the vacuum residue feed and by vacuum flashing of the cracked residue. High distillate yields are obtained, while still producing a stable liquid residual product, referred to as liquid coke. Figure 4 shows a typical flow sheet of the DTC process. This process, combined with gasification and/or power generation, is attractive in an existing refinery environment with vacuum distillate conversion capacity.

Essential in the production of this liquid coke is the use of Shell Visbreaking Vacuum Flashing technology, which is characterized by low vapor loading making use of proprietary internals and a proprietary design transfer line to the flasher. Vacuum flashers based on Shell's Vacuum Flasher Technology achieve cycle times between clean-outs of more than 18 months.



**Figure 4. Simplified process diagram of DTC process.**

To date 4 Deep Thermal Conversion units are in operation. In two cases this involved a revamp of an existing Shell Soaker Visbreaker unit. In addition, two units are planned for revamp, while one grass-roots unit is currently under construction.

## REFINERY ECONOMICS IMPROVEMENT

Integration of the thermal conversion process with gasification in a refinery offers major advantages in addition to the significant improvement of refinery margins. Firstly, the capability to process high-sulfur crudes increases. This enhances the flexibility of the refinery which allows to purchase high-sulfur, lower-cost crudes. Next, an abundant source of hydrogen is now available, which provides the possibility for the refinery to increase hydrocracker and hydrotreating capacity. This allows to shift the product pattern towards more gasoil, as fuel oil is converted into gasoil with high cetane numbers. If the syngas is used to generate power, the refiner will have the opportunity to enter the liberalizing electricity market. Furthermore, the refiner will reduce the air emission significantly. Sulfur is concentrated in the heavy fraction of the crude, which is removed almost completely in the syngas treating unit of the SGP plant. Further, the particulate emission due to fuel oil use is greatly reduced.

This paper chooses to concentrate on the economic benefits. In what follows, two cases are presented to illustrate the economic benefits quantitatively.

### *Basis of Economics assessment*

In calculating the economic benefit, simple gross margins are used as a parameter instead of carrying out in-depth economic calculations. The gross margin, defined as the value difference between the products and feedstocks, is a straight-forward measure of the value addition of a processing unit.

Capital investment costs have not been taken into consideration in this paper, because both processes, The Shell Gasification Process and The Shell Thermal Conversion Process are well known in the refinery industry for their low capital investment costs. Operation costs depends strongly on cases. They are not taken into account, in order that the conclusions in this paper can be generalized.

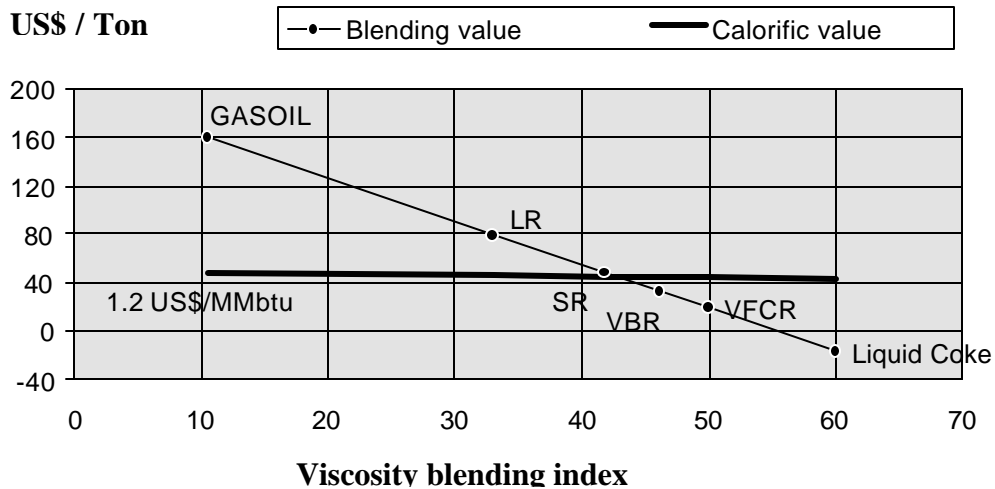
Vacuum residue is used as the feedstock to the integrated thermal conversion and SGP plant. Oxygen is taken as a feed to the plant. Oil and gas products are C4- gas, naphtha, gasoil and waxy distillates. Hydrogen and electricity are end products. The syngas is not used in the gross margin calculation, as it is an intermediate product. VFCR and liquid coke are products of the thermal conversion unit, but not major end products of the integrated unit. As a simplification, steam is excluded in the calculation both as a product and as a utility.

Clearly, the outcome of the margin calculations depends on the prices that are used for the feed and product streams. The prices were therefore chosen with care. The prices are summarized in Table 3. These are used throughout this paper.

**Table 3 Assumptions for the economic evaluations**

# INTEGRATION OF GASIFICATION WITH THERMAL RESIDUE CONVERSION

Item	Price, US\$/ton
Vacuum residue	48
Oxygen	30
Gas (C4-)	125
Naphtha	160
Gasoil	160
Waxy	120
Vacuum flashed cracked residue	33
Liquid coke	18
Hydrogen	700
Electricity	40 US\$/MWh



**Figure 5. Value of liquid hydrocarbons**

The valuation of the vacuum flashed cracked residue and liquid coke is essential for evaluation of the margin of the thermal conversion units. The valuation of the refinery streams is based on Figure 5 in which the commercial value and calorific value of a fuel-oil component is plotted against a viscosity blending index. This index can be viewed as a representation of the viscosity of an oil fraction to be used as a component in the commercial fuel oil pool. As can be seen from the graph, the higher the viscosity the lower the value as commercial fuel oil blending component.

The calorific value and the blending value of the vacuum flashed cracked residue set the limits of the range in which its price varies. To utilize the calorific value as such, the stock can be burned within the refinery to avoid the cost and handling difficulties. Expensive flue gas treating is necessary to meet the emission specification, however. Therefore, the VFCR was valued at 33 US\$/t. This is the middle point of the calorific value and the blending value of the stock.

The liquid coke would have a negative blending value because of its high viscosity from Figure 5. It is, however, valued at 18 US\$/ton, as can be seen from Table 3. The basis for this valuation is its calorific value and a value of 0.5 US\$/MMBTU for petroleum coke, which sets the low limit of the price.

Besides the oil and gas product streams, hydrogen and electricity prices are important input parameters. A hydrogen price of 700 US\$ is a typical figure for a large-scale hydrogen plant in the refinery environment. Oxygen price is less sensitive than the hydrogen price but still an important cost factor. It is taken as 30 US\$ per ton, which is a typical figure for an air separation plant with this type of scale. A 40 US\$/MWh price for electricity is a realistic price for today's dynamic electricity market, and is used in the calculations.

### ***Application Case 1: Visbreaking and SGP***

The Shell Pernis refinery in The Netherlands is one of the largest in the Royal/Dutch Shell Group. It is a highly complex site with a capacity of about 18 MMt/y (400,000 bbl/d). The recently completed refinery upgrading project Per+ consisted of the integration of a 1650 t/d gasification unit with the thermal conversion unit. The SGP unit processes the residue from the thermal conversion unit and produces hydrogen for the hydrocracker as well as syngas and high-pressure steam for the co-generation power plant. The thermal conversion unit in the refinery, a Shell Soaker Visbreaker, processes a wide range of feedstocks, being part of a very complex refinery. It is originally designed for usual conversion levels, compatible for commercial and refinery fuel oil production.

The gasification capacity is such that the sufficient amount of hydrogen is produced for the hydrocracker and a clean fuel is generated for the gas turbines of the co-generation power plant. A co-generation power plant comprises two gas turbine and two steam-turbine generator sets that use the clean gas from the gasification as well as all the steam generated in the effluent boilers of the gasification.

Since the refinery processes a complex diet of crude, a simplification is done in the present calculation of the gross margins. A Middle East vacuum residue is used in this integration configuration with feed properties of API of 5.7, CCR of 22 and a viscosity of 770 cSt@100°C. The visbreaker upgrades the vacuum residue to light products, and the bottom is gasified in the SGP trains. The feeds and products to the integrated VBU and SGP unit are summarized in Table 4 in which the calculated overall gross margin is also shown.

**Table 4 Economics for VBU-SGP integration**

	Flow, t/d	Value, 1000 US\$/d
<b>Feed</b>		
Vacuum residue to VBU	2800	134
Oxygen	1570	47
<b>Products</b>		
Gas (C4-)	64	8
Naphtha (ECP 165°C)	131	21
Gasoil (ECP 350°C)	391	63
Waxy (ECP 520°C)	559	67
Hydrogen, 99.9 % purity	285	199
Electricity	113 MW	108
<b>Economics, US\$/ton feed to VBU</b>		
Gross margin		<b>102</b>

When the gross margin of 102 US\$ is compared with that of 28 US\$ for the visbreaker without integration with SGP, it is evident that the SGP adds really a great value to the products. This quantum improvement can be attributed largely to the high value of hydrogen product for this refinery. Therefore, it can be concluded that the SGP is an effective and economic route of making hydrogen. The contribution of electricity to the margin is also significant, which indicates the incentives to upgrade residue to electricity.

Oxygen is an important cost factor. As was indicated before, a typical price was assumed for the oxygen. With the increasing number of gasification projects which require large-capacity air separation unit, the oxygen cost is expected to decrease in the future.

### *Application Case 2: Liquid Coke Gasification*

The Deep Thermal Conversion unit in this example operates with a conversion which upgrades more than 50 % of the feed to light products. The residue produced, i.e., the “liquid coke”, can still be pumped to the SGP at higher temperatures.

The SGP process can gasify the liquid coke with minor modification of the process and equipment. The installation of the SARU unit is essential for this configuration, which eliminates the soot and ash circulation in the process.

Table 5 shows the summary of economics for this case. Besides the gross margin calculation of the DTC-SGP configuration, that of the VBU-SGP configuration processing the same amount of vacuum residue is also shown as a reference case. Half of the syngas produced in the SGP is used for making hydrogen, whereas the other half is sent to IGCC for electricity generation. An overall efficiency of 52 % was used for power generation from syngas. To make the comparison on a consistent and equal basis, the energy feed in MWth to the gasifier in the VGU-SGP configuration is set equal to that in the DTC-SGP. This can be seen from the identical output of hydrogen and electricity from both configurations.

Due to its slightly higher heating value, the VBU VFCR is left with a small excess stream in addition to feeding the SGP. This stream can be blended back to fuel oil.

**Table 5 Economics for DTC-SGP integration**

Case	VBU+SGP	DTC+SGP
	Value, 1000 US\$/d	
<b>Feed</b>		
Vacuum residue	192	192
Oxygen	54	54
<b>Products</b>		
Gas (C4-)	11	19
Naphtha (ECP 165°C)	30	53
Gasoil (ECP 350°C)	89	115
Waxy (ECP 520°C)	96	108
VFCR	18	
Hydrogen, 99.9 % purity	165	165
Electricity	173	173
<b>Economics, US\$/ton feed to VBU or DTC</b>		
Gross margin	<b>84</b>	<b>97</b>

The general trends in this DTC-SGP integration are nearly identical to those in the VBU-SGP case. The gross margin improved from 34 US\$ for the DTC unit, viz. Table 1, to 97 US\$, when the liquid coke from the DTC unit is gasified in the SGP. It can also be seen that the margin improves in the DTC-SGP integration case, as compared to that in the VBU-SGP case. Therefore, both the thermal conversion margin and the SGP margin (including hydrogen and power) are improved by using DTC instead of VBU, while capital costs will be virtually equal. As was mentioned previously, the DTC selectively produce more gasoil. This is clear from Table 5, as the waxy distillate value remains almost constant, while the gasoil value increases by nearly 30 %.

This configuration of integrating the SGP and DTC processes in upgrading the refinery residue exploits the full potential of the synergetic effects of both technologies. It is a recommended route for refiners who consider to upgrade their refinery residue.

## CONCLUSIONS

The integration of the Shell Gasification Process and Shell Thermal Residue Conversion technologies lead to significant economic benefits to refineries. The synergetic effect comes from the high conversion of the residue to lighter oil products by the thermal conversion and upgrading of the heavy thermal conversion bottom to electricity and other products for the refinery, like hydrogen. The DTC technology

improves the thermal conversion to a new limit. The SGP is able to gasify the liquid coke with a minor modification of the process and equipment. The successful development and commercial operation of the Root and Ash Removal Unit is essential for this application. With the configuration of DTC-SGP integration, a maximum improvement of gross margin can be obtained. This configuration exploits the full potential of the synergetic effects of integrating the SGP and Thermal Residue Conversion technologies in upgrading the refinery residue. It is a recommended route for refiners who consider to upgrade their refinery residue.

## ABBREVIATIONS

API	American Petroleum Institute gravity, a measure of density of oil
BFW	Boiler feed water
CCR	Canradson Carbon Residue, a measure of coke forming tendency of oil
DTC	Deep thermal conversion
ECP	End cut point
HCU	Hydrocracking unit
LR	Long residue, also called atmospheric residue
PGP	Power generation plant
SARU	Soot Ash Removal unit
SGP	Shell Gasification Process
SR	Short residue, also called vacuum residue
SRU	Sulfur recovery unit
SWS	Sour water stripping unit
VBR	Visbroken residue, bottom of visbreaking unit
VBU	Visbreaking unit
VFCR	Vacuum flashed cracked residue
WHE	Waste heat exchanger