Crude refinery feedstocks are gradually growing heavier and more sour. At the same time, more stringent environmental requirements have come into force. This has led to a dramatic increase in both demand and size of hydrogen plants. Furthermore, it is becoming a regular feature to process all different feedstocks in addition to natural gas.

As a leading supplier and contractor for reforming and gasification technologies, Uhde designs and realises facilities for the production of hydrogen and synthesis gas (syngas) from solid, liquid or gaseous feedstocks. For the production of hydrogen, various technologies are available, and their different H₂/CO ratio could be of considerable importance (Figure 1).

Uhde has extensive experience in all relevant technologies, developing flowsheets to meet all project specific requirements. Due to the various optimisation possibilities, a Capex/Opex investigation is advantageous, with parameters and criteria set jointly with the customer for each individual project.

This article will focus on the Shell gasification process (SGP) and steam reforming for the production of hydrogen, describing the current status of these technologies and presenting an outlook of expected future requirements as well as respective development possibilities.

Steam reforming
Steam reforming is the most widely used technology for producing hydrogen, and Uhde’s proprietary reformer design has proved successful in over 60 plants worldwide. Typical feedstocks include natural gas, LPG, naphtha, refinery offgases and/or mixtures thereof. The Uhde design offers clear advantages over competing systems, particularly with respect to adaptation and flexibility, to respond to varying demands in refineries.

In steam reforming plants, the feed is normally desulfurised, mixed with steam and converted to syngas over a nickel containing catalyst. The process is complemented by the adiabatic carbon monoxide (CO) shift and a pressure swing adsorption unit to obtain high purity hydrogen. Process options include feed compression and/or evaporation, adiabatic feed prereforming and/or HT/LT-shift to process heavier feeds and/or optimise feed/fuel consumption and steam production.

Operating conditions of steam reformers vary depending on the individual application. Over the past decades, Uhde has designed and built reformers for a wide range of established commercial applications, with outlet temperatures ranging 740 - 950 °C and pressures of up to 50 bars.

Such a wide range of operating conditions necessitates a versatile reformer design to ensure utmost operational reliability and flexibility. The Uhde proprietary reformer design has proved its suitability to satisfy various demands and features the following specific advantages:

- Well proven, top fired design with tubes made of centrifugally cast alloy steel.
- Enhanced reformer tube lifetime.
- Unique proprietary cold outlet manifold system.
- Prefabricated advanced and modularised shop tested convection bank design.
- Proven process gas cooler design.
- Bisectional steam system for the environmentally friendly, full recovery of process condensate and production of high pressure export steam.

Figure 2 is a simplified representation of the essential components of the Uhde reformer.

The feed stream to the reformer is distributed to the reformer tubes via a flexible inlet manifold system. The tubes are arranged in parallel rows and each row is connected to a separate cold outlet header. The burners are arranged in the furnace arch. At the bottom, tunnels collect the flue gas.

Top fired designs are essential as only top firing enables the heat to be distributed in parallel to the reformer tubes and concurrently with the process fluid direction. The high heat flux is at the top where the heat is efficiently removed by the endothermic hydrocarbon conversion, and low heat flux is at the bottom where the reaction is at its equilibrium conditions. The result is an average tube wall temperature that is fairly constant along the entire tube length. Figure 3 presents the extremely uniform temperature profile of the Uhde reformer.

For reformer firing, Uhde uses down firing, forced draft low NOx burners, which offer extremely stable and complete combustion with well defined flame profiles over a wide range of fuels. Furthermore, top firing reduces the number of burners and the failure risk to the minimum. Figure 4 illustrates the excellent combustion behaviour and flame picture of the radiant box.

Uhde uses computational fluid dynamics (CFD) to optimise the reformer box, taking into account the various required parameters to deliver an appropriate closed solution for the hydraulic design. This is another important factor for maximising feedstock and/or fuel flexibility and operational reliability.

All the above, together with the use of state of the art micro alloy tubes, allow a uniform process condition to
ensure plant availability and extremely long reformer tube lifetimes of 15 years or more. This is demonstrated in Figure 5.

Since the late 1960s, Uhde has succeeded in eliminating the use of hot pigtails in the reformer outlet manifold which were a considerable source of failure in steam reforming plants. The Uhde proprietary cold outlet manifold system is maintenance free and ensures an excellent overall plant reliability. As presented in Figure 6, it allows the separation of the ability to withstand high temperatures from that of withstanding high pressure and reduces the number of critical elements to the minimum.

Uhde's tube-to-manifold connection is as reliable as any other pipe connection in the plant. A gas tight, shop welded and shop tested funnel and tube conduct the reformed gas down into the refractory lined manifold.

The manifold is equipped with sufficient gas barriers and an internal liner to shield the refractory lining. It is delivered to the site in ready made, dried out sections with the transfer line. Figure 7 and 8 show the details of the system and its excellent accessibility.

The process gas cooler downstream the reformer is subjected to a high heat flux. Intensive research and development, strict design requirements for critical parts (such as ferrules or the bypass system), a proper selection of materials and in-house thermal design are the basis for a high reliability and an extremely long lifetime of the process gas coolers. Their main features are:

- Thin flexible tube sheet design.
- Full penetration tube to tube sheet welds.
- Use of ferrules to limit the heat flux at the tube inlet.
- Internal bypass with steam cooled damper blades.
- Double layer refractory lining for the inlet and, if necessary, for the outlet chamber with high duty bricks on the hot surface.
- Minimised risk of metal dusting by a proper process design and selection of materials.

The ever increasing demands made on the reformer and heat recovery system as a result of operation over a wide range of loads with different fuels and changing feeds call for a great deal of expertise and experience in designing the radiant and convection section.

Uhde designs convection banks using its proprietary in-house computer programs, based on the experience and feedback integration of many executed projects. This offers validated optimum solutions for the given plant requirements and plot space restrictions.

High efficiency levels can be achieved by preheating the combustion air up to 500 °C and the feed/steam up to 630 °C.

Figure 9 shows Uhde's completely prefabricated modules, which assure easy transportation, economical construction and fully shop tested quality levels. The headers can be inspected through removable cover plates and the coils can be removed separately, if required.

**SGP for hydrogen production**

Hydrogen can also be generated by partial oxidation in a gasification unit. Refinery residues and petroleum coke are the cheapest feedstocks for gasification units. Gasification is a very versatile process which can be used for converting even the heaviest 'bottom of the barrel' refinery residues into clean syngas. This syngas can subsequently be used to produce hydrogen, power, fuel gas or steam for any refinery purpose, as well as producing gases for the chemical industries.

With over 100 gasifiers built based on eight different gasification technologies, Uhde has been a world leader in the field of gasification for over 60 years.

The Shell gasification process (SGP) is a reliable, efficient and environmentally friendly process. Over the past 40 years, more than 168 SGP units have been built worldwide, many of them for the production of ammonia and methanol. However, at present the focus is more on power and/or hydrogen coproduction. An example of the successful implementation of such a project is the PER+ refinery upgrading project at the Shell Pernis refinery near Rotterdam in the Netherlands. The Pernis SGP plant has been operating successfully since the end of 1997.

The SGP process, initially developed in the 1950s, was primarily used with fuel oil and bunker C oil as feedstocks.
By the 1970s vacuum (short) residue had become the standard feed. In the 1980s, vacuum residues were concentrated even further by visbreaking and C4/C5 deasphalting. Over time, the feed became heavier and more viscous, and contained higher levels of sulfur and heavy metals.

The Shell coal gasification process (SCGP) began as a joint development between Uhde and Shell in the 1970s, and is the basis for gasification of solid feedstocks such as coal and petroleum coke, which is growing increasingly attractive in regions of high natural gas and high oil prices.

**Basic reactions**
Gasification or partial oxidation is a non-catalytic process; a combination of exothermic and endothermic reactions, thermal cracking, steam reforming, etc. The net reaction $2\text{CH}_n + \text{O}_2 \rightarrow 2 \text{CO} + n \text{H}_2$ ($1 < n < 4$) is exothermic and produces a gas containing mainly CO and H$_2$. The raw syngas (or syngas) contains small quantities of CO$_2$, H$_2$O and H$_2$S and impurities, such as CH$_4$, NH$_3$, COS, HCN, N$_2$, Ar and ash; the quantities of these are determined by the composition of the feedstock, the oxidant and the actual gasification temperature (1300 - 1400 °C for SGP and up to 1600 °C for SCGP).

Hydrocarbon fuels, such as natural gas, refinery gas, bunker C oil, vacuum residue, vacuum flashed cracked residue, asphalt, liquid waste, Orimulsion, hard coal, brown coal, lignite, petroleum coke and biomass can all be used as feedstock for the SGP and SCGP gasification processes.

**Future trends and developments**
From 1st January 2009, the sulfur contents in diesel and gasoline in Europe will be limited to a maximum of 10 ppmw, resulting in additional hydoroprocessing requirements for refineries, and thus an increasing demand for hydrogen.

Furthermore, the majority of high sulfur fuel oil has traditionally been used as fuel for the ship industry. Since European regulations prohibit the use of high sulfur fuel oil for shipping from 2006 in the Baltic Sea, and from 2007 in the Channel and the North Sea, the further residue upgrading and integrated hydrogen generation via gasification will soon become a necessity for many European refineries.

Due to these reasons, it is now becoming a regular feature for Uhde to process refinery offgases (ROG) obtained from various refinery process units as an alternative feedstock in the steam reformer. Uhde is currently working on a number of refinery upgrading projects, including major refiners such as Shell, BP, Neste Oil Oyj and CNOOC, amongst others. There are, however, some considerations to be taken into account when designing such a plant.

**Processing ROG**
The first decision to make when processing ROG in the hydrogen plant is where to process the stream. If ROG has a very high hydrogen content and sufficient pressure, it may be fed directly to the PSA. It is, however, necessary to consider critically all components that may be present in the stream, as the design of the PSA is affected differently by different components. In a natural gas based hydrogen plant using steam reforming, the PSA is fed light gas consisting of methane, hydrogen, carbon oxides, water vapour and inert gases such as nitrogen. On the other hand, ROG can contain heavy components such as hydrocarbons in the range of C$_2$ to C$_6$. Processing such heavy components in a not accordingly designed PSA can affect the operation of the PSA and result in a loss of overall PSA efficiency, and thus consequently in a loss of hydrogen production.

ROG with lower hydrogen content can be directly fed to the steam reformer. In this case, the higher hydrocarbons are reformed and converted to hydrogen with some residual methane, as is the case with processing natural gas.

However, it is important to consider the amount and type of higher hydrocarbons that may be present in the ROG. This can determine the type of catalyst needed in the reformer. If there is a substantial amount of heavy components, it is often recommended to use a split charge of catalyst with the top layer of a potassium promoted type and an appropriate H$_2$O/C ratio. Using such a catalyst leaves a greater margin to carbon formation in the top section of the tubes.

ROG may be a stream rich in hydrogen with a high
sulfur content, therefore processing ROG could place a large load on the desulphurisation unit, and the consumption of zinc oxide is increased compared with natural gas processing.

ROG can also contain unsaturated hydrocarbons, which needs also to be considered in the design of the desulphurisation unit. Olefins will be converted to saturated hydrocarbons by reaction with hydrogen across the nickel-molybdenum or cobalt-molybdenum catalyst in the desulphurisation unit. The resulting temperature rise across the catalyst should be moderate and the outlet temperature should be kept below approximately 400 °C. In some cases, a cooling arrangement is required. The temperature rise will be moderated by the addition of natural gas so all operating cases and combinations of ROG and/or natural gas have to be considered.

**Steam reformer sizing**

A number of issues need to be decided before the steam reformer can be designed for processing ROG in a hydrogen plant.

In the refinery, the hydrogen plant is a utility plant and its primary task is to satisfy the refinery hydrogen requirements, and secondly to supply surplus steam to the refinery steam header. Considering the importance within the overall refinery operation, the hydrogen plant must be capable of meeting the requirements of reliability, availability and flexibility to process different feedstock and fuels in varying conditions.

The reliability and availability of hydrogen plants are secured by the following measures:
- Process related design, e.g. the selection of moderate and technically proven process parameters.
- Design of the equipment, e.g. use of proven equipment; use of redundant equipment such as two pumps per 100%; certain safety margins between operating and design figures.
- Safe instrumentation design, e.g. use of 2/3 voting trip system.

The flexibility of a hydrogen plant is largely denoted in that:
- Capability of processing different feedstocks is provided or loss of one feedstock can be compensated.
- Possible feedstock analysis variations can be covered without causing any problems.
- High turndown ratio can be achieved.

When designing a steam reformer, the key question is what happens when ROG supply fails. This can occur when, for example, ROG is a low pressure stream and causes the ROG compressor to trip.

Hydrogen in the ROG is more or less passing through the reformer without a high heat input requirement, whereas steam reforming of natural gas requires a large heat input. This leaves the following options:
If the steam reformer is designed for the case of ROG plus natural gas, it will not be able to produce the same amount of hydrogen in case of loss of ROG and keeping its severity of operation.

If the steam reformer is designed to produce the full amount of hydrogen from natural gas, it is operating at turn down conditions while processing ROG plus natural gas. The plant is then oversized during natural gas processing, with accordingly reduced Capex/Opex compared with the above case.

For reformer tubes to be designed for 100,000 hrs with various feeds available at different times, it is necessary to determine or estimate the periods when these feeds are present. In addition, the production requirement during those periods for the plant must be taken into account. Once these factors are known, the design of the plant and the tubes can proceed to target the overall tube lifetime of 100,000 hrs. These considerations should be worked out between the designer of the reformer and the operating company/refinery during the engineering phase.

**Control of the steam reformer**

The control of the steam reformer becomes another important issue when loss of ROG occurs and full production of hydrogen is desired. In this case, the feedstock character changes from a hydrogen rich mixture to typically natural gas. The control system needs to cope with this change and be able to maintain steam to carbon inlet the reformer and increase firing rapidly as natural gas in replacing the ROG and natural gas mixture. The change occurs with a slight delay while the desulfurisation is being purged of the gas mixture and replaced by natural gas only.

As the gas is changing toward natural gas, the firing of the reformer is increased and this has to be done without over firing the reformer or forming carbon on the reforming catalyst. The difficulty of this depends on how much ROG in relationship to natural gas is being fed to the reformer and on its difference in composition from the natural gas.

In those cases where ROG is the major part of the feed and hydrogen production has to be maintained, it can become important to replace such ROG by natural gas almost instantaneously. Such a situation can occur due to a ROG compressor trip. To ensure immediate natural gas availability at the correct flow and pressure can require a detailed study of the dynamics of the connecting gas pipeline or piping system within the refinery.

**Conclusion**

This article shows that designs of hydrogen production units, based on partial oxidation or steam reforming, are becoming more and more versatile and integrated into the refinery environment. Such integration needs experience and close partnership between all parties concerned.

Uhde is well suited to design and build such hydrogen plants, while identifying and considering all the relevant aspects to deliver the best tailored concept for each purpose.

The most important goals are flexibility with respect to feed and fuel, availability and operational reliability with optimised Capex/Opex parameters. Uhde has the appropriate experience and tools to cut this Gordian knot together with the customer and to avoid contradictory solutions.

Due to the strongly increased hydrogen demand, Uhde foresees a high potential for new steam reforming and partial oxidation plants. The latter have the advantage of also processing bottom of the barrel feedstocks, which is an increasingly important issue.