

4000 mtpd Ammonia plant based on proven technology

Today's state of the art capacity of a world scale ammonia plant is about 2000 mtpd. Driven by economies of scale the first of the next generation of large scale plants – based on Uhde license with a capacity of 3300 mtpd – is currently under construction for SAFCO in Al Jubail, Kingdom of Saudi Arabia. In advance of a continued trend towards even larger plants, Uhde has already checked this concept for capacities of 4000 mtpd and beyond and found it fully viable. Some details are discussed here.

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Introduction

Brief capacity history of world scale ammonia plants

Already the first commercial scale ammonia plant – built by Uhde in 1928 – put up a capacity of 100 mtpd. This number was not to be significantly exceeded until turbo compressors were introduced into ammonia processing and plant capacities rapidly increased to about 1000 mtpd in mid to late 1960's. From those days on a continuous rise of world scale plant capacities occurred and is still going on. The following plants may be recognized as milestones of the recent history:

1988 Hydro Agri, Sluiskil E (Sluiskil, the Netherlands)
1750 mtpd - Braun license
1991 BASF (Antwerp, Belgium)
1800 mtpd - Uhde license

2000 P.T. Kaltim Pasifik Amonik (Bontang, Indonesia)
2000 mtpd - Haldor Topsoe license
2005 Burrup Fertiliser (Burrup, Australia)
2200 mtpd - KBR license
2006 SAFCO (Al-Jubail, KSA)
3300 mtpd - Uhde license

From a more generalized point of view three market trends can be distinguished, each one aiming at production cost savings:

- Improvement of plant energy efficiency already reached an optimum in the 1990s (e.g. BASF, Antwerp, Belgium).
- Relocation towards low cost natural gas sites is in full progress. Currently almost no plants are being built in high cost gas areas.
- Progressive cost reduction by plant capacity scale up (economy of scale) is expected to be the future trend. The above mentioned 3300 mtpd single train plant – currently under construction and to be commissioned in 2006 – illustrates this.

Process concepts for the next generation

The above mentioned trend towards large scale ammonia plants is recognized by almost all major licensors with each one having its own process concept for the next generation ammonia plant. The most popular concepts are summarized below:

Oxygen-fired ATR

Recently a front-end concept originating from heavy fuel oil gasification with two stage HT shift and two stage CO₂ removal (Rectisol & liquid nitrogen) has been presented to operate with an oxygen-fired auto-thermal reformer at high pressure and natural gas as feedstock. The process is proposed for capacities around 4000 mtpd. Up to now, no reference plant has been built, thus the operating conditions of the ATR are non-proven.

Excess air blown ATR in combination with heat exchange reforming

This approach is based on an excess air blown ATR and a heat exchange reformer, both of which are fed with fresh feed/steam mixture in parallel. The excess nitrogen is removed in a cold box. The synthesis loop operates at low pressure and uses a ruthenium based catalyst. There are references for each of the characteristic process steps, however, especially for the heat exchange reformer the maximum capacity that has been built is much lower than that expected for a next generation plant (i.e. about 4000 mtpd).

Enriched air-fired ATR

An intermediate option between the oxygen-fired ATR and the excess air blown ATR is the oxygen-enriched air fired ATR concept. Conventional downstream gas processing may be employed, however, the extra duty for the CO₂ removal due to the autothermal heat supply should be considered as in the other autothermal front-ends.

Uhde Dual Pressure Process

In contrast to the above mentioned concepts the Uhde Dual Pressure Process [1] focuses on the debottlenecking of the conventional synthesis loop instead of modifying the front-end process, which is not considered to be critical if based on Uhde technology. By insertion of a once through synthesis reactor at an intermediate pressure level the production capacity can be raised by about 65% still using proven equipment. The concept is the key to the impressive capacity of 3300 mtpd in a

single train, which is currently under construction by Uhde for SAFCO in Al-Jubail, KSA.

Furthermore, there are other good reasons to stay with a conventional, externally heated front-end layout.

- superior hydrogen yield
- less duty for the CO₂ removal unit
- No need for an external air separation unit or process integrated cold box technology. Adding an air separation unit adds cost, either capital investment or operating cost, if oxygen is supplied over the fence.

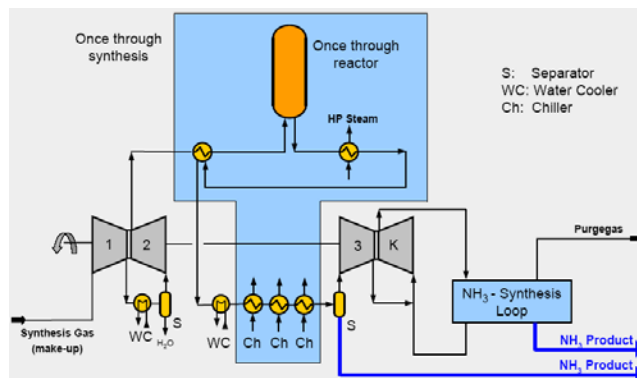


Fig. 1: Uhde Dual Pressure Process - once through reactor in between the synthesis gas compressor casings

Recent design experience from the world's largest ammonia plant

Uhde has already gained experience from the design and construction of a next generation ammonia plant, the above mentioned SAFCO IV plant. This results in a significantly reduced scale-up factor and therefore means considerably improved 'bankability' to the customer. After commissioning of SAFCO IV in 2006 Uhde will have the full range of experience necessary to realize such projects in a highly efficient way.

These financial considerations are mainly based on equipment and machinery issues. However, there are a number of minor issues, which in combination can put time schedule, budget or plant quality at risk. These aspects are to be discussed later on.

Uhde Dual Pressure Process assessment for 4250 mtpd

Overview

Based on the above mentioned experience, Uhde carried out a detailed study to validate the SAFCO IV process concept for capacities around 4000 mtpd. Any possible critical items such as turbo compressors, large liquid pumps and static equipment as well as piping and valves, have been thoroughly examined. 4250 mtpd was chosen as the target capacity.

Static equipment

Primary reformer

Due to its highly modular design a primary reformer can generally be scaled up quite easily since the design of each reformer tube and burner group can remain unchanged. However, at least the manifold system has to be enlarged and therefore to be checked.

A primary reformer for 4250 mtpd is expected to consist of about 540 tubes (5 inch in diameter). Uhde's cold outlet manifold system has already been applied to top fired reformers with up to 960 tubes. The following list gives the basic data of some large primary reformers:

plant	prim. reformer dimensions L x W x H ¹ [m x m x m]	No. of tubes
QAFCO 4 2000 mtpd	18.1x13.7x12.2	288
SAFCO IV 3300 mtpd	19.1x17.9x13	408
<i>plant study</i> 4250 mtpd	20.2x22.1x13	540
Qafac (Methanol)	14x49x12.6	960

¹ H: heated length of reformer tubes

Convection bank

For the convection bank a design with horizontal tubes has been chosen. This is well proven in refinery service. Any single coil is designed according to API and ASME code respectively. The dimensions will be about 22m x 25m x 13m.

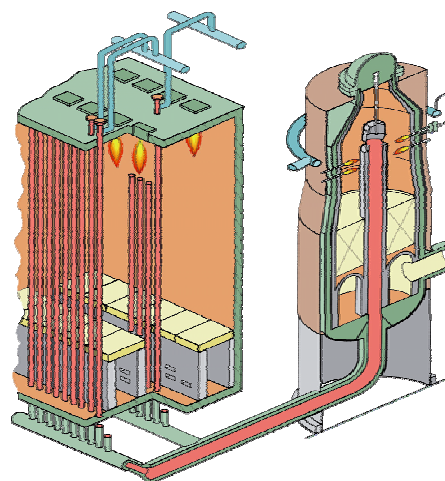


Fig. 2: Primary and secondary reformer acc. to Uhde design (top fired radiant section, cold outlet manifold, central riser pipe, ring-shaped arch)

Secondary reformer

The secondary reformer will slightly exceed the dimensions of SAFCO IV. However, much larger autothermal reformers have been built, which operate under even more severe conditions. In addition it has to be kept in mind that the pressure retaining wall is reliably kept cool by means of a refractory lining and a water jacket, even if the inside temperature is very hot. Furthermore the span of the refractory arch of an Uhde secondary reformer is only about half that of other designs due to the ring-shape design around the central riser pipe (see fig. 2, also).

plant	secondary reformer dimensions	
	Ø [m]	H [m]
QAFCO 4 2000 mtpd	4.5	18
SAFCO IV 3300 mtpd	5	20
<i>plant study</i> 4250 mtpd	5.7	22

Reformed gas waste heat boiler

For technical and economic reasons the maximum capacity of a single reformed gas waste heat boiler is about 3800 mtpd, thus a dual flow design has to be chosen for larger plants. For a 4000 mtpd plant one of these boilers will be of the same design as the one installed in QAFCO 4, Qatar. The design of such a boiler system for 4250 mtpd is of course well within the bounds of feasibility as can be seen from the 3300 mtpd single flow design of SAFCO IV. Concerning the dual flow design, the change from a single waste heat

boiler to two parallel waste heat boilers may introduce problems due to flow mal-distribution resulting in changes in temperatures and piping stresses. The design incorporates two inlet nozzles on the steam superheater following the waste heat boilers, and a common steam drum. The technical risk of applying parallel boilers is considered to be relatively low since it can be mitigated by a conservative design of the piping systems connections of these waste heat boilers. Furthermore, the application of parallel waste heat boilers downstream of the secondary reformer is standard design in other processes, and another process features a single steam drum for several boilers from different plant sections. So, the risk is assessed to be acceptable and Uhde intends to employ two parallel waste heat boilers receiving hot gas from the secondary reformer.

CO₂ removal

Using BASF's aMDEA process for CO₂ removal in a 4250 mtpd plant admittedly results in impressive equipment dimensions. A conventional process layout results in absorber dimensions of Ø 6.9 m (top: 4.6 m) x 50 m. The diameters of HP and LP flash vessels are calculated to be 6.7 m and 8.7 m respectively.

However, the aMDEA process has many references and there are no concerns from the process point of view – acid gas removal units of similar dimensions are currently being specified and built for LNG plants. Another settling argument may be, that the step from SAFCO IV to 4000 mtpd corresponds to an increase of 13 % in diameter (see table below, also). Elsewhere capacity scale-up factors of about 2, which correspond to a factor of 1.4 in diameter, are still considered to be conservative.

plant	absorber Ø x cyl. H [m ²]	HP flash Ø [m]	LP flash Ø [m]
QAFCO 4 2000 mtpd	5.0 (3.3) x 43.9	4.9	6.1
SAFCO IV 3300 mtpd	6.1 (4.1) x 37.3	5.6	7.6
<i>plant study</i> <i>4250 mtpd</i>	<i>6.9 (4.6) x 38</i>	<i>6.7</i>	<i>8.7</i>

Nevertheless, the feasibility of the logistics for such equipment closely depends on the plant location. The transport to sites without easy access to a waterway is at least considered to be difficult. However, due to the export orientation of these large plants, a site location close to the sea is to be expected.

Ammonia converters

The Uhde Dual Pressure Process (which is implemented in SAFCO IV, but not in QAFCO 4) makes it possible to use almost unmodified equipment dimensions while raising the synthesis capacity by a factor of 1.65. For instance, the diameters of different converters are given in the table below. The additional once through converter indeed tends to be a large item, but is far smaller in diameter and volume than the low pressure loop converter designed by Uhde for CIL, Canada. This is still true at a production capacity of 4250 mtpd. The operating pressure of the once through converter has already been applied in the synthesis loop of the Puyang plant. The dimensions of the 4250 mtpd loop converters have to be slightly prorated. However, here also a significant technological risk is not to be expected.

plant	converter	op. press. [bar]	Ø [m]
CIL 1128 mtpd	loop conv.	87.5	5.45
Zhong Yuan Chem.	loop conv.	110	3.2
Fert. 1000 mtpd			
QAFCO 4	loop conv. I	207	3.01
2000 mtpd	loop conv. II	203	2.86
	OT converter ¹	110	3.21
SAFCO IV			
3300 mtpd	loop conv. I	207	3.01
	loop conv. II	203.4	2.86
<i>plant study</i>	<i>OT converter¹</i>	<i>110</i>	<i>3.4</i>
<i>4250 mtpd</i>	<i>loop conv. I</i>	<i>207</i>	<i>3.0</i>
	<i>loop conv. II</i>	<i>203.4</i>	<i>3.1</i>

¹ Converter of the once through synthesis, see fig. 1

Waste heat boilers (Synthesis Loop)

The critical design parameter of the synthesis gas waste heat boilers is the maximum tube sheet temperature, which corresponds to tube sheet thickness and thus to diameter and capacity. For the desired capacity of 4250 mtpd the temperature of the tube sheet core can reliably be kept away from the critical limit where nitriding and embrittlement begins.

Rotating equipment

Natural gas compressor

The natural gas compressor is in general not a critical component of a typical ammonia plant. Some plants even operate without such a machine. However, in the common case where the natural gas pressure at battery

limit is not sufficiently high, it is still needed. Then its operating conditions are generally similar to those of an inline compressor of a natural gas pipeline. Since these machines are sometimes very large, they can be taken as a reference for the natural gas compressor of a 4250 mtpd ammonia plant. This statement is also supported by design studies of different manufacturers. Availability of large capacity natural gas compressors is not an issue.

plant	impellers	power [MW]	speed [min ⁻¹]
QAFCO 4 2000 mtpd	3/3	3.466	14400
SAFCO IV 3300 mtpd	6	4.342	10102
<i>plant study</i> <i>4250 mtpd</i>	6	<i>5.400</i>	<i>10500</i>

Process air compressor

The process air compressor may be one piece of equipment which cannot simply be scaled up, since the LP casing of the conventional 2-casing machine would become a really heavy item. Nevertheless there is still a reference for the casing size, but not for the desired flow. This constraint is even more critical for processes which use excess air or autothermal reforming in the front-end because of the increased air flow required.

However, there are several choices for the required high flow air compressor. Taking SAFCO IV as the starting point, the most obvious and straightforward solution may be a 3-casing compressor– with LP casings as used for SAFCO IV, i.e. once this is operational there will be a complete reference. On the other hand, there are still manufacturers who have the appropriate technology to construct a reliable 2-casing compressor, although they do not have references for the required capacity. The 3-casing solution may be the least risky, but it seems to be technically feasible to use a 2-casing compressor with the benefit of fewer parts resulting in possible cost savings. The data for 4250 mtpd given below are for the 2-casing option:

plant	impellers	power [MW]	speed [min ⁻¹]
QAFCO 4 2000 mtpd	2/2//2/4	14.923	6440/12119
SAFCO IV 3300 mtpd	2/2//2/4	25.344	5135/8672
<i>4250 mtpd</i> <i>(2 casings)</i>	<i>2/2//3/3</i>	<i>31.000</i>	<i>4500/9000</i>

An integrally geared compressor is another option. Even though there is no reference for a steam turbine driven integrally geared compressor, it is remarkable that some units with operation conditions close to those needed here are currently under construction.

The technology exists today for the construction of a process air compressor for the conventional process and there is a choice of different solutions. Most of the compressors in similar service are found in air separation, terephthalic acid and acetic acid plants. Lately, the size of air separation plants has increased and reference compressors exist for the conventional ammonia process. Acetic acid plants operate at similar pressures as an ammonia plant front-end but with somewhat lower flow requirements than that required for the large scale plants. Which compressor type is eventually chosen will depend to a large degree on the input from the client. The plant arrangement work done so far on the 4250 mtpd plant has been based on an in-line solution with 2 or 3 casings.

Synthesis gas compressor

The operating conditions of the synthesis gas compressor are highly specific to ammonia plants. In no other application does a compressor set have to cope with a similar combination of flow, molecular weight and discharge pressure. Consequently, there is no design for a synthesis gas compressor for 4250 mtpd with a complete reference. However, some of the largest synthesis gas compressor sets ever built operate in recent Uhde plants and from SAFCO IV (3300 mtpd) to a 4250 mtpd plant is just a reasonably small step. Additionally, the synthesis gas compressor duty of the Uhde Dual Pressure Process will be far smaller than with a conventional synthesis concept. For instance, the compressor trains of QAFCO 4 (2000 mtpd, conventional synthesis loop) and SAFCO IV (3300 mtpd, Uhde dual pressure process) are very similar, since the synthesis gas volume flow to the high pressure loop is significantly reduced by the ammonia synthesis and separation in-between the compressor casings.

Detailed technical studies in close cooperation with proven manufacturers resulted in feasible concepts for the compressor and the associated steam turbine, too. For reference reasons a dual flow steam turbine may be the first choice. However, a single flow solution is also available.

Regarding the compressor casing size and the number of impellers, there are references for the specified compressor in similar applications. Synthesis gas com

pressors of comparable dimensions are operated in methanol plants and are under construction for ammonia service.

plant	impellers	power [MW]	speed [min ⁻¹]
QAFCO 4 2000 mtpd	5/4//8/1	27.331	9535
SAFCO IV 3300 mtpd	4/4//6/1	28.600	9701
<i>plant study</i> 4250 mtpd	4/4//7/1	38.000	9000

It may be correct that the eventual limit for ammonia plant capacity will be based on machinery issues [2], but at 4250 mtpd satisfactory compressor and turbine solutions for the synthesis gas compressor train are available when applying the dual pressure process.

Refrigeration compressor

Refrigeration plants making use of ammonia as the refrigerant are widely used. Additionally, the operating conditions of a refrigeration compressor are not that demanding, thus a scale up from 3300 to 4250 mtpd is not expected to be critical. This is also reflected by the results of studies by different manufacturers. Ammonia refrigeration compressors for these capacities are available from a number of vendors.

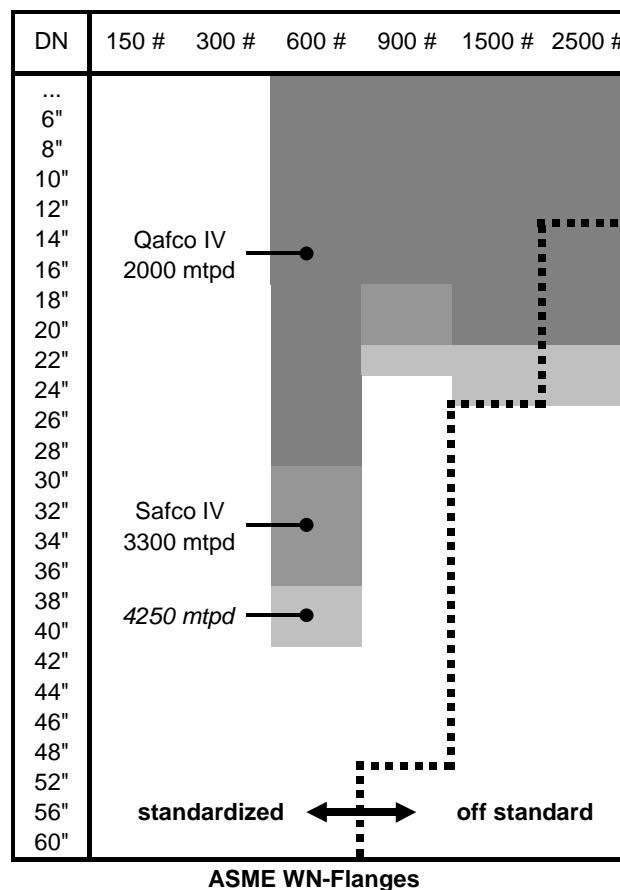
Large pumps

Capacity limitations of pumps are generally not that critical, since liquid pumps are often likely to be doubled for reliability reasons, which can also be done for capacity scale up. For example, this has already been done for the semi-lean solution pump of the CO₂ removal unit, which was realized as a 1 of 2 arrangement for QAFCO 4 (2000 mtpd) and as a 2 of 3 system for SAFCO IV (3300 mtpd). Consequently, a combination of the pump type of QAFCO 4 and the SAFCO IV arrangement will be well suited to the flow requirements of a 4000 mtpd plant and will have sufficient references. For 4250 mtpd only a minor scale up has to be done. For lean solution pumping or boiler feed water service, as well, no parallel pumps will be needed.

Piping and valves

As already stated in the introduction, the synthesis loop has to be considered as the main bottleneck of the conventional process scheme. Besides several equipment items already discussed above, the availability of

appropriate piping material is another critical point. The table given below shows the maximum standardized nominal diameter of piping material (here: weld neck-flanges) and the largest used nominal diameters of different plants broken down by pressure ratings.



It can clearly be seen, that the front-end piping (600#, sometimes 900#) for a 4250 mtpd plant is well within the limits of the ASME code. This is still true for main parts of the Uhde Dual Pressure Process synthesis piping (1500#), however, a conventional loop would be limited to below 3000 mtpd. Some hot high pressure lines (2500#) are already off standard at 2000 mtpd. In detail this is the piping from the gas/gas heat exchanger to ammonia converters and back to the gas/gas heat exchanger. However, this is obviously a problem that is under control for conventional capacities and is not expected to be critical at capacities discussed here.

Furthermore it should be kept in mind, that the stiffness of a pipeline depends on its diameter to the fourth power, thus additional allowances have to be made for expansion loops in order not to exceed admissible nozzle loads. A conservative prorating is of great importance here, since unforeseen piping stresses can

lead to severe difficulties during detailed engineering when the plot plan has to be changed.

Several control valves, which from SAFCO IV experience are known to be demanding, have also been checked in cooperation with manufacturers. A solution was found for every single one of these items.

Besides these major issues, there are also some minor points, which need to be considered during engineering and procurement of the plant:

- With increasing line sizes operating controls like hand-wheels move out of the operators' reach. To ensure plant operability, additional platforms and stagings have to be provided. However, this equipment may in some cases hinder the accessibility of other equipment. This has to be born in mind when considering plot space, not only in the detail engineering phase.
- For some valves a simple scale up may be unfeasible – a change of the valve type will then be required. However, the new type may be heavier by a factor of 5, for example. This should already have been considered for instance for structure loads.
- For accuracy, flow measurements typically require a certain diameter-related straight length in inlet and outlet piping – often not crucial for smaller line sizes. However, enlarging the diameter of the piping may result in unexpected problems, since expansion loops will also take more space.

Uhde has the process concept and – based on SAFCO IV – the experience to avoid such problems and to design a high quality plant with high reliability and operability.

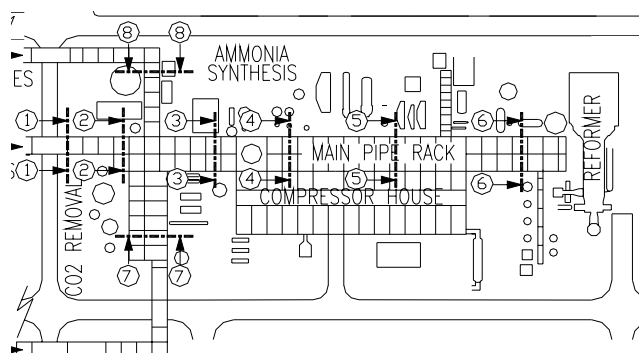
Plant arrangement

From a plant arrangement point of view, the following points need consideration:

- pipe rack dimensions
- arrangement of large turbo-compressors and accompanying condensers (compressor house dimensions)
- required plot area (overall plant arrangement plan)

As shown in detail below, the pipe rack dimensions of a 4250 mtpd plant are considerable, of course. However, even in the case of numerous redundant drive systems with electric motor and steam turbine in paral-

lel, as discussed here, the dimensions remain feasible. For a more common driver concept, which does not utilize turbine drives for pumps and fans, the pipe rack dimensions will be smaller.



pipe rack		rel. dimensions at 4250 mtpd (base case 3300 mtpd)	
section	level	height	width
2-2	1	111%	120% (7-7: 100%)
...	2	115%	
7-7	3	118%	
8-8	1	114%	100%
	2	117%	
	3	118%	

note: 1-1 to urea synth. (optional, dep. on urea capacity)
 7-7 to main substation / cooling water system
 8-8 to offsites/utilities

The arrangement of turbo compressors and accompanying condensers and intercoolers has also been checked. Even with a 3-casing process air compressor the compressor house of the 4250 mtpd plant has just 20% more interior space than the 3300 mtpd plant. The required plot space may in some cases only be a minor cost issue, however, where space is limited, the plant dimensions can easily become decisive for the whole project. The comparison of ammonia plant dimensions below clearly shows the advantages of a single train plant with respect to this point. Incidentally, the SAFCO IV project is one of these, where plot space is tight. The plant arrangement data given below are based on the SAFCO IV plant layout. Therefore a tailor-made design for a concrete project may deviate from this data.

plant	plot width [m]	plot length [m]	area [m ²]
QAFCO 4 2000 mtpd	95	222	21090
SAFCO IV 3300 mtpd	105	222	23310
plant study 4250 mtpd (2x2000 mtpd)	120	270	32400 (42180)

Economic evaluation

It is in the nature of chemical plant construction that a detailed cost estimation needs to be based on several very project specific pieces of information and therefore cannot be done here. However, based on actual data taken from executed contracts and the SAFCO 4 project, an indication can be given on how a capacity scale up effects cost.

Starting with capital expenditure (CAPEX) and setting the specific cost per tonne (i.e. cost / capacity) of a 2000 mtpd plant to 100% the specific cost of a single train 4000 mtpd plant will be around 86%. This figure corresponds to a cost degression exponent of 0.78. Comparing with the degression exponent reached by smaller plants it can be seen that some equipment has to be paralleled (see reformed gas waste heat boiler), or may need some modification to make a scale up feasible. On the other hand the relatively small plot space will result in further cost reduction on owner's side.

Concerning operating costs (OPEX) it can be stated, that compared to conventional synthesis technology the higher energy efficiency of the Uhde Dual Pressure Process reduces operating costs by about 4%. Considering a capacity of 4000 mtpd this corresponds to about 1.6 million US dollars/year. Further savings on owner's side may result from reductions of insurance fees, maintenance cost and personnel cost.

Safety

Finally making reference to the focus of the symposium – safety in ammonia plants – it is obvious that the present high plant safety level is a result of prolonged evolution of equipment and safety measures. The introduction of new equipment and especially new process schemes involves new risks and has to be done extremely carefully. In this context, a scale up factor of

2 and above as well as referencing a new process scheme on a component basis seems to be a high risk. However, as shown above, there is no need to leave the safe evolutionary path of development. Based on the Uhde Dual Pressure Process the technological achievements of the past can be projected forward, thus combining the advantages of progressive cost reduction and proven technology and maintaining the safety and reliability of previous plants at 4000 mtpd and above.

Conclusion

The current trend to larger scale ammonia plants with capacities in the range of 4000 mtpd is obvious and well-founded in plant economics. The technical feasibility of such a plant – concerning static and rotating equipment as well as piping and arrangement – was found fully viable. This is even true for turbo-compressors, which formerly have been regarded as the limiting equipment. Considering economics, the expected economy of scale was confirmed. Furthermore, the 4000 mtpd capacity can be reached with Uhde technology on the basis of long-term experience and a new 3300 mtpd reference plant.

Uhde is convinced that large scale plants using the Dual Pressure Process at present constitute the best trade-off between plant safety and economic risk on the one hand and economic benefit by economy of scale on the other.

References

- [1] D. Lippmann, J. Larsen: *Expanding Ammonia Plant Capacity Limits with Proven Technology*. Nitrogen Conference 2002, Doha, Qatar, 2002
- [2] S.E. Nielsen: *Ammonia Plant Capacity Considerations*. 46th Annual Safety in Ammonia Plants and Related Facilities Symposium, Montreal, Canada, 2001