



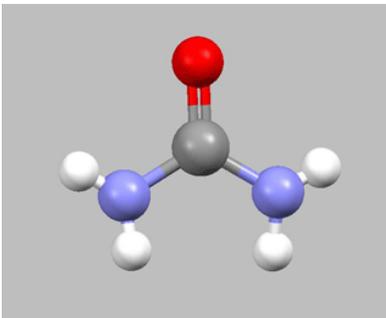
university of
groningen

Snamprogetti Urea Production and Purification

Bachelor Assignment Chemical Engineering

CHBOST-09
13/06/2016

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Executive Summary

The purpose of this project was to model a *Snamprogetti* urea manufacturing plant with the capacity to produce 12,500 kg/h of molten urea (99.6 wt% pure), and to investigate the technology, equipment, and hazards involved in the process.

The further intention of the project was to gain an insight into the operations of the plant and determine whether the modelled process could be operated more sustainably by reducing the steam consumption of the system.

The discovery of urea's industrial importance as a fertilizer dates back decades and this permitted steady and successful evolution of the production process. The technology to produce the organic substance commercially from ammonia and carbon dioxide feed stocks has therefore been carefully developed and fine-tuned for almost 100 years by various licensors.¹

The early process developments were largely concerned with improving operating conditions, to ensure higher conversions and thus lower raw material expenses. The *Saipem* (*Snamprogetti*), *Stamicarbon*, and *Toyo Engineering* processes employed in industry today can achieve around 99% conversion of raw materials through the use of the total recycle and stripping technologies developed.¹

However, as the importance of sustainable plant operation has become more evident, research in chemical manufacturing has become focused on achieving the same results in a more efficient and sustainable manner. Our project also addressed this matter, by investigating the steam consumption of the *Snamprogetti* wastewater treatment facility.

By modelling the *Snamprogetti* process, utilising Aspen Plus modelling software, it was determined that 12,500 kg/h of urea could be produced from 7600 kg/h of ammonia and 9200 kg/h of carbon dioxide. The steam consumption of this process was investigated and could be divided into 10 t/h of medium pressure steam demand and around 6 t/h low pressure steam demand.

By focusing on the steam consumption of the wastewater treatment section of the plant, it was identified that 6.8 wt% urea was evaporated during the final concentration stage of the process and entered the wastewater treatment facility. This wastewater required hydrolysing to ensure that less than 10 ppm urea was left in the process condensate to comply with emission regulations.

The idea of reducing steam consumption in the wastewater plant by reducing the urea concentration in the water requiring treatment led to the modelling of two possible improvements for the original plant design.

The improvements both relate to recycling the urea, which was evaporated in the vacuum section of the plant to ensure the urea does not enter the wastewater treatment section. The first solution was a scrubbing system modelled for the vacuum section. It was based on a concept developed by *Urea Casale* (the urea recycle system, URS) and produced wastewater containing 23 ppb urea. The second idea was an alternative to the scrubbing system, where condensers were used instead of scrubbers. This system produced water with 402 ppm urea.

Both systems were found to require less MP steam and more LP steam than the original model. The scrubbing system allowed for the complete removal of the hydrolyser, whereas the condensing system still required the unit to reduce the urea concentration in the effluent to safe levels. Therefore, the scrubbing system reduced MP steam consumption by 2000 kg/h, and the condensing system reduced MP steam consumption by 1800 kg/h. However, unlike the condensing system, the scrubbing system also required the introduction of 600 kg/h of water to supply the scrubbers with scrubbing medium.

Thus, the goal of reducing total steam consumption in the wastewater section was achieved by introducing either of the two urea recycle systems to the model. Despite the model not being a precise representation of reality, we therefore recommend the addition of either of these improvements to reduce MP steam consumption of the process.

To ensure the recommended solutions are financially attractive to potential investors, further research should be carried out on the cost and efficiency of the two alternatives regarding the equipment required in each case. The availability and price of resources (water, natural gas, steam) must also be taken into account to fully determine whether the calculated steam savings will translate to significant fuel savings in the utility section, as this will determine the extent to which the recommended recycling systems will improve the sustainability of the manufacture of urea.

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Abbreviation list

ASH	analyzer switch high	P	pressure
CEI	chemical exposure index	PAH	pressure alarm high
CFD	computational fluid dynamics	PAL	pressure alarm low
CSTR	continuous stirred-tank reactor	PFD	process flow diagram
CW	cooling water	P&ID	process and instrumentation diagram
EXPV	expansion valve	PI	pressure indicator
FEI	fire explosion index	PIC	pressure indicator controller
FI	flow indicator	ppb	parts per billion
FIC	flow indicator controller	ppm	parts per million
FPV	flow pneumatic valve	PPV	pressure pneumatic valve
FFC	flow fraction control	PSH	pressure switch high
FL	flow low	PSL	pressure switch low
HAZOP	hazard and operability study	PSV	pressure safety valve
HP	high pressure	PT	pressure transmitter
I	current	SV	safety valve
ISBL	inside battery limit	TAH	temperature alarm high
LAH	level alarm high	TAL	temperature alarm low
LAL	level alarm low	TE	temperature element
LH	level high	TIC	temperature indicator controller
LIC	level indicator controller	TPV	temperature pneumatic valve
LL	level low	TSH	temperature switch high
LP	low pressure	TSL	to safe location
LPV	level pneumatic valve	TT	temperature transmitter
LSH	level switch high	U	voltage
LSL	level switch low		
MED	medium		
MOC	material of construction		
MP	medium pressure		
MSDS	material safety data sheet		
NFPA	national fire protection association		
No.	number		
NRV	non return valve		
OSBL	outside battery limit		

Chapter 1. Introduction

Urea is an organic white compound manufactured worldwide, in various shapes and sizes, from ammonia and carbon dioxide. It is most commonly used by the agricultural industry as a fertilizer, but is also used as an intermediate product in the production of melamine and has thus found uses in the manufacture of plastics.²

Due to its importance in farming, the technology to commercially produce urea dates back to the early 1920s.¹ Over the lifetime of the process the technology has experienced many overhauls and had many improvements implemented. Urea was initially produced in a ‘once-through’ process, where any unreacted materials were discarded and the overall conversion of CO₂ to urea was around 75%. Today, the stripping technology and recycle processes, further discussed in the chemistry section of this report, have enabled conversions of up to 99%.¹

Due to the complexity of the modern day process, a variety of techniques to produce urea have been patented. The best-known licensors of the technology are *Saipem (Snamprogetti)*, *Stamicarbon*, and *Toyo-Engineering*.

To develop an understanding of the urea production process, the *Snamprogetti* technology licensed by *Saipem* was investigated and modelled in Aspen process modelling software. The aim of reproducing the *Snamprogetti* process was not only to gain an insight into the process, but also to identify any areas where improvements could be made in future to steer the plant in a more sustainable direction.

As was previously mentioned, many improvements have already been made and continue to be made by the licensors of the technology and engineering companies dedicated to revamping ammonia and urea plants. However, as society becomes more aware of its environmental footprint and the large part the chemical processing industry plays, the research for process improvements has become mainly focused on sustainability.

By modelling a 12500 kg/h urea producing plant and researching the chemistry, the technology, the equipment, and the hazards involved in the process, the areas of possible improvement were revealed. As high-utility consumption translates to unsustainable operation and high operating costs, the greatest steam users were identified as potential targets for process improvement.

It was decided to further investigate the steam supply to the wastewater section of the plant in order to limit the effect any possible improvements would have on the more complex urea producing and purifying sections of the plant.

With the incentive to improve the sustainable operation of the urea production plant and reduce the operating cost of the process, it was the purpose of this project to further investigate whether the steam demand of the wastewater treatment section could be reduced and provide insights and results formulated in this paper.

Chapter 2. Process and Technology

2.1 Chemistry

2.1.1 History

Urea has a long and interesting history. It was first discovered in 1727 by the Dutch scientist Herman Boerhaave, when he was able to isolate the compound from urine.^{3,4} A century later, in 1828, urea was synthesized in a chemical lab for the first time. The reaction, which was discovered by Friedrich Wöhler, was a milestone in chemistry, since it was now possible to make an organic compound from two inorganics substrates without the participation of living organisms. The reaction discovered by Wöhler is as follows:

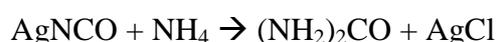


Figure 1: Friedrich Woehler reaction

Research on the synthesis of urea has continuously progressed since it was first discovered. In the beginning of the 20th century, urea was commercially synthesized by the hydration of cyanamide obtained from calcium cyanamide⁵:

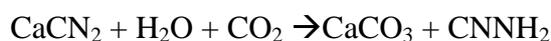


Figure 2: first commercial synthesis of urea

After the invention of the Haber-Bosch process in 1913, where ammonia is synthesized from hydrogen and atmospheric nitrogen on an industrial scale, both ammonia and carbon dioxide were easier to obtain. This made it possible to develop a new synthesis route for urea. The new route, invented in 1922, is known as the Bosch-Meiser process. In this process, ammonia and carbon dioxide are reacted in two reversible steps:

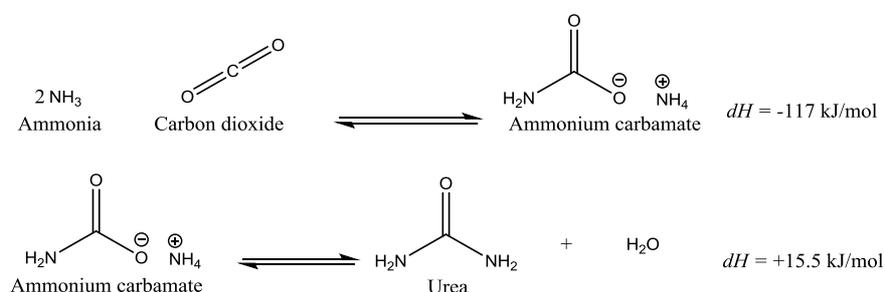


Figure 3: Bosch-Meiser process

First, liquid ammonia reacts with gaseous carbon dioxide, forming ammonium carbamate. This reaction is fast and exothermic. In the second slow and endothermic step, ammonium carbamate is decomposed to urea and water. The overall reaction is exothermic, since the

energy released in the first equilibrium reaction is much higher than the heat needed for the decomposition of ammonium carbamate (see Figure 3).

Although the total reaction is exothermic, full conversion of the substrates is never achieved. The conditions in the process should thus be chosen to increase the conversion towards urea as much as possible. However, the conditions that favor the first equilibrium are detrimental to the second one and the conditions that favor the second equilibrium negatively affect the first one.

The optimal conditions in the synthesis of urea are therefore a compromise: the reaction is carried out at high temperatures (around 190°C), which enhances the dehydration of ammonium carbamate, but diminishes the production of ammonium carbamate. This is compensated for by carrying out the reaction under high pressures, thereby shifting the first equilibrium towards ammonium carbamate formation. Furthermore, the vessel in which this reaction is carried out should be of a considerable size, to allow the slow formation of urea to reach equilibrium.

2.1.2 Development of commercial urea processes

Since the conversion of urea is incomplete, the product of the reaction should be purified and separated from unreacted ammonia, water and unchanged ammonium carbamate. In the past, the ammonium carbamate was separated by lowering the pressure to atmospheric conditions, so that ammonium carbamate could decompose to ammonia and carbon dioxide. This type of process is called “once-through”. Recycling the ammonia and carbon dioxide to make urea was not considered economical, since they would need to be compressed again. Thus, ammonia was used to make other products, like ammonium nitrate or ammonium sulfate, while carbon dioxide was thrown away.

After some years of research, some processes were invented where it was possible to reuse the substrates in the same process. This was done by depressurizing in stages: first to 18-25 bar and then to 2-5 bar. Afterwards, the solution was passed through a carbamate decomposer, from where the ammonia and carbon dioxide were recombined and passed through a carbamate condenser, whereas the remaining ammonium carbamate was recycled to the previous section.

This recycle process (known as “total recycle”) has two main disadvantages. Firstly, the flow scheme of such a process is rather complex, and so is the amount of process equipment needed. Secondly, since there is a considerable amount of water recycled in the carbamate solution, the conversion of urea is lowered, thereby lowering the overall efficiency of the plant. For this reason, in the early 1960s, the Dutch company Stamicarbon came up with the stripping concept. This invention not only solved both aforementioned issues, but also improved the heat recovery of the process.

The position of both equilibriums involved in the synthesis of urea depends on the partial pressures of the reactants. In the total recycle process, the overall pressure reduction lowers the partial pressure of both reactants, enhancing the decomposition of ammonium carbamate. The stripping concept works by not lowering the partial pressure of only one of the reactants. This is done by feeding carbon dioxide to the stripper and then rerouting it to the reactor, instead of feeding it directly to the reactor. This way, the ammonia in the stripper is ‘stripped

out', lowering the partial pressure of ammonia and thus enhancing the decomposition of ammonium carbamate.

The stripping technology was then modified by competitors, such as Montedison, Toyo Engineering Corporation, Urea Casale and Snamprogetti (now Saipem). For this project, the Snamprogetti technology was further investigated and modelled.

In contrast to other stripping processes, the Snamprogetti technology does not use carbon dioxide as stripping agent, but instead stripping is carried out with ammonia, or thermally. The stripping agent is also not fed directly to the stripper, as is the case with Stamicarbon technology, but instead the excess of ammonia present in the synthesis solution is used as 'self-stripping' medium.

2.2 Process Description

2.2.1 BFD of the process

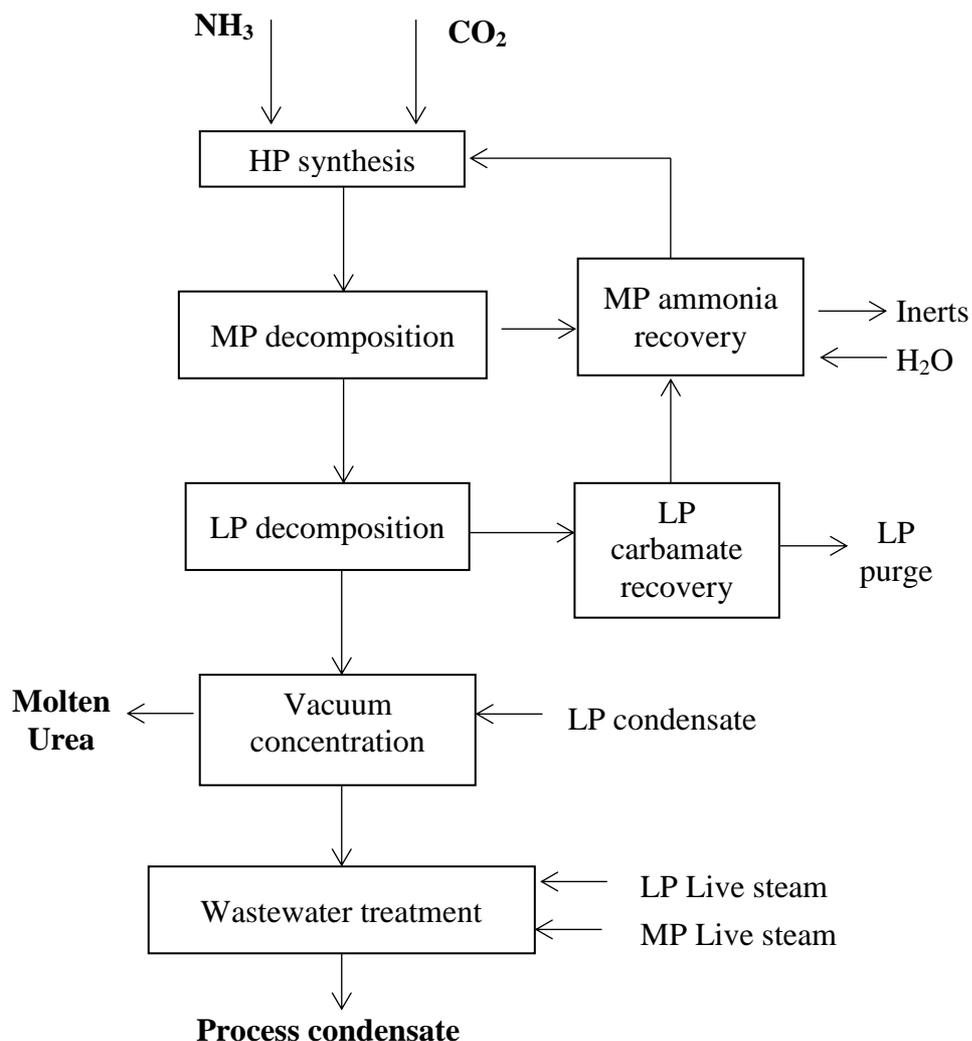


Figure 4: BFD of Snamprogetti process

2.2.2 PFD of the process

The Snamprogetti process is a urea manufacturing process that is designed to operate with an excess of ammonia. This ensures a high conversion of CO₂ in the reactor (65%), but requires an extensive network of purification steps and recycles to purify the product and increase process efficiency (see Figure 4). Below, a ‘walk-through’ of each of these sections is described, in order to clarify the process flow diagram (Figure 5).

Codes for the PFD:

High pressure section

R1101	Reactor
K1101	CO ₂ compressor
P1103	High pressure ammonia pump
EJ1101	Ejector
V1101	Carbamate separator
E1102	Stripper
E1101	High pressure carbamate receiver

Medium pressure section

V1201	Ammonia receiver
C1201	Medium pressure decomposer and rectifier
P1203	Ammonia booster pump
C1202	Ammonia-carbamate separation column
E1201	Medium pressure carbamate condenser
C1203	Scrubber
E1202	Ammonia condenser
P1202	Pump
P1201	High pressure carbamate pump

Low pressure section

C1301	Low pressure decomposer and rectifier
C1302	Preheater/ preconcentrator
E1301	Low pressure carbamate condenser
V1301	Low pressure carbamate receiver
P1201	Pump
P1202	Pump

Vacuum section

V1401	Vacuum evaporator
E1401	Heater
V1402	Vacuum evaporator
E1402	Heater
E1403	Condenser
E1404	Condenser
EJ1402	Vacuum ejector

Wastewater treatment section

T1501	Wastewater tank
E1501	Heat exchanger
C1501	Wastewater stripping column
R1501	Hydrolyzer
P1501	Pump
P1502	Pump
E1504	Heat exchanger
E1502	Heat exchanger
E1503	Condenser

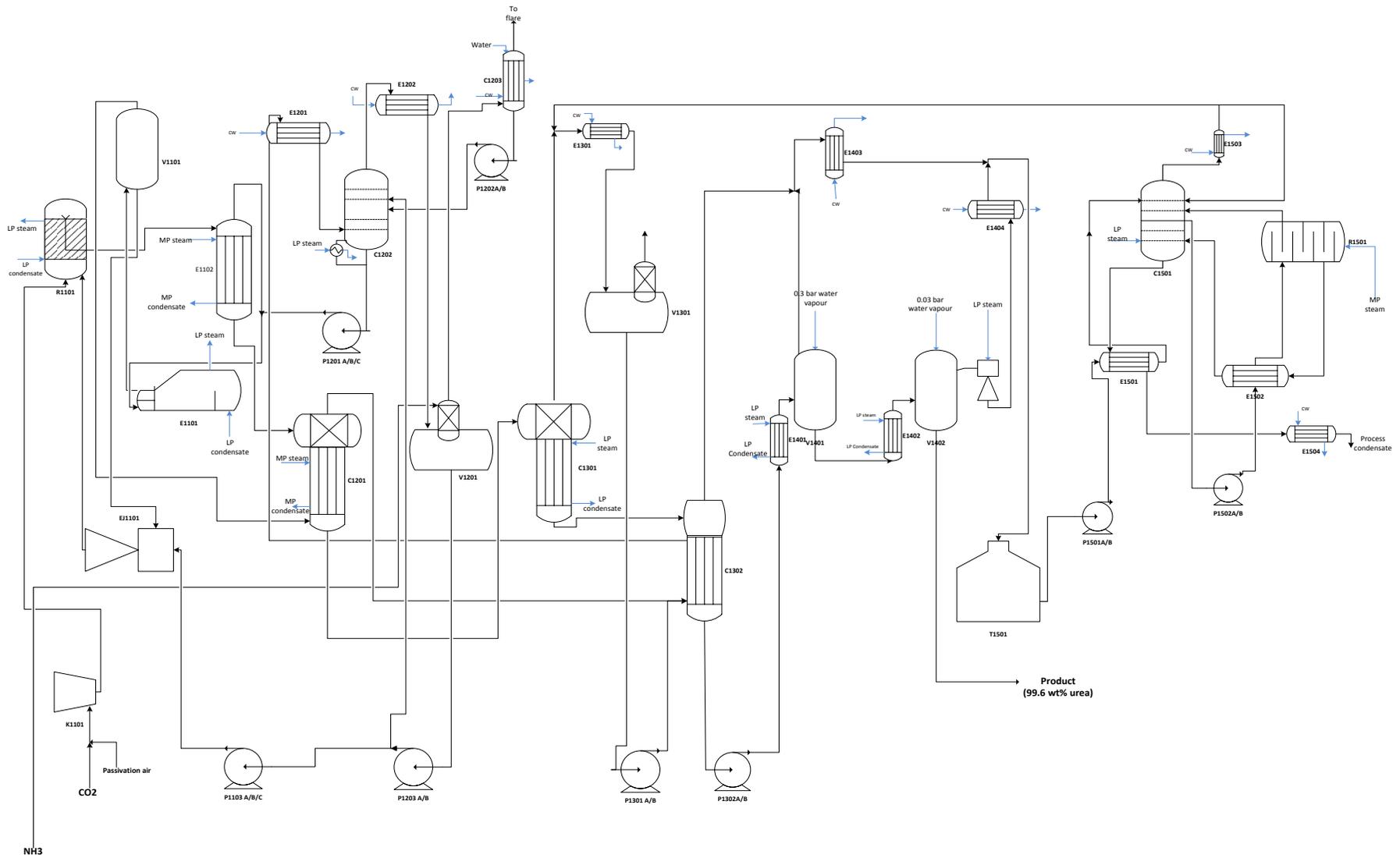


Figure 5: PFD of Snamprogetti urea production plant

2.2.3 High pressure section

In the HP section of the Snamprogetti process, the urea is synthesised from ammonia and carbon dioxide, at a pressure of 150 bar and at 188°C. These conditions are chosen as they best allow the simultaneous occurrence of the two reactions that form urea (as was explained in the chemistry section).

The CO₂ is fed directly into the reactor (R1101) after it leaves the compressor (K1101), whereas the ammonia is fed to the reactor from the ammonia receiver (V1201) in the MP section of the process. The ammonia is pumped to 200 bar in the high pressure ammonia pump (P1101) and fed through an ejector (EJ1101), where it draws in carbamate solution from the carbamate separator (V1101). The composition of these two streams determines the strictly regulated NH₃: CO₂ ratio inside the reactor and subsequently the conversion.

The stream leaving the reactor contains 34 wt% urea and the rest comprises ammonium carbamate, water and ammonia. To obtain a product that meets purity specifications, purification steps are needed, the first of these is the stripper (E1102).

The stripper is a falling film heat exchanger which facilitates the decomposition of ammonium carbamate into ammonia and CO₂. These gasses help strip additional ammonia from the liquid thereby purifying the product stream to the point where it contains 42 wt% urea. The off-gasses from the stripper are sent to the high pressure carbamate receiver (E1101), where they are condensed to form ammonium carbamate, which in turn is fed back into the carbamate separator and subsequently to the reactor. The urea solution coming from the stripper makes its way to the medium pressure section of the process.

2.2.4 Medium pressure section

The medium pressure section of the process contains only one unit for the purification of the urea solution, this unit being the medium pressure decomposer (C1201). However, it is a vital part of the plant since it ensures that pure ammonia and carbamate solution are recovered and fed back to the high pressure synthesis section.

As mentioned above, the only purification step occurs in the medium pressure decomposer, which purifies the urea solution to 62 wt% urea. The purified urea liquor then makes its way to the low pressure decomposer (C1301) and the resulting off-gasses are transferred to the shell of the preheater (C1302), where they are absorbed and react, thereby heating the endothermic reaction occurring within the unit. This procedure helps to increase the energy efficiency of the plant.

The MP section also receives the fresh ammonia feed for the entire plant. As mentioned before, it is fed into the ammonia receiver (V1201) from where it is fed back to the rest of the process by the ammonia booster pump (P1203). This flow is split before it enters the high pressure ammonia pump and a fraction is fed into the ammonia-carbamate separation column (C1202).

The carbamate solution coming from the shell of the preheater and subsequently the MP carbamate condenser (E1201) is fed into the bottom of the column, whilst the aqueous

ammonia solution coming from the scrubber (C1203) and the liquid ammonia from the receiver are fed into the top. The column is a necessary step in recovering pure ammonia, by separating it from the rest of the recycled solution. This results in a flow of carbamate solution being fed to the high pressure carbamate condenser and a stream of pure ammonia going back to the ammonia receiver via the ammonia condenser (E1202). In the ammonia receiver any remaining vapours (inerts and ammonia) are released to the scrubber, where the inerts are scrubbed of ammonia before being emitted (or flared).

2.2.5 Low pressure section

The LP section is the last section that is aimed at the decomposition of ammonium carbamate to purify the product. This purification occurs within in the low pressure decomposer (C1301), where the urea liquor is purified to 69 wt%. The resulting urea solution moves into the preheater (C1303), where its purity is raised to 86 wt% before it is transferred to the vacuum evaporation section.

The off-gasses from the low pressure decomposer are fed into the low pressure carbamate condenser (E1301) together with the waste water recycle and subsequently into the carbamate receiver (V1301). From the carbamate receiver the carbamate solution will make its way into the preheater shell where it will mix with the medium pressure decomposer off-gas to form a carbamate solution of higher concentration. This solution is transported to the ammonia carbamate separation column, as was described above.

2.2.6 Vacuum evaporation section

The vacuum evaporation section is, as the name suggests, aimed at concentrating the urea solution through evaporation of any remaining water. The preceding steps sufficiently reduce the ammonia and ammonium carbamate content, making water the biggest contamination of the product.

The urea liquor is transported from the preheater into the first vacuum evaporator (V1401) through a heating element (E1401). The lower pressure of 0.3 bar will ensure that enough water evaporates to increase the purity to 96 wt% urea. The last evaporation step consists of a similar setup, with a vacuum evaporator (V1402) and a heating exchanger (E1402), only the pressure is even lower (0.03 bar) in order to evaporate the last remnants of water and increase the purity of the urea up to 99 wt%.

The evaporated water is brought to atmospheric conditions and condensed in two heat exchangers (E1403 and E1404), before it is sent to the wastewater treatment section.

2.2.7 Wastewater treatment section

The wastewater treatment section is required to ensure that the water that is released from the production process meets environmental standards and to reduce losses of feed materials.

The water coming from the vacuum evaporation section enters a tank (T1501) that ensures the wastewater treatment section does not suffer from fluctuations in flow. From there it is

fed into a heat exchanger (E1501) to take heat from the outgoing clean water and reduce energy consumption.

The heated water then enters a stripping column (C1501), where the ammonia and CO₂ are separated from the water. In the center of the column there is an outflow that leads to the hydrolyzer (R1501), a reactor that decomposes the urea and carbamate into their base components. The water from the hydrolyzer is fed back into the stripping column to ensure the separation of the ammonia and CO₂. The stripping column has two major outflows: one at the top, consisting of water with ammonia and CO₂ in high concentration, a portion of which is recycled back to the LP section of the plant, and one at the bottom, which is the cleaned water that is released from the plant.

The process streams will be followed in closer detail, and the equipment introduced above will be explained further in the following technology section.

2.3 Technology

The conditions required to successfully convert ammonia and carbon dioxide to molten urea of 99.6 wt% purity are severe, ranging from 0.03 bar to 150 bar and 40°C to 200°C. These conditions and the highly corrosive intermediate product, carbamate, necessitate the use of unique equipment, constructed of appropriately strong and highly corrosion resistant material (for further details on the equipment MOC and dimensions see the equipment list in chapter 5).

7600 kg/h ammonia and 9200 kg/h carbon dioxide are supplied to the urea plant by a nearby ammonia plant (OSBL). The ammonia stream, containing some impurities (2% methane), is sent directly to the MP ammonia receiver (V1201) from where it is distributed throughout the plant. The carbon dioxide is combined with a degree of passivation air, a measure to provide corrosion protection to the at-risk vessels, before being fed to a compressor.

2.3.1 High pressure synthesis section

The high pressure synthesis section starts with the CO₂ compressor, this compressor raises the pressure of the CO₂ and the incorporated 0.25 vol% passivation air from 5 bar to 150 bar. The compressor can be driven by either a steam turbine or an electrical motor, each of which has their own advantages and disadvantages.

When selecting a piece of equipment as expensive as the compressor, it is important to carefully weigh up all factors. Selecting a steam turbine would result in a big supply of low pressure steam for use elsewhere but the trade off would be a compressor that requires a lot of maintenance and with a down time ranging from 1 to 30 days. Selecting an electrical compressor would mean that there is no excess of low pressure steam but the compressor will be more energy efficient and has a lower downtime of half an hour on average.¹

The compressor consists of 4 stages with intercooling to increase the efficiency and subsequently decrease the power consumption of the compressor. The material of the

compressor must be able to withstand high temperatures and pressures up to 180°C and 150 bar.

The compressed CO₂ enters the bottom of the reactor. The reactor is an equi-current bubbling column, meaning that the CO₂ and the ammonia and carbamate solution enter the reactor from the bottom and leave at the top. This setup causes the reactor to exhibit plug flow behavior, and the added Snamprogetti™ supercup trays help to maintain this behavior. The supercup trays also serve several other purposes: they ensure uniform gas distribution between stages and are able to determine the CSTR and PFR behaviour of each stage as seen in Figure 6.

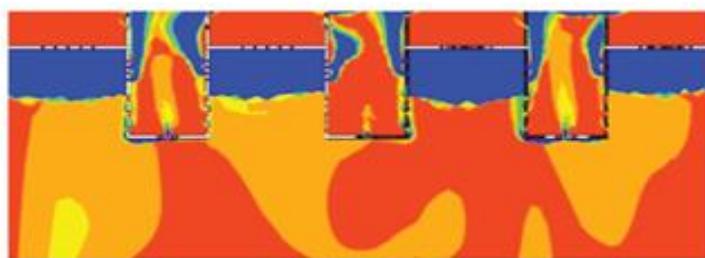


Figure 6: CFD image of supercup trays in the reactor⁶

Figure 6 also illustrates the final function of the supercup trays. The cups act as small CSTRs within the reactor, as they are confined spaces that have near perfect mixing and can increase the residence time up to 70%⁶. This allows the residence time in the reactor to remain 25 minutes whilst keeping a smaller reactor¹.

The increased residence time combined with the high operating temperature of 188°C, pressure of 150 bar and an ammonia:carbon dioxide ratio that is kept at the optimum of 3.2-3.6⁷ ensures a high conversion in the reactor (65%)⁸. These harsh conditions warrant a suitable material of construction such as 25-22-2 CrNiMo with a titanium or zirconium lining.

The urea solution leaving the reactor which contains about 34 wt% urea is led to the stripper where it is purified by removing and recycling the excess carbamate, ammonia and CO₂. The stripper is a falling film type heat exchanger that operates at the same pressure as the reactor and concentrates the urea solution to 43 wt%. The impurities are removed by adding medium pressure steam to the shell of the stripper which allows for the endothermic decomposition of ammonium carbamate. The released ammonia and CO₂ act as stripping agents for the down-coming liquid, which pools in the bottom of the stripper to prevent gas from flowing to the medium pressure decomposer.

Like the reactor, the stripper is subjected to harsh conditions of 150 bar and temperatures up to 205°C. Combined with the highly corrosive ammonium carbamate present in the solution, these conditions have up until recently significantly reduced the lifespan of the stripper. The stripper was commonly flipped every two years to ensure corrosion and erosion of the tubes would occur equally to all areas of the unit and to increase the lifespan of the stripper, this was a tedious and costly practice. This problem has been averted with the introduction of Omagabond® by Saipem. Omagabond consists of grade 3 titanium and zirconium 702, increasing the lifespan of the stripper from 5-10 years up to at least 25 years⁹.

The gasses released from the stripper are fed into the high pressure carbamate condenser together with the carbamate solution coming from the separation column. The carbamate condenser is a kettle reboiler with the carbamate solution flowing through the tubes and the hot water residing in the shell. Inside the carbamate condenser the ammonia and carbon dioxide are condensed to form ammonium carbamate through an exothermic reaction, the heat of this reaction is used in the formation of low pressure steam (4.5 bar, 147°C) for other parts of the plant.



Figure 7: HP carbamate condenser during transport¹⁰

By using the exothermic carbamate formation within the condenser to heat LP condensate, it is possible to almost completely regain the heat lost in the decomposition of ammonium carbamate in the medium pressure decomposer. This vastly increases the overall efficiency of the plant and diminishes the amount of fuel needed in the boilers. Again, the presence of carbamate, temperatures of 150°C and pressures of 150 bar require a MOC like Omegabond or 25-22-2 CrNiMo with a titanium or zirconium lining.

The carbamate solution coming from the carbamate condenser is transported to the carbamate separator where the remaining gases are separated from liquid. The only function of this vessel is to separate the gases and liquids coming from the carbamate condenser. The liquids are then recycled back to the reactor through the ejector. The gases on the other hand are fed into the medium pressure decomposer, to act as stripping agents and to reduce the heat requirement for the decomposition of ammonium carbamate.

In the ejector (Figure 8) the high pressure ammonia is fed through a nozzle thus increasing the speed of the liquid and lowering the pressure. This creates a small suction on the line perpendicular to the ammonia feed, thereby drawing in carbamate solution from the separator. The ejector acts as a mechanical pump by transporting the carbamate solution to the reactor by mixing it with the ammonia flow.

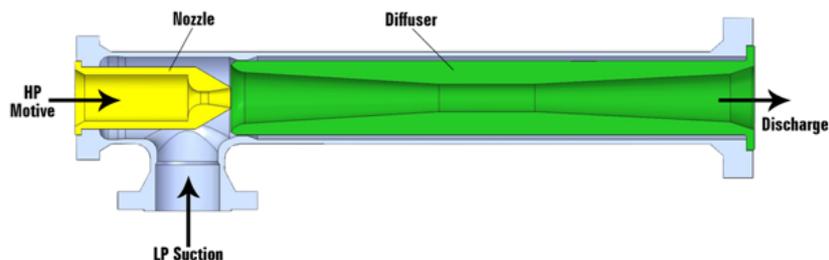


Figure 8: ejector¹¹

The high pressure ammonia pump is a reciprocating pump or plunger pump that receives ammonia from the ammonia receiver and increases its pressure from 18 to 200 bar. The plunger pump has a seal that is stationary and the plunger moves through the seal creating the positive displacement of the liquid. Plunger pumps are well suited for the range of operation required, since they are capable of dealing with high pressures however it is advised to run two pumps in parallel since reciprocating pumps are better suited for lower volumetric flows than centrifugal pumps.

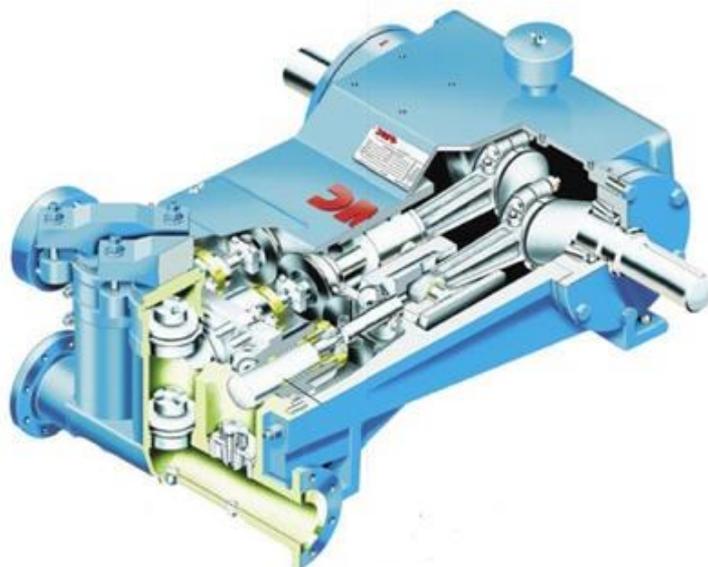


Figure 9: Plunger pump, showing internals¹²

2.3.2 Medium pressure purification and ammonia recovery section

The 42 wt% urea solution exiting the bottom of the HP stripper at 150 bar is let down to 18 bar through an expansion valve, before it enters the MP decomposer. The purpose of the MP decomposer is to concentrate the solution to 62 wt% urea, by decomposing residual carbamate.

The MP decomposer is divided into three units (Figure 10); the solution is fed into the top separator section where free NH_3 and CO_2 are flashed, whilst the rest of the solution passes through pall ring packing and is distributed through ferrules to the falling film type heat exchanger middle section. The carbamate within the solution undergoes endothermic decomposition to NH_3 and CO_2 as the falling film is heated by MP steam (shell side) and heated and stripped (tube side) by the counter-current gases coming from the HP carbamate

separator. The solution is then collected for a short time in the holder section of the unit to achieve a liquid level thus, ensuring no vapour escapes to the LP section¹³. Upon exiting the MP decomposer, the 62 wt% urea solution passes through an expansion valve to the LP purifying section.

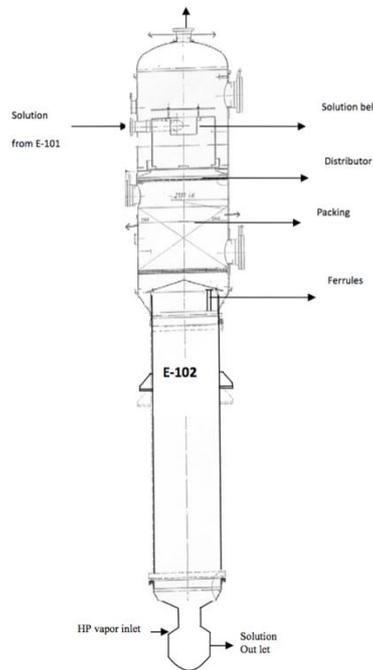


Figure 10: diagram of MP decomposer¹³

The MP decomposer must be designed to withstand temperatures up to 210°C and 18 bar pressures. These conditions have led to the development of improved stainless steel varieties between the various urea licensors and material vendors (see equipment list in chapter 5 for details). For example, VRV S.p.A. constructs MP decomposers from the high corrosion resistant, high strength 25-22-2 CrNiMo (Figure 11).



Figure 11: Transport of a MP decomposer¹⁴

Another important design aspect of this unit is limiting the hold-up of the urea solution in the bottom section, as long residence times at high temperatures increase the formation of the unwanted side product, biuret.

The top product of the MP decomposer consists of free gases (mainly NH_3) released during initial flashing of the urea solution coming from the HP stripper, and the NH_3 and CO_2 resulting from the decomposition of carbamate. These gases are transferred to the shell of the pre-heater (C1302), found at the beginning of the vacuum section, in order to save utility cost.

The gases are mixed with a solution of carbamate exiting the LP carbamate receiver (V1301, see LP description below for details) and are partially condensed, thereby partially reacting to form carbamate. By performing this condensation and exothermic reaction in the shell of the preheater, the heat required to further concentrate the urea solution therein must not be supplied by steam⁸.

Upon exiting the pre-heater shell, the partially condensed gases enter the MP carbamate condenser where the corrosive stream is further condensed, leaving at 75°C to enter the bottom of the ammonia-carbamate separation column (C1202).

The separation column is an integral part of the NH_3 recovery section operating within the MP section of the plant. It is designed to separate carbamate solution and CO_2 from pure NH_3 , thereby providing the pathway for unreacted NH_3 liquid to be returned to the reactor.

The distillation column has three inputs to ensure satisfactory separation. The mixed phase carbamate solution coming from the MP carbamate condenser is fed into the bottom of the column, whilst a fraction of the cool stream of pure liquid NH_3 leaving the ammonia receiver (V1201) is fed to the top of the column and a stream consisting largely of water from the scrubber (C1203) enters just below.

The free gases remaining in the carbamate solution exit the solution upon heating and rise through the bubble-cap trayed column. The CO_2 , NH_3 , inerts and water vapour meet the downcoming flow of NH_3 and water and are cooled and condensed, thus the NH_3 and CO_2 react to form carbamate. This process of absorption, condensation and reaction ensures only NH_3 and inerts remain to exit the top of the column¹⁵.

The resulting bottom product is ammonium carbamate solution (12 t/h), which is recycled via a centrifugal multistage HP carbamate pump (P1201) to the HP carbamate condenser. Industry uses a variety of corrosion and erosion resistant materials for this heavy duty pump, for example vendor Sundstrand USA produces multistage centrifugal pumps, for this purpose, from Duplex SS 16¹⁷.

Temperatures experienced within this unit range from $45 - 75^\circ\text{C}$, considerably lower than those for the MP decomposer however, due to the corrosive carbamate solution and the operating pressure of 18 bar the column requires MOC similar to the decomposer.

It is also important to ensure the carbamate solution exiting this column is at a temperature and of a composition at which the carbamate therein is dissolved, thus avoiding crystallization and clogging of the bubble-cap trays within the column and also the connected piping and pumping equipment. The required water content is a complex relationship between the amount of carbamate, NH_3 , CO_2 , and water found in the solution (further details on carbamate composition out of this unit can be found in the MP section of appendix 2)¹⁸.

The 7000 kg/hr gaseous ammonia and inerts leaving the separator are transferred to the ammonia condenser (E1202), in order to turn the condensable gases at 45°C into liquid NH₃ at 40°C, which is then fed to the ammonia receiver.

Despite the small temperature change, the condenser requires a large surface area to provide the necessary heat exchange (see equipment list in chapter 5). The incorrect composition of the gases (inclusion of CO₂ in NH₃ stream) entering the condenser could result in a dangerous situation of carbamate formation and crystallization upon condensation thus, accessibility for maintenance should be considered when designing the ammonia condenser¹⁹.

The ammonia receiver (V1201) is a vessel in the MP section which receives pure feed NH₃ from the ammonia plant (OSBL) and recycled NH₃ with inerts from the ammonia condenser. The receiver vessel not only provides the storage for the recovered NH₃, but also ensures the NH₃ is supplied to the process at constant pressures. This is important for the reliable operation of pumping equipment and the units being supplied¹⁶.

The ammonia receiver is also designed to provide the urea plant with a degree of independence from the ammonia plant. In industry these vessels are built to be approximately half full during normal operation, and must be of a capacity to ensure between 30 and 60 minutes of continuous supply of liquid NH₃ to the process during no feed situations¹⁶. These conditions require the horizontal vessel to be around 50 m³ (see equipment list in chapter 5).

A large tank of liquid ammonia is a serious hazard in the case of necessary or accidental pressure letdown, as the volume of NH₃ will vapourize (see the safety reports in appendix 3 for details) thus, pressure indicators, PSVs and connections to appropriate emergency absorbing systems (OSBL) are essential for this vessel.

During normal operation, the inerts entering the receiver exit through the recovery tower situated atop the receiver (Figure 12). Due to a substantial amount of NH₃ exiting the horizontal vessel along with the CH₄, N₂ and O₂, the design of the packed tower is such that the NH₃ feed entering the receiver is in fact fed through the top of the tower to condense the rising NH₃ vapours, before the remaining gases are released to the scrubber. From literature, the appropriate packing for the tower are raschig rings²⁰.

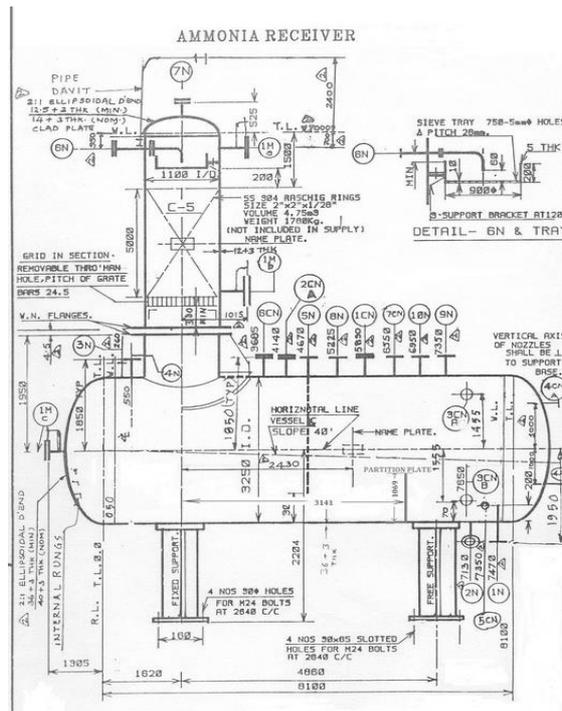


Figure 12: Technical drawing of ammonia receiver ¹⁶

The inerts are released to the scrubber (C1203), whilst the pure NH₃ is distributed from the vessel with means of a centrifugal pump (P1203) to the ammonia-carbamate separation column and to the HP reaction vessel. The pump is not a heavy duty pump as it is only required to overcome pressure drop in the pipes (see equipment list).

The inert gases leaving the ammonia receiver are still saturated with NH₃, as the recovery tower is not able to efficiently remove much of the NH₃. Therefore, the gas stream must be scrubbed before it can be purged to the environment, or sent to a flare.

Thus, water is fed to the top of a scrubbing column fitted with valve trays, to absorb the rising NH₃ gases ¹⁵. The purge must be monitored by concentration analysis to ensure the plant is operating within environmental regulations, regarding allowable NH₃ emissions. Industry suggests all vents of a urea plant should release no more than 2-4 kg/h of NH₃ ²¹. The desired purge concentration is achieved through the addition of high volumes of scrubbing water (750 kg/h) to the top of the column.

The bottom part of the scrubbing column is fitted with an area of heat exchange, such that the heat of absorption of ammonia in water can be controlled. The 65°C aqueous ammonia stream is then recycled to the ammonia-carbamate separator by pump (P1201). Again, this is not a heavy duty pump, as it is required only to overcome frictional losses in the piping system and must deal with a relatively low volume of non-viscous medium.

The size of the scrubbing tower is very much dependent on the volume flow of vapours which require scrubbing. Therefore, the design of this column will depend on the amount of inerts introduced to the system.

2.3.4 Low pressure purification section

The solution coming from the medium pressure decomposer (C1201), which contains 62 wt% of urea, is led to the top part of the low pressure decomposer and rectifier (C1301). In the top part of the vessel, the released flash gasses are removed²², while the remaining liquid flows down the tube side of the falling film part of the low pressure decomposer. While flowing down the decomposer, the remaining ammonium carbamate is decomposed to ammonia and carbon dioxide. This is an endothermic reaction, and so low pressure steam is fed to the shell side of the decomposer to supply the heat needed. The bottom product, which is now 68 wt% urea, is then sent to the preheater, where further decomposition takes place.



Figure 13: LP decomposer¹⁴

The released flash gasses, which are mainly composed of ammonia, water and carbon dioxide, are then mixed with the gasses coming from the wastewater treatment section and condensed in the tube side of the low pressure carbamate condenser (E1301). This is done by using cooling water. The condensed stream (with a vapor fraction around 11%) then flows to the low pressure ammonium carbamate receiver. This vessel, which is kept at 40°C and the same pressure as the low pressure decomposer and rectifier and the low pressure carbamate receiver (4.5 bar), is designed in such a way that, in case of shutdown, the vessel could hold the carbonate solutions in the entire plant¹⁵.

Furthermore, since the amount of ammonium carbamate in the receiver is substantial (around 30 wt%), choosing the correct material of construction is important. To avoid any corrosion and thus to maintain the low pressure carbamate receiver for a long time, an appropriate MOC should be a high corrosion resistant material, like for instance Safurex.

Next to storing the carbonate solution, the vessel also separates ammonia from the inerts, by feeding fresh water to the top of the packing. This way, the remaining ammonia in the inert gas stream is dissolved, while the remaining inerts (O₂, CO₂, N₂) are purged to the atmosphere¹⁹. The bottom effluent of the receiver is then pumped to the shell side of the preheater (C1302), where it is mixed with the released flash gases from the medium pressure decomposer. In the shell side of the preheater, the remaining ammonia and carbon dioxide are reacted to ammonium carbamate, and the whole solution is condensed. This way, heat is supplied to the tube side of the preheater.

In the tube side of the preheater (also known as pre-concentrator), the urea solution coming from the low pressure decomposer (which was first expanded from 4.5 bar to 0.34 bar) is further concentrated¹⁵. First, the released flash gases are separated in the top, and thereafter they are fed to the condenser (E1403) in the vacuum section and subsequently treated in the wastewater treatment section. The bottom effluent of the preheater, which is now 87 wt% urea, is then further purified and concentrated in the vacuum section.

2.3.5 Vacuum purification/evaporation section

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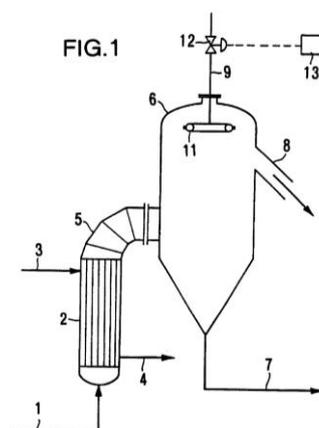


Figure 14: Vacuum evaporator²³

The 86 wt% urea solution leaving the preheater will enter the first evaporator apparatus. In the heat exchanger section the solution goes through the tubes and the temperature is raised to 130°C. In the tubes the stream is expanded from 0.25 to 0.5 bar. The heating of the apparatus is achieved by condensing low pressure steam. In the heat exchanger a part of the solution evaporates.

This mixture is then led to the cyclone. Where a difference in density is used to separate the two phases. The gases will go up with centripetal force and the liquids will go down within the cyclone. The extra water inlet is to prevent fouling of the upper part of the cyclone. This fouling consists of biuret and other derivatives of this product. The fouling isn't substantial but will build up in time. The water vapour will go through the nozzles at the top of the vessel. This can be done toroidal or axial.²³ The evaporators are also designed to accommodate tracing, in order to maintain the temperature therein²⁴. The resulting liquid phase will thus be concentrated to 96 wt% urea. The MOC for these units is stainless steel.²⁵

This highly pure solution will leave through the bottom and go to the next evaporation stage, where it enters a similar unit of a different size, temperature and pressure. The vapour phase from the first evaporator will go to a condenser, which also operates at sub-atmospheric pressures. In this condenser the vapours from the preheater are also condensed.

In the second evaporator unit the process flow will again first go through a heat exchanger part. There it is heated to 134-144°C. The vacuum is supplied by a steam ejector system and is 0.02-0.1 bar. The steam ejector system requires at least two stages to reach this vacuum.²⁶ The fouling in the top of the unit is worse at higher temperatures and lower pressures. So again, a water vapour inlet at the top is required to reduce the crystallization of biuret and related compounds.

The resulting liquid product flowing out of the bottom of the second evaporator will be pure enough for sale or further use in the melamine plant. The urea weight percentage achieved at the end of the purification process is ~99.6%.

The vapours from the second gas-liquid separation cyclone will mix with the steam in the steam injector and this mixture will be condensed in a second condenser. The condensed stream will go to the waste water tank to be treated in the waste water treatment section.²⁷

2.3.6 Waste water treatment section

The condensed vapors from E1403 and E1403 consist of 6.8 wt% urea and 5.3 wt% ammonia. This concentration is unsafe to be released into the environment. In the wastewater treatment section, ammonia and CO₂ is stripped out the water and recycled to the synthesis part, while urea is hydrolyzed and decomposed. The concentration of urea and ammonia in the purified water should meet the specification to be released in the environment.

In the Netherlands, the total amount of nitrogen in wastewater is legislated to be less than 15 mg/L. This could mean either 18 ppm ammonia or 32 ppm urea²⁸. In this plant the target is to get both ammonia and urea below 10 ppm.

The wastewater is collected in a tank (T1501), which is able to store wastewater in case more wastewater is produced or the wastewater section has to shut down.

The treatment can be specified in three parts. The first part is the top section of the stripping column (C1501). Before the wastewater enters the top of C1501, it is pumped to 4.5 bar by P1501 and preheated in E1501. The purpose of the top part of C1501 is to strip the wastewater from ammonia. It is stripped by the vapor from the bottom part of C1501 and by the vapor from the hydrolyzer (R1501). The effluent of the top part of C1501 is going to the hydrolyzer (R1501) and the top vapor is condensed in E1503 and partially refluxed and partially recycled to the carbamate condenser (E1301), to be ultimately fed to the reactor.

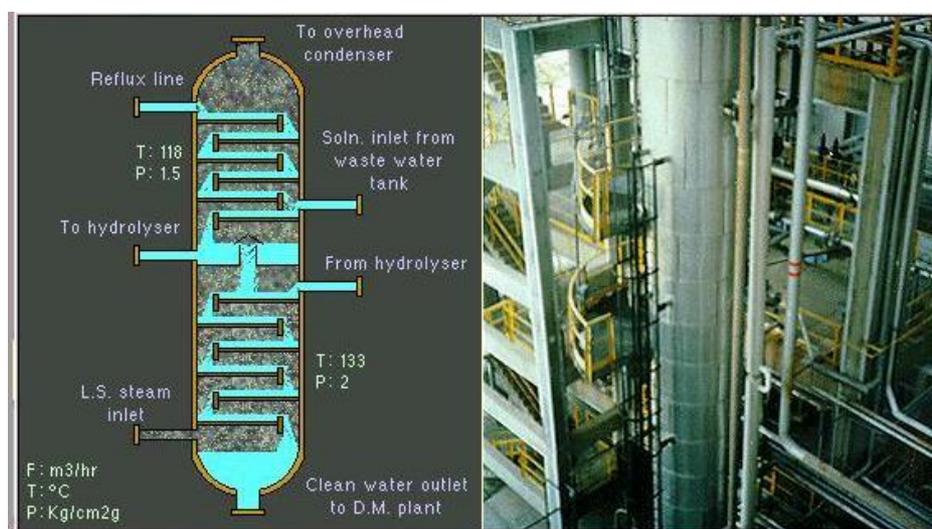


Figure 15: wastewater stripping column C1501²⁹

The effluent of the top part of C1501 is pumped to 20 bar by P1502 and preheated in E1502 before entering the hydrolyzer (R1501), which can be considered the second stage. In the hydrolyzer, urea is hydrolyzed to carbamate and carbamate is decomposed into ammonia and CO₂, which is the reverse reaction occurring in the reactor (R1101).

The overall reaction in the hydrolyzer is endothermic. The heat required to achieve a temperature of 200-240°C, is supplied by MP live steam, which also acts as a stripping agent. The pressure at which the hydrolyzer is operated is 20-40 bar and the residence time 20-40 min. The hydrolyzer consists of a horizontal cylindrical reactor with 8-12 vertical baffles, to achieve plug-flow behavior, as can be seen in Figure 16.

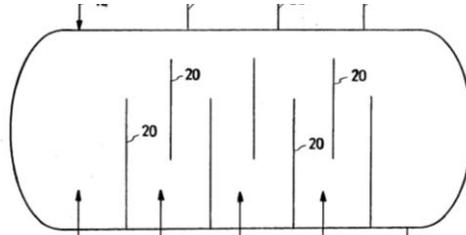


Figure 16: hydrolyzer³⁰

The top vapor of the hydrolyzer is fed to the bottom stage of the top section of C1501, to supply heat and act as a stripping agent. The effluent is fed to the top of the bottom section of C1501 after cooling down in E1502 in which it provides heat for the incoming stream for the hydrolyzer.

In the bottom part of C1501 the remaining ammonia and CO₂, which is produced in the hydrolyzer, is stripped out of the water. Live steam is used as heat supply and stripping agent. The top vapor is fed to the top section of C1501. The purified water is cooled down in E1501, in which it provides heat for the incoming stream of the top section of C1501. The process condensate is cooled down further in E1504 to finally be released in the environment.

2.3.7 Piping

Piping will not be discussed throughout the remainder of this report however, it is important to note that the piping system will be subject to the same harsh process fluids and process and atmospheric conditions as the rest of the plant and thus compatible MOC must be chosen for all pipes. Mannesmann for example, produces piping for the urea process from stainless steel grade UNS S31050, the same material used to construct and combat the highly corrosive conditions of many of the units described above³¹.

The product stream of increasingly pure molten urea transferred through each section of the process places further demands on the pipes conveying this fluid. The molten urea is maintained at temperatures not far above crystallization point (this point depends on the water/ urea concentration of the solution, see appendix 4 for details) to ensure the stream remains molten, but to avoid side reactions which occur at increasing temperatures. Thus, the affected pipes must be jacketed in order to maintain the desired temperatures³².

Chapter 3. Utilities

3.1 Utility Requirements

Table 1: Utility demand and production

Utility	conditions	kW	kg/h
MP steam required	225 °C, 25.5 bar	4257	8106
MP live steam required	225 °C, 25.5 bar	1050	2000
LP steam required	148 °C, 4.5 bar	2400	4019
LP live steam required	148 °C, 4.5 bar	1403	2350
LP steam produced	148 °C, 4.5 bar	2210	3701
Cooling water	25 °C, $\Delta T = 10^{\circ}\text{C}$	$1.18 \cdot 10^4$	$1.02 \cdot 10^6$

3.2 Utility Specification

3.2.1 Medium pressure steam

The medium pressure steam required in the urea plant is produced in a boiler, burning natural gas. The conditions at which it is modelled is at 225 °C and 25.5 bar.

Medium pressure steam is required in E1102 and C1201 for heat and in R1501 as live steam, as can be seen in Figure 17. The total MP steam requirement is $1.011 \cdot 10^4$ kg/h. The MP steam condensate produced is 8106 kg/h and is at 225 °C and 25.5 bar. This is returned to the boiler feed water system after it is vented in a flasher, to remove inert gasses. Also 318 kg/h LP steam condensate is returned to the boiler, see Figure 21. The remaining 1682 kg/h of boiler feed water has to be bought in.

The MP steam grid is connected to the LP steam grid by an expansion valve. The expansion valve opens if the pressure difference is too high between the MP and LP grid. If the pressure difference is too high, this means that there is too much MP steam produced, which increases the pressure in the MP steam grid and/or the LP steam supply is insufficient.

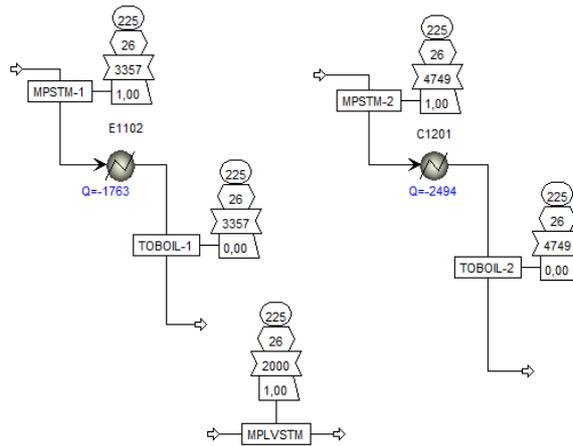


Figure 17: Aspen model of total MP steam consumption

3.2.2 LP steam

The LP steam required in the plant is modelled to be at 148°C and 4.5 bar. A total of 6369 kg/h is required, of which 3701 kg/h is produced in E1101 and R1101, as can be seen in Figure 18. The remaining 2668 kg/h has to be bought in from neighboring plants.

To not be dependent on neighboring plants, the capacity of the boiler of MP steam should be high enough to produce 2668 kg/h additional, which is fed to the LP steam grid through an expansion valve to produce LP steam. However, as many plants produce an excess of LP steam, purchasing the remaining requirement could be the cheapest alternative.

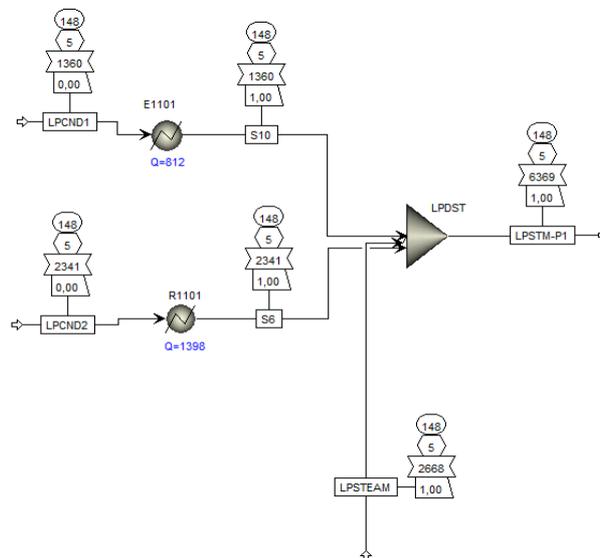


Figure 18: LP steam input

LP steam is required for heating in C1202, C1301, E1401 and E1402, as can be seen in Figure 19. This produces a total of 4019 kg/h of LP steam condensate. From the LP steam

condensate 3701 kg/h is recycled to E1101 and R1101 to produce LP steam. The remaining 318 kg/h is sent to the reboiler to produce MP steam, as can be seen in Figure 21.

A total of 2350 kg/h of LP live steam is required in C1501, V1401, V1402 and EJ1401, as can be seen in Figure 20.

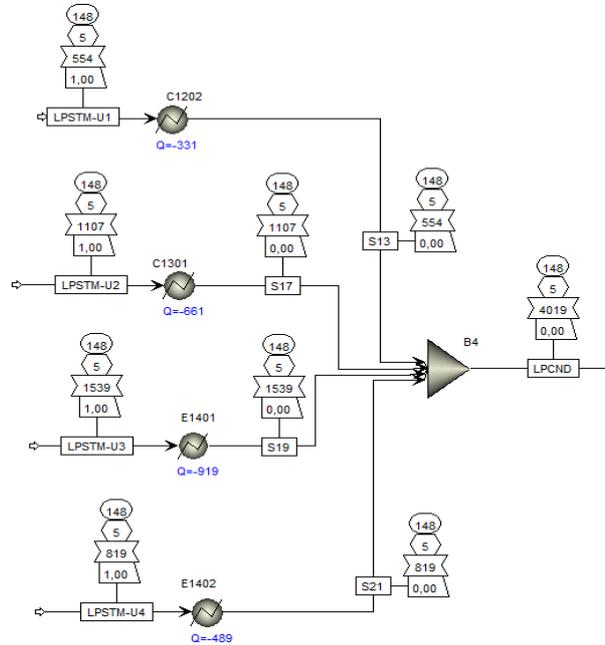


Figure 19: LP steam consumption

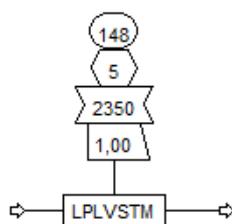


Figure 20: LP live steam consumption

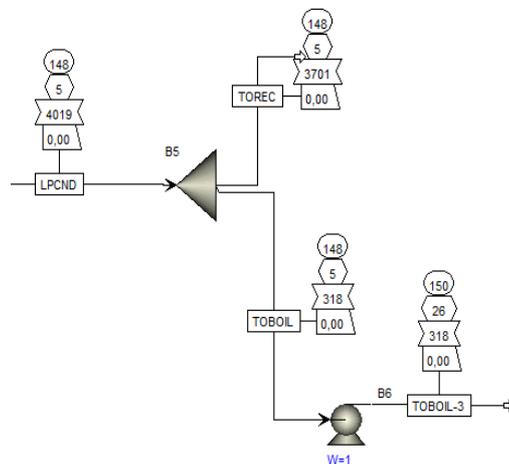


Figure 21: LP condensate distribution

Chapter 4. Mass and Energy Balance

4.1 Aspen PFD

The diagram below is an overview of the entire process, to give an indication of where the sections which will be referred to hereafter can be found in the Aspen file. The five main sections have been indicated in colour and are shown in closer detail below. For a review on how the units of each section were modelled in Aspen see appendix 2.

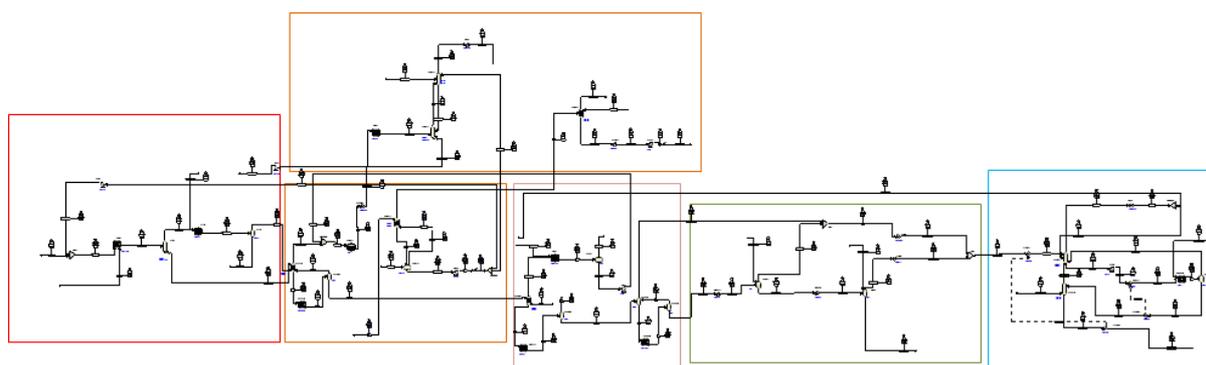
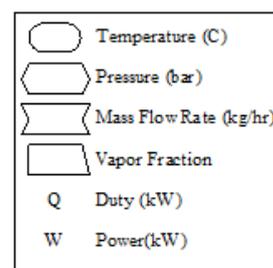
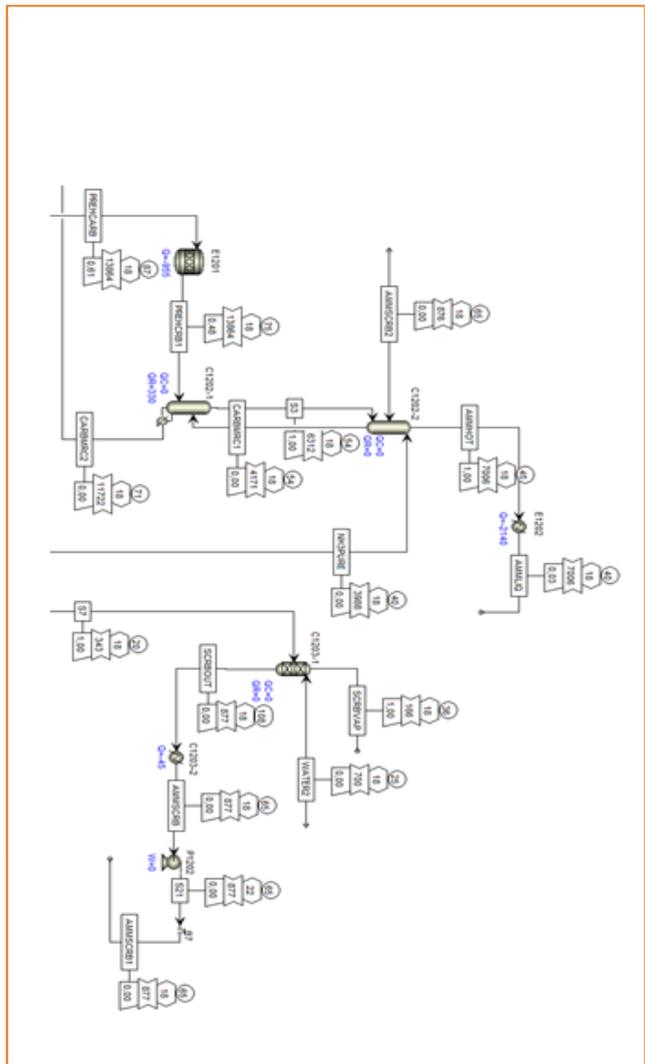
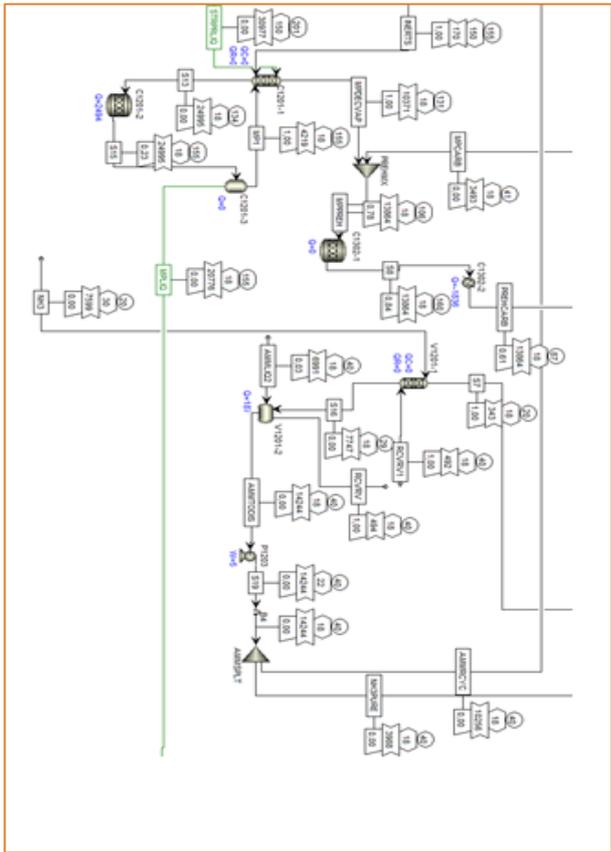
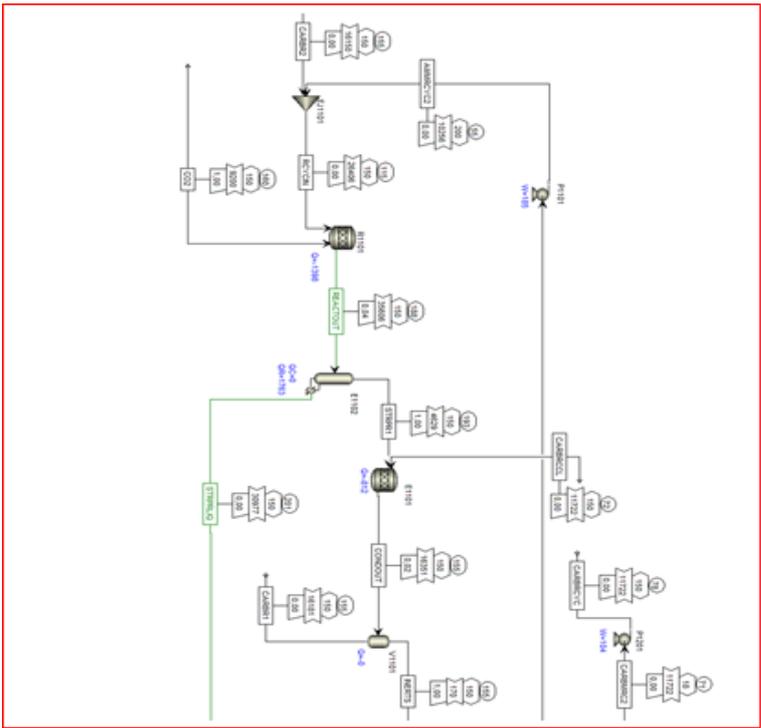


Figure 22: Overview of Aspen PFD

4.1.1 Keys for reading the model

Section	Team member responsible throughout report
HP section	Marc Van der Linden
MP section	Marcelle Hecker
LP section	Jesus Rodriguez Comas
Vacuum section	Winfried de Haas
Wastewater section	Ron Meulman





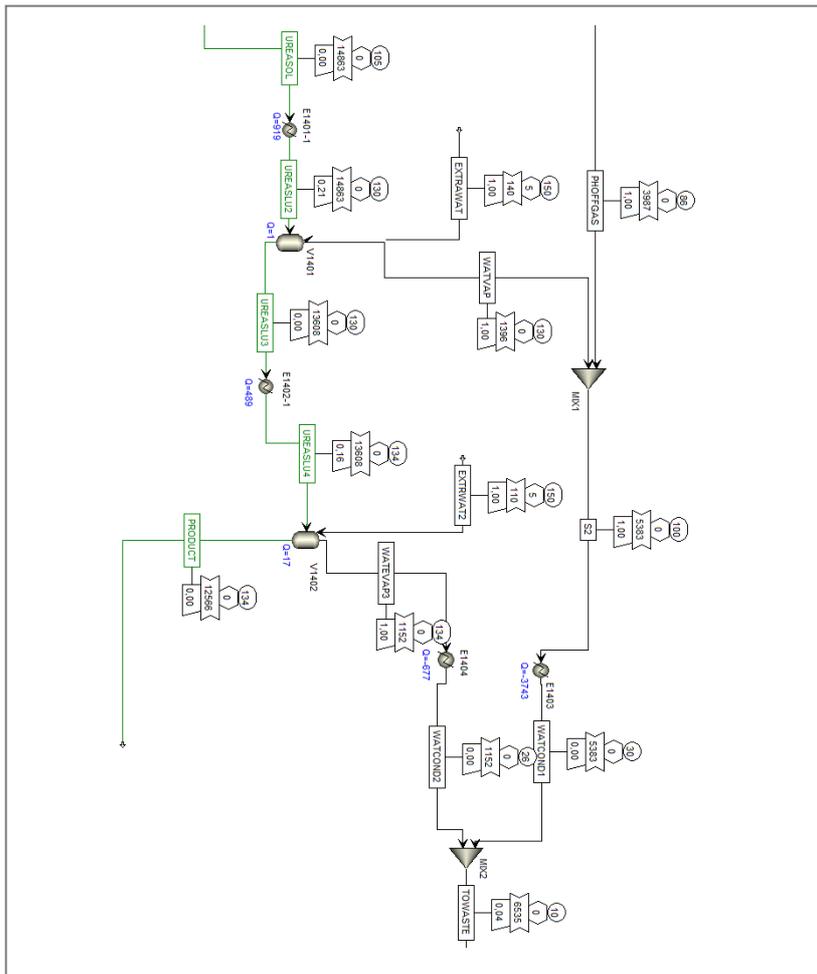
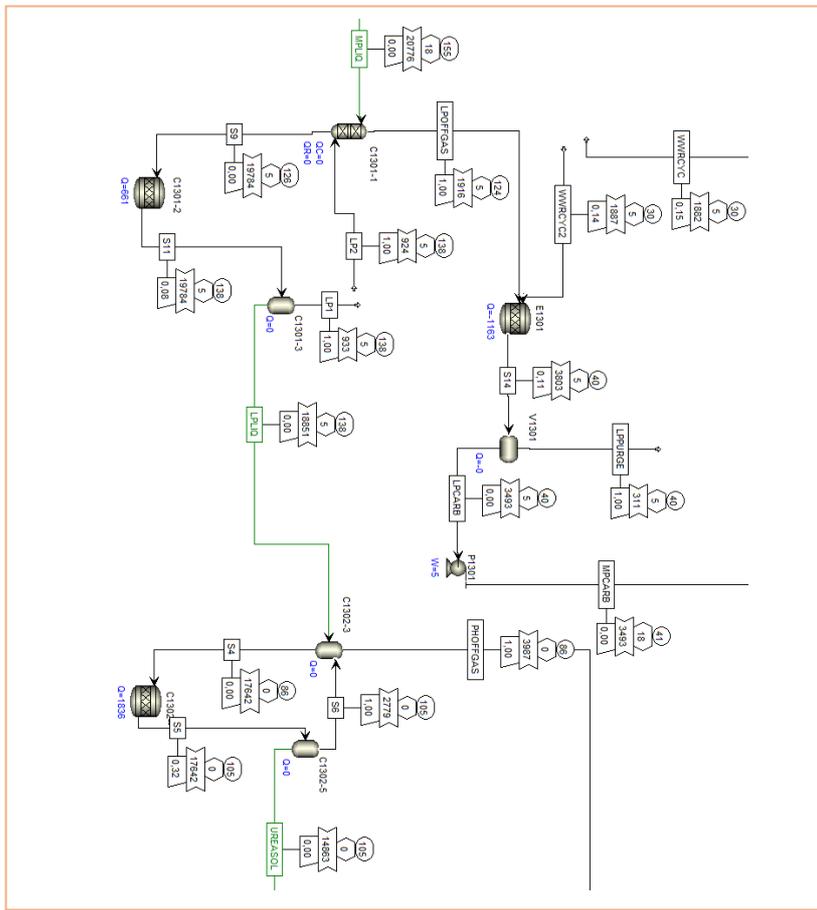


Figure 24: Aspen model of LP and vacuum section

4.2 Stream Summary

The mass and energy balances outlined below show only the major streams into and out of the process. The model however, contains many more internal streams and recycles, the details of which can be found in the stream summary table replicated from Aspen (appendix 2).

It should be noted when interpreting the Aspen model that many recycle streams were not connected, due to the calculation difficulties this would have caused. Instead they were named xxx1 and xxx2 to symbolize their relation. The fact that their mass flow was not identical was taken account of by using all of the outgoing streams rather than their incoming counterparts to establish an overall mass balance. The streams that should be disregarded have been shown in red in appendix 2.

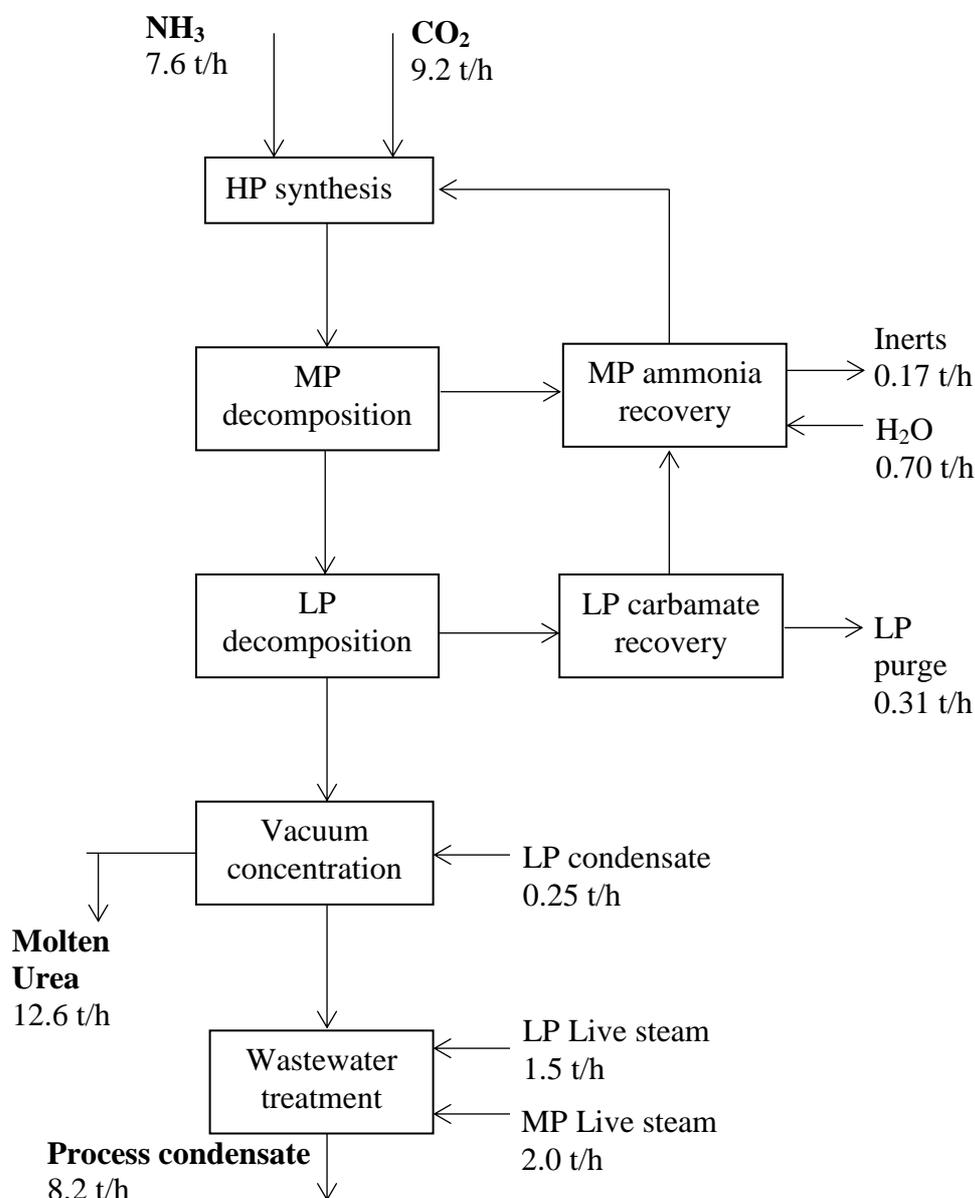


Figure 26: BFD with Mass Balance

4.2.1 Mass Balance

Table 2: Mass Balance

Overall Mass Balance								
Mass flow in (t/h)	CO2	NH3	EXTRA WAT	EXTRAW AT2	WWSTEAM1	WWSTEAM2	WATER2	TOTAL
	9200	7599	140	110	2000	1500	700	21249
Mass flow out (t/h)	PUREWAT2	PRODUCT	SCRBVA P	LPPURGE				
	8153	12566	166	311				21196
Balance (in - out)								53

The discrepancy in the mass balance is due to the unconnected recycle streams (as mentioned above). The unconnected recycles have been tabulated below for clarification. The accuracy of the flow values has been left, as was calculated in aspen, in order to show the difference in recycles.

Table 3: Unconnected recycles

Recycles								
In-going (kg/h)	WWRCRC2	AMMLIQ2	AMMSCRB2	CARB R2	CARBRC CL	LP2	RCVR V1	TOTAL
	1887	6991	876	16150	11722	924	492	39042
Out-going (kg/h)	WWRCRC2	AMMLIQ	AMMSCRB1	CARB R1	CARBRC YC	LP1	RCVR V	
	1882	7006	877	16181	11722	933	494	39095
Balance (in -out)								-53

4.2.2 Energy balance

The energy balance shows a production of energy. This is due the fact that the reaction to urea from ammonia and CO₂ is exothermic.

The enthalpy flows of each stream can also be found in the Aspen stream summary provided in appendix 2. For further details on how the utilities are consumed, see chapter 3.

Table 4: Energy Balance

Energy Balance							
Energy input (MW)	Pump power	MP steam	MP live steam	LP steam	LP live steam	cw	Total
	1.3	4.3	1.1	2.4	1.4		23.1
Energy output (MW)							
				2.2		11.8	14
Balance (In-Out)							-3.5

4.3 Control

An overview of how the urea plant is controlled in normal operations is given here. For further clarification on how controls, or lack thereof, effect the process see the hazard analysis for each section of the plant in appendix 3.

4.3.1 Capacity control

Level control

The process is controlled in various ways with regards to pressure, temperature and level. Most of these controls only maintain ideal conditions within a piece of equipment. Few however are able to influence the entire plant, the most notable example of this is the level control in the process line.

Each piece of equipment in the process line has a level control and this level control influences the outflow from that specific piece of equipment by opening or closing a valve (Figure 27). Increasing or decreasing the outflow of the equipment will consequently alter the level in the equipment. The outflow determines the flow to the rest of the process making this the control which has the most significant influence on the capacity of the plant.

The other type of control that will determine the plant capacity, is the flow control on the streams feeding the process. The ratio control on the carbon dioxide and ammonia feeds will affect the flow to the reactor because it controls the flow to the compressor and the flow to and from the ammonia receiver. These flows will in turn determine how much material will enter and leave the reactor so this controller can significantly influence the capacity of the plant.

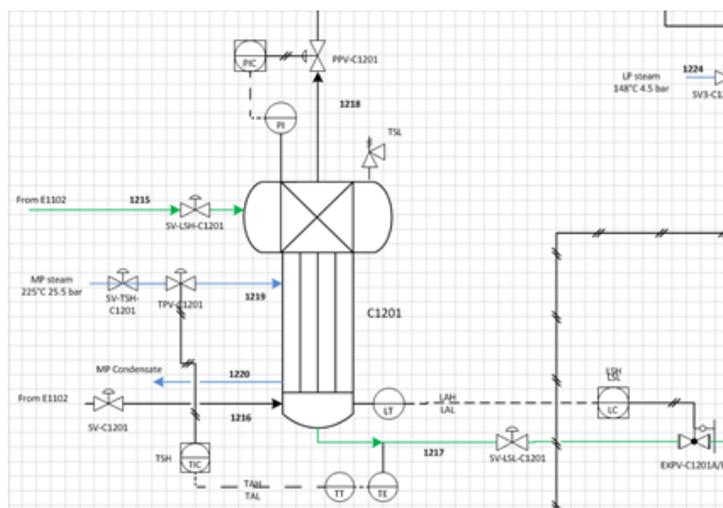


Figure 27: an illustration of various types of control

4.3.2 Unit and condition control

Temperature control

As stated before, not all of the control is as influential to the plant capacity as the ones mentioned above, an example is the temperature control on the vessels that require steam. The temperature control will regulate the temperature by controlling a valve that will limit the steam flow to the equipment to cool it down. The excess steam is sent to a back-up condenser to avoid disturbing the overall steam flow to the process. The opposite happens when the temperature needs to increase, the valve will open to increase steam supply, again this will be accommodated in the utility section (Figure 27).

A similar situation is encountered in some of the heat exchangers where cooling water is used. Their temperature is regulated by a valve that regulates the flow of the cooling water. However, this valve regulates the flow of a recycle surrounding the heat exchanger. This ensures that the temperature inside the heat exchanger does not become too low, which is necessary for the heat exchangers that are not allowed to be cooled below a certain temperature. These heat exchangers are ones that process carbamate solutions, where excessive cooling could lead to crystallization, and the MP ammonia condenser, as it feeds into the ammonia receiver and thereby regulates the vessels temperature.

Pressure control

Pressure is another parameter which must be controlled. The pressure control in most vessels is aimed at relieving the excess of gas that may be present by opening a valve, or retaining more gas by closing it. In most cases this will influence the next piece of equipment since it will receive a larger or smaller vapour stream. However, in most cases the gases are used to reduce the heat duty of the next piece of equipment, so any problem that should follow from this will be negated by the next vessels temperature control. A notable exception to this is the ejector in the vacuum section, here the pressure control will regulate the steam flow through

the ejector to maintain a constant pressure. Since the steam is subsequently condensed and fed into a tank, this will not disturb the flow in the wastewater section.

Flow control

Pumps are an example of equipment that is most sensitive to these changes. To protect the pumps, flow transmitters are installed that are equipped with a low flow switch, which will stop the pump once the flow has fallen below a certain threshold (Figure 28). A notable exception to this is the high pressure ammonia pump (P1101), this pump runs at a constant speed and the flow control will regulate the recycle that provides the pump with a constant feed. This is done because positive displacement pumps have a nearly constant outflow regardless of the head, so by keeping the flow constant the head will remain fairly constant as well (

Figure 29).

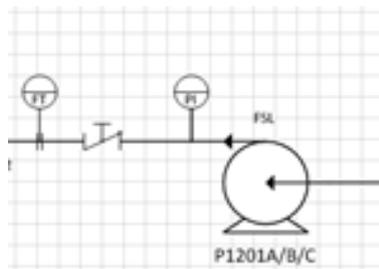


Figure 28: variable speed pump control

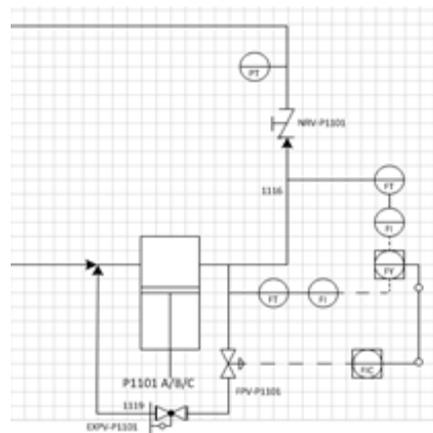


Figure 29: reciprocating pump flow control

Chapter 5. Equipment List and Specification

5.1 Equipment List

Reactors

Code	Name	Type	T (°C)	P (bar)	MOC	MED	Size
R1101	Reactor	Equicurrent bubbling column	188	150	External 25-22-2 Cr-Ni-Mo Lining zirconium	Ammonia, CO ₂ , carbamate, urea and water	Volume: 22.5 m ³
R1501	Hydrolyzer	Bubbling plug flow reactor	203	20	Stainless steel	Water NH ₃ Urea Carbamate CO ₂	5.59 m ³

Columns

Code	Name	T (°C)	P (bar)	MOC	MED	Size
C1101	Carbamate separator	155	150	External 25-22-2 Cr-Ni-Mo Lining zirconium	Ammonia, CO ₂ , carbamate, water	Height: 4.1 m Diameter: 1 m
C1201	MP decomposer	155-201	18	Duplex SS	Urea solution (carbamate, urea, NH ₃) CH ₄ , N ₂ , O ₂	Top: Diameter: 0.75m Height: 3.1m Middle: Surface area (heat exchanger section): 41.3m ² Bottom: Diameter: 0.75m Height: 3.8m

C1202	Ammonia-carbamate separation column	45-75	18	Sandvik2RE69 (00Cr25Ni22Mo2 - UNS31050)	water, NH ₃ , Carbamate solution, CH ₄ N ₂ , O ₂	Diameter: 0.6m Height: 12.5m
C1203	MP scrubber	25 - 65	18	Sandvik2RE69 (00Cr25Ni22Mo2 - UNS31050)	Water, NH ₃ , CH ₄ , N ₂ , O ₂	Diameter: 0.3m Height: 4.2m Surface area (of cooled section): 1m ²
C1301	Low pressure decomposer and rectifier	138	4.5	AISI 316L	Urea solution, ammonia, ammonium carbamate	Top separator: D= 0.39m H=1.3 m (same as medium pressure decomposer) Heat exchanging area: 54 m ²
C1302	Vacuum Pre-heater/pre-concentrator	135	0.34	Top part (trays): AISI 316L; Bottom part (heat exchanger): Safurex	Shell side: water, ammonia and ammonium carbamate; tube side: urea solution in water	Same geometry and same type of heat exchanger (falling film type) as C1301; Upper part has no trays, but an expansion section with the same size as the top part of the low pressure decomposer (as well as the medium pressure decomposer)

						Heat exchanging area: 282m ² *
C1501	Wastewater stripping column	127-148	4.5	Stainless steel	Water NH ₃ Urea CO ₂	Height: 23.18 m Diameter 0.58 m

Vessels

Code	Name	T (°C)	P (bar)	MOC	MED	Size
V1201	Ammonia receiver	20-40	18	Sandvik2RE69 (00Cr25Ni22Mo2 - UNS31050)	NH ₃ CH ₄ N ₂ O ₂	Horizontal vessel: Volume: 51.8m ³ Diameter: 2.9m Height: 8m Tower: Diameter: 0.4m Length: 4.8m
V1301	Low pressure carbamate receiver	40	4.5	Safurex	Water, ammonia, ammonium carbamate	Ratio D/L chosen at 0.4; D= 2.93m L=7.31m
V1401	Vacuum evaporator	130	0.3	Stainless steel ²⁵	Urea solution(86%)	Diameter: 1.46 m Height: 5.85 m
V1402	Vacuum evaporator 2	134	0.03	Stainless steel ²⁵	Urea melt(96%)	Diameter: 3.06 m Height: 12.2 m

Heat exchangers

Code	Name	T cold stream (°C)	T hot stream (°C)	P (bar)	MOC	MED	Q (kW)	Utility flow (kg/h)	SA (m ²)
E1101	High pressure carbamate condenser	135-155	148	150	External 25-22-2 Cr-Ni-Mo Lining zirconium	Ammonia, CO ₂ , carbamate and water	812	LP condensate: 1316	60
E1102	Stripper	188-201	225	150	Duplex steel shell Omegabond® tubes	Ammonia, CO ₂ , carbamate, urea and water	1763	MP steam: 3357	65.3
E1201	MP carbamate condenser	25-35	87-75	18	Duplex SS	Carbamate solution	955	CW: 8.23*10 ⁴	22.1
E1202	Ammonia condenser	25-35	45-40	18	Sandvik2R E69 (00Cr25Ni22Mo2 - UNS31050)	NH ₃ CH ₄ N ₂ O ₂	2141	CW: 1.84*10 ⁵	223
E1301	Low pressure carbamate condenser	84	20	4.5	2 RE 69/25/22/2	Gaseous ammonia, water and carbon dioxide	1105	CW: 2.20*10 ⁴	49
E1401	Heat exchanger before evaporator	105-130	148	0.3	Stainless steel	Urea solution	920	LP steam: 1539	11.1
E1402	Heat exchanger	130-134	148	0.03	Stainless steel	Urea solution	490	LP steam: 839	10.9

	before vacuum evaporator 2									
E1403	Condenser	25-35	103-40	0.3	Stainless steel	Contaminated water vapour	3743	CW: 3.22×10^5	142	
E1404	Condenser	25-35	134-40	0.03	Stainless steel	Contaminated water vapour	677	CW: 5.83×10^4	20.3	
E1501	Heat exchanger	29-106	90-148	4.5	Stainless steel	Water Urea NH ₃	554	n/a	13.6	
E1502	Heat exchanger	143-198	150-203	20	Stainless steel	Water Urea NH ₃	539	n/a	114	
E1503	Condenser	25-35	30 - 129	4.5	Stainless steel	Water NH ₃ CO ₂	1899	CW 1.63×10^5	62.7	
E1504	Heat exchanger	25-35	40-90	1	Stainless steel	water	471	CW 4.05×10^4	19.1	

Pumps

Code	Name	Type	P (bar)	Pmax (bar)	T (°C)	MOC	MED	Volume flow (m ³ /hr)	Power requirement (kW)	U (V)	I(A)
P1 101	High pressure ammonia pump	Plunger pump	182	200 bar	55	Duplex steel	Ammonia	18.5	184	690	267
P1 202	MP ammonia-water pump	Variable flow	4	22	65	Duplex SS	Aqueous ammonia (20 wt%)	0.36	0.97	400	2.43

							amm onia)				
P1 203	MP ammo nia pump	Var iabl e flo w	4	22	40	Duplex SS	amm onia	25.9	5.19	400	13
P1 201	HP carba mate pump	Ce ntrif uga l mul tist age	32	50	70- 80	Duplex SS	Carb amat e soluti on (43 wt% carba mate, water , amm onia)	13	104	690	203
P1 301	Ammo nium carba mate pump	Var iabl e flo w	13. 5	20	40	AISI 316L	Water , amm onia and amm oniu m carba mate	3.69	4.67	400	11.7
P1 302	Pump	Var iabl e flo w	0.1	1	105	AISI 316L	Urea soluti on in water	12.3	0.04	400	0.1
P1 401		Var iabl e flo w	0.7	1		Stainle ss steel	Conta minat ed water	107.8	2.9	400	7.25
P1 402		Var iabl e flo w	0.9 7	1		Stainle ss steel	Conta minat ed water	1.04	0.095	400	0.24
P1 501	Waste water pump	Var iabl e	3.5	4.5	40	Stainle ss steel	Water Urea NH ₃	6.39	1.77	400	4.43

		flow									
P1 502	Pump to hydrolyzer	Variable flow	15, 5	20	143	Stainless steel	Water Urea NH ₃	9.23	9.72	400	24.3

Compressor

Code	Name	Type	P (bar)	Pmax (bar)	T (°C)	MOC	MED	Volume flow (m ³ /hr)	Power requirement (kW)	V (V)	I (A)
K1101	CO2 compressor	Electrical centrifugal compressor	148	148	160	Duplex steel	CO ₂ and 0.25 vol% passivation air	In: 2657 Out: 42.17	978 kW	1.0* 10 ⁴	97.8

Steam ejector system

Code	Stages	P suction side (bar)	P motive medium (bar)	MOC	MED	Volume flow (m ³ /hr)	LP steam requirement
EJ 1101	Ejector	145	200 bar	25-22-2 Cr-Ni-Mo Lining zirconium	Ammonia, carbamate and water	38.4	-
EJ 1401	2	0.03	4.5	Stainless steel	Contaminated water vapour	9820	580 kg/hr

5.1.1 Materials of construction

The equipment in the urea plant is subject to critical conditions of high pressure, high temperature and corrosive medium. To achieve the most reliable equipment performance, various stainless steel grades have been developed by urea technology licensors and material vendors (Table 5). The MOC of the units listed above was either found in literature or determined using the tables listed below.

Table 5: MOC used by different licensors³³

Material Grade	C	Cr	Ni	Mo	N ₂	Others
SS 316L	0.03	16.0-18.0	10.0-15.0	2.0-3.0	-	P ≤ 0.045; S ≤ 0.03
SS 316L UG	0.02	16.0-18.0	13% min	2.0-3.0	< 0.10%	P ≤ 0.015; S ≤ 0.01
25 Cr-22Ni – 2Mo (SNAMPROGETTI)	0.02	24-26	21-23.5	2.0-2.6	0.10-0.15	P ≤ 0.02; S ≤ 0.01; B ≤ 0.0015
SAFUREX (STAMICARBON)	0.03	28.0-30.0	5.8-7.5	1.5-2.6	0.3-0.4	Cu ≤ 0.8
DP28W (TOYO)	0.03	27.0-28.0	7.0-8.2	0.8-1.2	0.30-0.40	W: 2.1-2.5

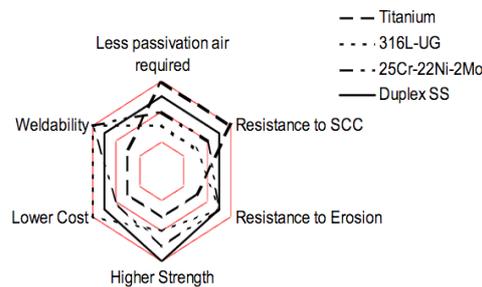


Figure 30: Important properties of MOC³³

5.1.2 Equations

The following equations were used for the estimation of equipment sizes. The derivations of the equipment, in order of process section, can be found in appendix 5¹⁹.

To find required flow rate of water in heat exchangers:

$$Q_H = m C_p \Delta T \quad (1)$$

Q_H = required heat transfer rate (kW)

C_p = specific heat capacity (kJ/kg°C)

M = mass flow (kg/s)
 ΔT = temperature difference(°C)

The log mean temperature difference:

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad (2)$$

Temperature difference when condensing steam:

$$\Delta T_{lm} = \frac{(t_2 - t_1)}{\ln \frac{(T_{sat} - t_1)}{(T_{sat} - t_2)}} \quad (3)$$

T_1 = inlet hot fluid temperature(°C)
 T_2 = outlet hot fluid temperature(°C)
 T_{sat} = saturated steam temperature(°C)
 t_1 = inlet cool fluid temperature(°C)
 t_2 = outlet cool fluid temperature(°C)

Calculating the surface area required for heat exchange:

$$Q_H = U A \Delta T_{lm} \quad (4)$$

A = surface area (m²)
 Q_H = required heat transfer rate (W)
U = overall heat transfer coefficient (W/m²K)
 ΔT_{lm} = log mean temperature difference(°C)

Calculating column size was done through Aspen and the use of the following formulae:
Volume of holding section of a column:

$$V = v \times t_r \quad (5)$$

V = volume (m³)
v = volumetric flow (m³ /h)
 t_r = residence time (h)

Volume of a cylinder:

$$V = \pi \times r^2 \times L \quad (6)$$

V = volume (m³)
r = radius (m)
L = length or height (m)

5.1.3 General remarks

The location and installation of the units listed above is dependent on the weight and size of the equipment. For ease of installation and maintenance for example, the HP equipment and all other heavy equipment is installed at ground level⁸. For further details about the lay-out of the plants see chapter 2 - Process and Technology. The distance required between units is identified by chemical and fire explosion analysis and can be found in appendix 3.

It should also be noted that the data given above is at operating conditions defined in Aspen. To allow for deviations in on site operating conditions, for example fluctuations in weather during the year, and to allow for small increases in process capacity, a safety factor of 10% should be added to all values.

All the valves, fittings, flanges, lines, controls etc. are not included in the equipment list. The equipment listed in this list is all ISBL. OSBL installations like cooling towers, flare systems and emergency equipment were not sized.

5.2 ISBL and OSBL Specification

Inside the battery limits (ISBL) are all the crucial equipment for the operation of the plant. This means that everything depicted in the PFD is ISBL (see Figure 5). The utilities connected to these units in the PFD are also ISBL. The rest of the plant is outside battery limits. Important units that are necessary for the plant but are OSBL are for example: flare systems, the cooling tower, the aqueous ammonia and urea tanks, the ammonia and carbon dioxide feedstock storage. The urea solution storage tank (required if, for example melamine plant is shut-down and cannot receive urea) before the preheater-C1302 is also OSBL.

Chapter 6. Research into Process Improvement

The modelling of the 12500 kg/h urea producing plant, and the research undertaken to understand the Snamprogetti process has led to the identification of potential sections for process improvement. As the issue of sustainability should be addressed by any suggestions for possible improvements, the utility demand of the urea process was targeted.

With the intention being to improve the sustainability of the plant and to reduce operating costs, it was therefore further investigated whether the steam consumption of the wastewater treatment section could be reduced.

It was found that the wastewater section requires steam for two units. The hydrolyser (R1501) requires 2000 kg/h of MP steam and the waste-water column (C1501) consumes 1500 kg/h of LP steam. To identify whether this section of the plant could be run more sustainably, the reason for the steam demand was traced upstream of the wastewater treatment facilities.

6.1 Early ideas for improvement

Initially the option of selling ammonia water was discussed as it would reduce the demand on the wastewater section thus, reducing the steam requirement. It would also decrease the recycled water, which was initially considered a positive outcome as the chemistry of producing urea favours low water concentrations (see Chemistry, chapter 2) and reducing excess water in the process would thereby increase conversion and thus production of urea. However, upon investigating the water content at critical sections of the process, it was found that the process as modelled in Aspen would not benefit from reducing water recycle.

The ammonia-carbamate separating column (C1202) was identified as having the highest risk of potential carbamate crystallization thus, the composition of the carbamate solution in the bottom stream was identified (42.6 wt% carbamate, 34.6 wt% ammonia and 22.7 wt% and traces of urea and CO₂) and the critical temperature of crystallization determined by calculating the N/C molar ratio of the stream and adjusting the wt% ammonia and CO₂ to match the calculated value (Figure 31).

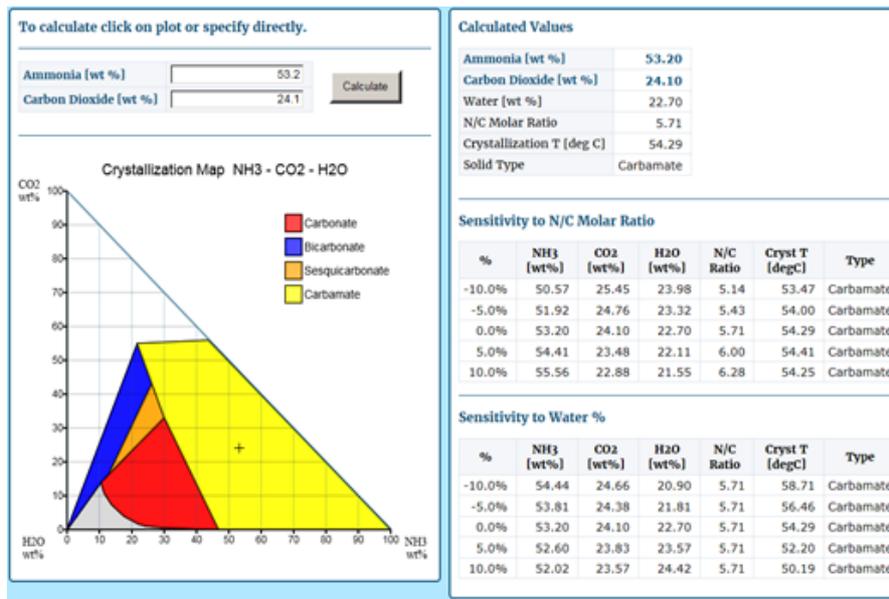


Figure 31: Determining temperature of carbamate crystallization¹⁸

The temperature of crystallization was found to be 54°C and the modelled stream temperature is 71°C. Decreasing the water content in the separation column would therefore lead to a higher crystallization temperature and would become dangerously close to the operating temperature. Any fluctuations in process conditions, for example composition variations or temperature changes could then lead to crystallization and clogging of equipment.

Therefore, the reduction of recycled waste water would only have a positive effect if additional water is added to the system in reality, which would mean that the water concentration in the C1202 is in fact higher than was modelled in this project.

As the selling of ammonia water and thus the resulting decrease in capacity of the wastewater column is not a viable solution for the modelled process, the second steam user - the hydrolyser, was investigated.

6.2 Promising ideas for improvement

6.2.1 Identification of the problem

The purpose of the hydrolyser is to decompose the urea remaining in the wastewater, in order to both clean the effluent of the plant and to recycle the resulting NH₃ and CO₂ (see theory section in chapter 2). The MP steam demand of the hydrolyser is thus directly related to the concentration of urea entering the wastewater treatment section.

It was found that the water requiring treatment contained 6.8 wt% urea. This composition was traced to the vacuum section upstream of the wastewater section. The pre-heater (C1302) evaporates 5.46 kg/h of urea, the first evaporator (V1401) releases 44.2 kg/h of urea and 398 kg/h of urea escapes the top of the last evaporator (V1402).

From these figures it was evident that by finding a solution to reducing the urea content entering the wastewater treatment section, the initial intention of reducing steam demand of the process could be achieved.

6.2.2 A concept design from literature

It was found in literature that the engineering firm, Urea Casale, has developed a urea recovery system (URS) (Figure 32), which supposedly recovers 96-97% of urea from the vacuum vapours. A design such as this could therefore solve the problem we had identified.³⁴

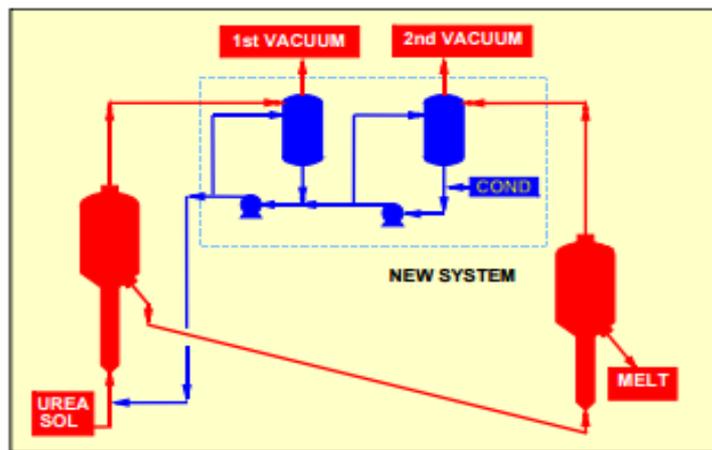


Figure 32: Casale URS³⁴

The design by the engineering company was used as the base concept for the process improvement modelled in Aspen. Several important modifications were made to ensure the design was optimal for our process (Figure 33).

6.2.3 PFD of the scrubbing system

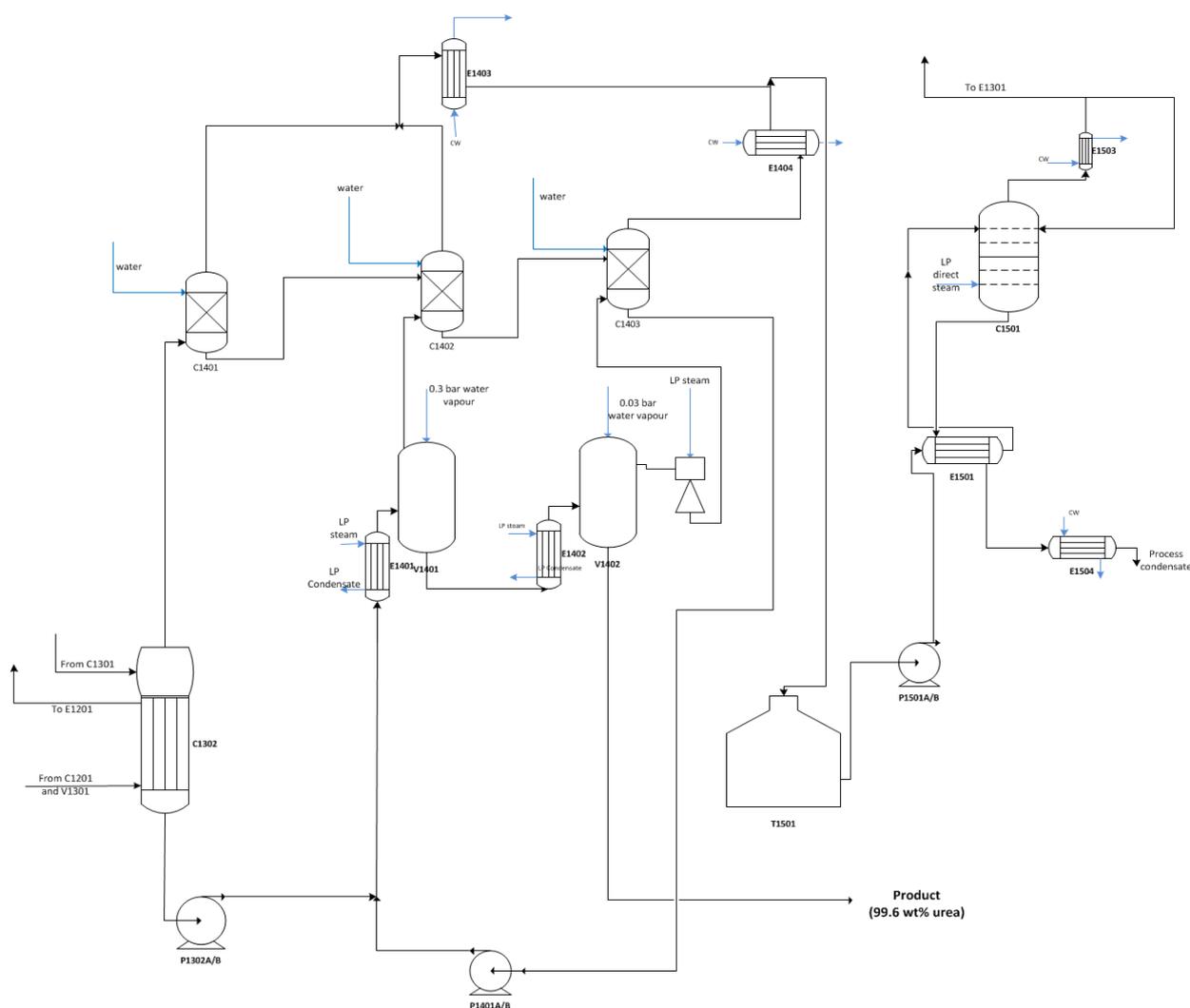


Figure 33: PFD showing the modification (scrubbers)

Three scrubbers were introduced in the vacuum section (Figure 33). The first (C1401) serves to scrub the vapours (and 5.46 kg/h urea) exiting the preheater, the second (C1402) is installed to scrub the vapours (and 44.2 kg/h urea) exiting the first evaporator, and the third scrubber (C1403) scrubs the vapours (and 398 kg/h urea) exiting the last evaporator.

The scrubbing of the vapours is achieved by feeding water and the bottom stream of the previous scrubber into the top of each unit. The scrubbed vapours are then condensed and sent to the wastewater collection tank (T1501), as before.

The bottom stream exiting the last scrubber contains 67 wt% urea and is recycled to the first evaporator.

6.2.4 Modelling the scrubbing system in Aspen

The details of the design can be seen in the Aspen model below (Figure 34) and the accompanying stream results (appendix 6).

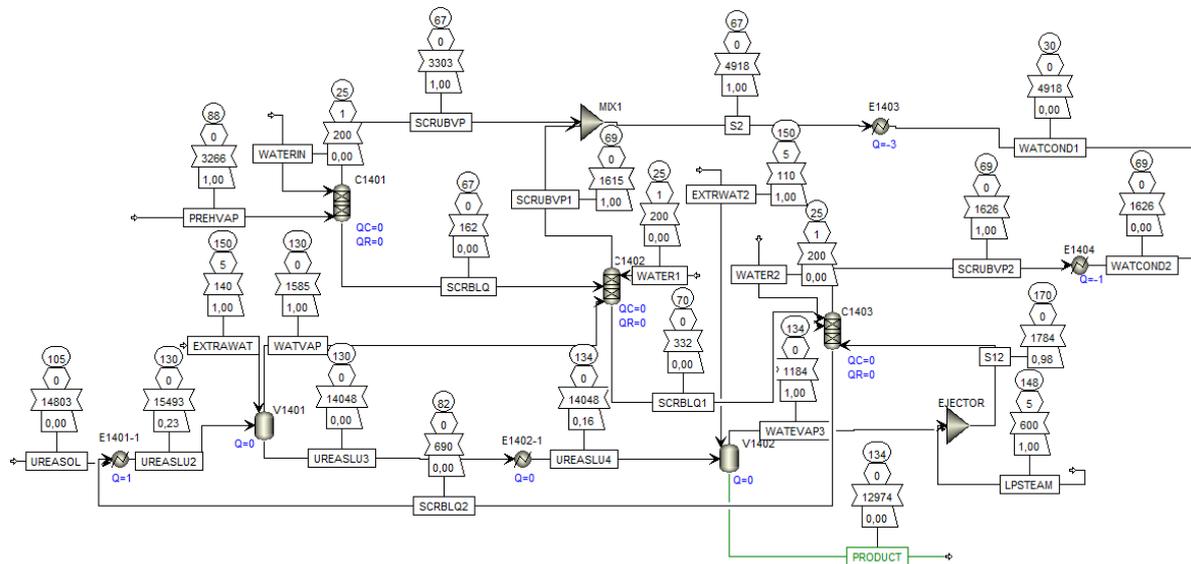


Figure 34: Aspen model of scrubbing system

The vapour of the preheater (PREHVAP) containing 0.2 wt% urea is scrubbed in C1401, which consists of three stages. 200 kg/h of water is added at the top. The scrubbed vapour (SCRUBVAP) consist of 0.15 ppb urea. 162 kg/h of liquid effluent (SCRBLQ) is produced of 3.3 wt% urea, which enters the second stage of C1402.

In C1402 the vapour of the first vacuum evaporator (WATVAP) is scrubbed, which contains 3.2 wt% of urea. 200 kg/h of water is added at the top. The scrubbed vapour (SCRUBVAP1) consist of 9.9 ppb urea. 332 kg/h of liquid effluent (SCRBLQ1) is produced of 17 wt% urea, which enters the second stage of C1403.

In C1403 the vapour of the second vacuum evaporator is scrubbed after the steam ejector (S12), which contains 23 wt% of urea. 200 kg/h of water is added at the top. The scrubbed vapor (SCRUBVAP2) consist of 83 ppb urea. 690 kg/h of liquid effluent is produced of 67 wt% urea, which enters the first evaporator as a recycle.

Table 6: Influence of scrubbing system on steam consumption

Utility	Original Steam requirement (kW)	Original Steam requirement (kg/h)	New Steam requirement (kW)	New Steam requirement (kg/h)	Steam saved (kg/h)
Heat exchanger (E1401)	919	1539	1051	1760	-221
Heat exchanger (E1402)	489	819	505	846	-27
Hydrolyzer (R1501)		2000		0	2000

The elimination of the hydrolyzer unit not only reduces steam requirements, but also means less equipment needs to be installed. For example, the heat exchanger for in and output of the hydrolyzer (E1501) and the pump to the hydrolyzer (P1502) would no longer be necessary, and the stripping column (C1501) can be simplified, by not having a top and bottom separation and thereby requiring less stages (for a comparison see original PFD in chapter two).

6.2.6 A comparison of the scrubbing system with a condensing alternative

After modelling the scrubbing system and determining its potential as a process improvement, it was investigated whether the same results could be achieved without adding additional water. This would be researched by implementing condensers in place of the scrubbers, to partially condense the vapour streams. The condensing alternative was therefore modelled in aspen to allow for a comparison of the two ideas:

6.2.7 PFD of the condensing system

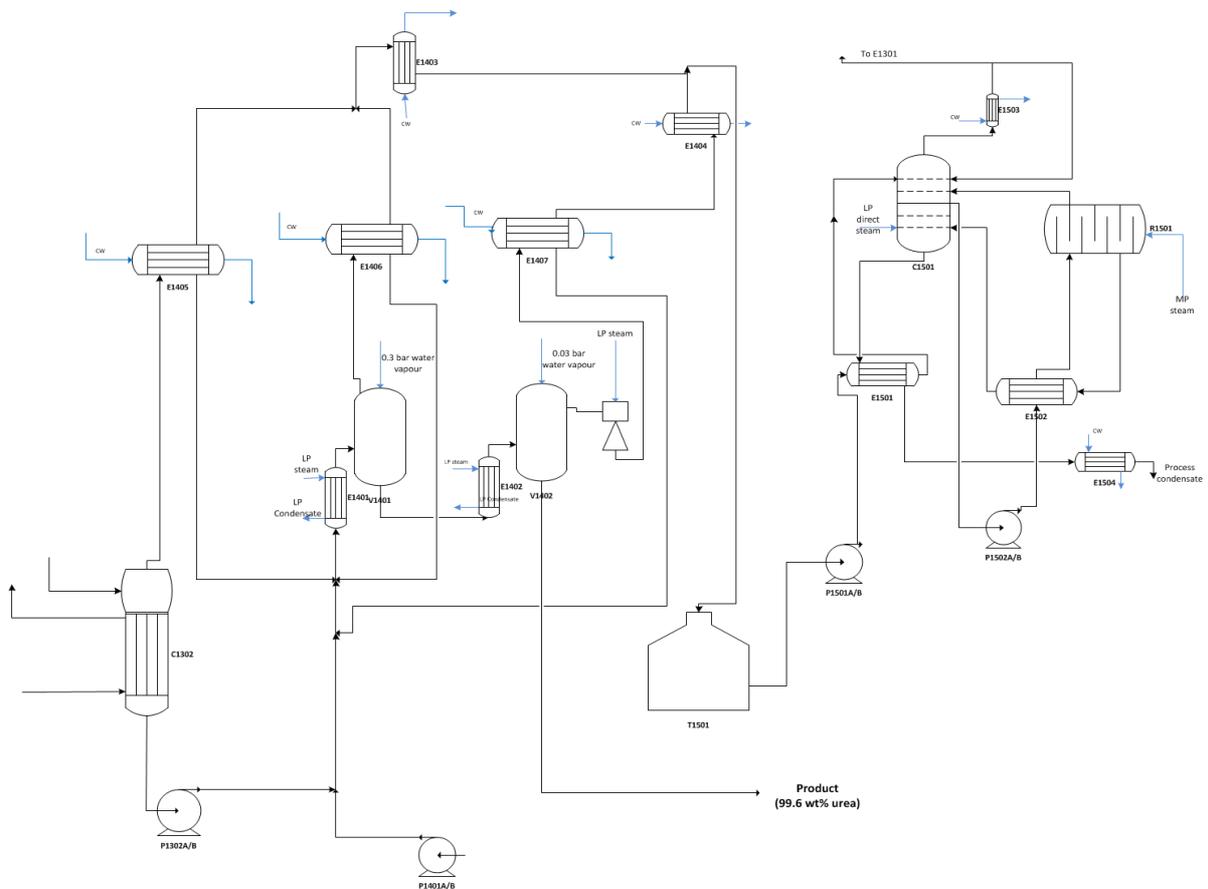


Figure 36: A PFD of a modified process (condensers)

6.2.8 Modelling the condensing system in Aspen

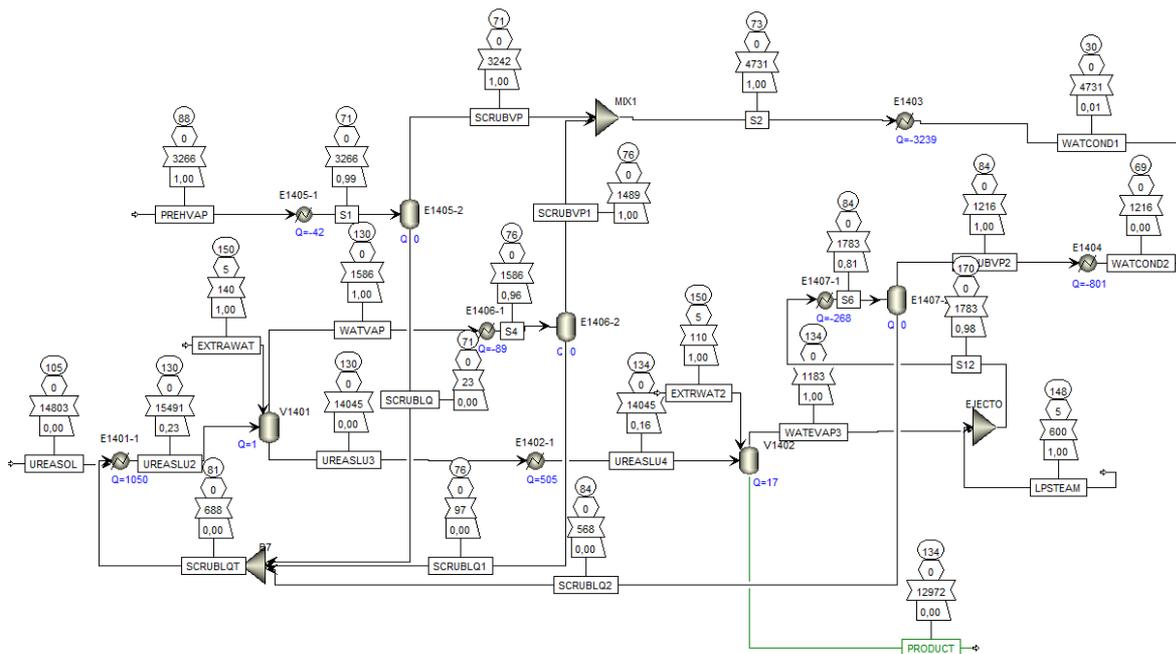


Figure 37: Aspen model of the condensing system

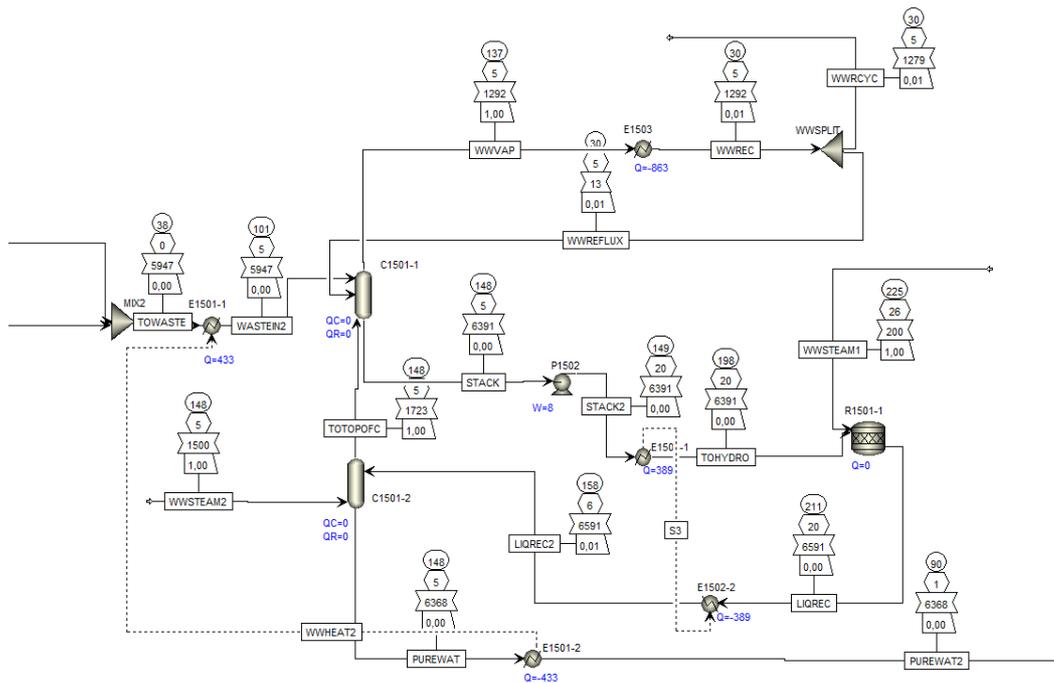


Figure 38: Aspen model of the wastewater section after installation of the condensers

The condensers E1405, E1406 and E1407 are used to partially scrub the vacuum vapors.

In E1405, 0,6 wt% of the vapour from the preheater is condensed, resulting in a liquid containing 7.9 wt% urea, which is recycled to the first evaporator. The remaining vapour contains 83 ppm urea.

In E1406, 4 wt% of the vapour from the first evaporator is condensed, resulting in a liquid containing 24 wt% urea, which is recycled to the first evaporator. The remaining vapour contains 399 ppm urea.

In E1407, 18.9 wt% of the vapour from the second evaporator is condensed, resulting in a liquid containing 72 wt% urea, which is recycled to the first evaporator. The remaining vapour contains 0.13 wt% urea.

The vapours are then condensed and sent to the wastewater collection tank (T1501), as before. The urea concentration of the wastewater is 402 ppm, which is too high to release into the environment. So in this case the hydrolyzer would still be required to remove the remaining urea.

The concentration of urea in the wastewater entering the treatment section could be decreased if a higher fraction of vapours were condensed. But to achieve a concentration of urea below 10 ppm, as was possible with the scrubbing system, the LP steam requirement of the vacuum evaporators would increase four fold. Thus, increasing condensation to achieve allowable urea emission levels without the use of a hydrolyser is not beneficial.

The total steam consumption of the condenser model was investigated in order to compare the results with the scrubbing system.

Table 7: Influence of condensing system on steam consumption

Utility	Original Steam requirement (kW)	Original Steam requirement (kg/h)	New Steam requirement (kW)	New Steam requirement (kg/h)	Steam saved (kg/h)
Heat exchanger (E1401)	919	1539	1050	1759	-220
Heat exchanger (E1402)	489	819	505	846	-27
Hydrolyzer (R1501)		2000		200	1800

From Table 7 it can be seen that the condensing system requires an additional 247 kg/h of LP steam and saves 1800 kg/h of MP steam.

By modelling both the scrubbing system and the condensing alternative, it can be concluded that both systems decrease the overall steam requirement. Both designs also increase the capacity of the urea production process by around 3%, because of urea being recovered rather than decomposed in the hydrolyzer (see stream summary in appendix 6).

The main difference between the two alternatives is that the equipment required in the scrubbing model is less, as three units could be entirely removed from the design of the wastewater section due to the efficiency of the scrubbers.

The MP steam savings for both systems are comparable, with the savings resulting from the complete removal of the hydrolyser in the scrubbing system being only 200 kg/h more than in the condensing system, where a hydrolyser was still required. The increase in LP steam required by the heat exchangers of the evaporation section is around 250 kg/h for both systems.

From the comparison it can be seen that either alternative is an improvement to the original design. The choice of which model to implement would be dependent on the efficiency of the scrubbers in reality and the cost of the equipment. If the Snamprogetti plant is already in operation the condensing system would possibly be the more attractive alternative as it would require less modifications. It is recommended to consider altering the original model in either of these two ways in order to reduce steam consumption and thereby improve the sustainability of the urea production process.

6.3 Conclusions and Recommendations

This research project dealt with modelling the production of 12500 kg/h of molten urea, from 7600 kg/h of ammonia and 9200 kg/h of carbon dioxide. The *Snamprogetti* urea technology was researched and simulated by employing Aspen modelling software to gain a deeper understanding of the process before possible improvements were investigated.

The successful conversion of ammonia and carbon dioxide into urea requires a wide range of process conditions, from 150 bar and 200°C, to vacuum conditions. Therefore, the process was divided into five sections namely; the HP synthesis section (150 bar), the MP purification and ammonia recovery section (18 bar), the LP purification section (4.5 bar), the vacuum purification/evaporation section (0.003 - 0.03 bar) and the wastewater treatment section. The technology, the equipment, and the hazards involved in the production of urea were thus evaluated for each step of the process.

Critical aspects of urea production are the hazardous substances involved. By analysing the process streams through each section and calculating the equipment size required to deal with the specified capacities, the most hazardous substances and their location of highest concentration within the plant were identified. Thereby, the effect of a chemical explosion or fire within the plant could be evaluated.

Liquid ammonia was identified as having the highest NFPA code of the major process substances and an accidental release of the substance from the reactor or the ammonia receiver (where volumes are largest) could lead to hazardous ammonia exposure up to 3 km from the plant. Both safety indexes indicated the distances required between process equipment units and the entire plant and the community to operate a safe facility.

The intermediate product, carbamate, was identified as being the greatest risk to normal operations due to its high corrosivity and the risk of it crystallizing and clogging equipment. A Hazop study was outlined to determine which controls were required to ensure the process could be brought to safe conditions in case of process deviations from normal operations, for example in the case of carbamate crystallization.

After studying the safety, the size, and the purpose of each section, ideas for improvement were developed. Due to the importance placed on achieving sustainable operations throughout most processing industries, the focus of this research was to investigate whether the modelled *Snamprogetti* plant could be operated more sustainably by reducing the steam consumption of the system. In particular, the goal was to determine whether the utility consumption of the wastewater treatment section could be reduced.

The high steam demand of the system became evident when studying the utilities, and in order to avoid remodelling the efficient and complex recycle systems at the front end of the plant, the wastewater section was singled out for improvement.

By identifying the greatest steam users of the section and analysing the reason for their steam requirement, it was found that a large amount of urea was evaporated during the final concentration steps of the process. Literature was found which detailed that this was indeed a problem faced in industry, and a basic drawing by *Urea Casale* served as the concept for the improvements that were added to the original model.

Two improvements were designed. One solution involved adding three scrubbers, one each for the preheater vapours and the two vacuum evaporator vapour streams. This urea recycle system, which closely resembled the design by Casale, proved very effective in Aspen plus. The urea in the wastewater was reduced to 23 ppb, an amount that could safely be emitted in the process condensate without requiring the hydrolyser unit to decompose residual urea. This meant that the 2000 kg/h of MP steam required by the hydrolyser was saved. However, as the scrubbing technique requires the addition of water, the LP steam consumption of the heat exchangers preceding the evaporators increased by 250 kg/h.

To investigate whether the scrubbing system could be improved, condensers were added in place of the scrubbers. Therefore, no added water was required. Modelling of this system proved that the condensers were not as effective in removing urea from the wastewater, as were the scrubbers, meaning that the hydrolyser could not be eliminated from the wastewater section. However, as the urea concentration was substantially reduced (400 ppm) the steam requirements of the hydrolyser dropped considerably, while the LP steam requirements of the heat exchangers remained the same as for the scrubbing system.

A comparison of both new models showed that the scrubbing alternative would save 200 kg/h of steam more than the condensing system, but in doing so would require 600 kg/h of added water. The scrubbing system would require several units less equipment than the condensing option due to the lower concentration of urea in the wastewater, however the real efficiency of the scrubbers remains to be determined by future research.

Thus, it is recommended to add either of the urea capturing systems to the original process, depending on local plant conditions. For example, if it is an existing plant requiring a revamp, investment savings of the scrubbing system are irrelevant as the equipment is already installed, in which case the condensing system is recommended. However, if a company is in the early stages of designing a new plant, the scrubbing option may be considered if the extra steam savings are deemed beneficial.

It is further recommended that future research should be conducted into the real efficiency of scrubbers, which could be implemented in industry and the cost of the equipment in question.

However, independent of which improvement is looked at, the *Snamprogetti* urea process could be run more sustainably through steam savings by implementing the appropriate urea capturing system to reduce the energy demand of the wastewater treatment section.

Appendix 1. Basis of Design

DESIGN BASIS FOR	INFORMATION DESIGN BASIS
<u>Snamprogetti urea production plant</u>	Process design: urea production Conceptual Engineering
PROJECT: 7	
Approved: Process Eng. Dept. Rijksuniversiteit Groningen	Date of issue: 13-06-2016 Page 61 of 235
Client : prof. ir. M.W.M. Boesten	

DRAFT

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.....UREA..... - PLANT

Urea Production Processes (UPP) project no. 7

By: **Winfried de Haas, Marcelle Hecker, Marc van der Linden, Ron Meulman, Jesús Rodríguez Comas**

Rev: 0, dated **13-06-2016**

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Note: In general there will be no attachments available at the start of the conceptual engineering

0. INTRODUCTION

The purpose of this document is to give general guidelines during the conceptual/basic engineering of the so-called **urea** plant/project. All numbers and values as well as descriptions have been agreed upon between the client and Engineering-company. Therefore this document will form the solid basis for the conceptual/basic engineering to be started. It is the intention of **UPP** to investigate with a **80 %** accuracy the feasibility of **urea** plant and to prepare all required documents to support the feasibility study. **The changes in this document are given in red.**

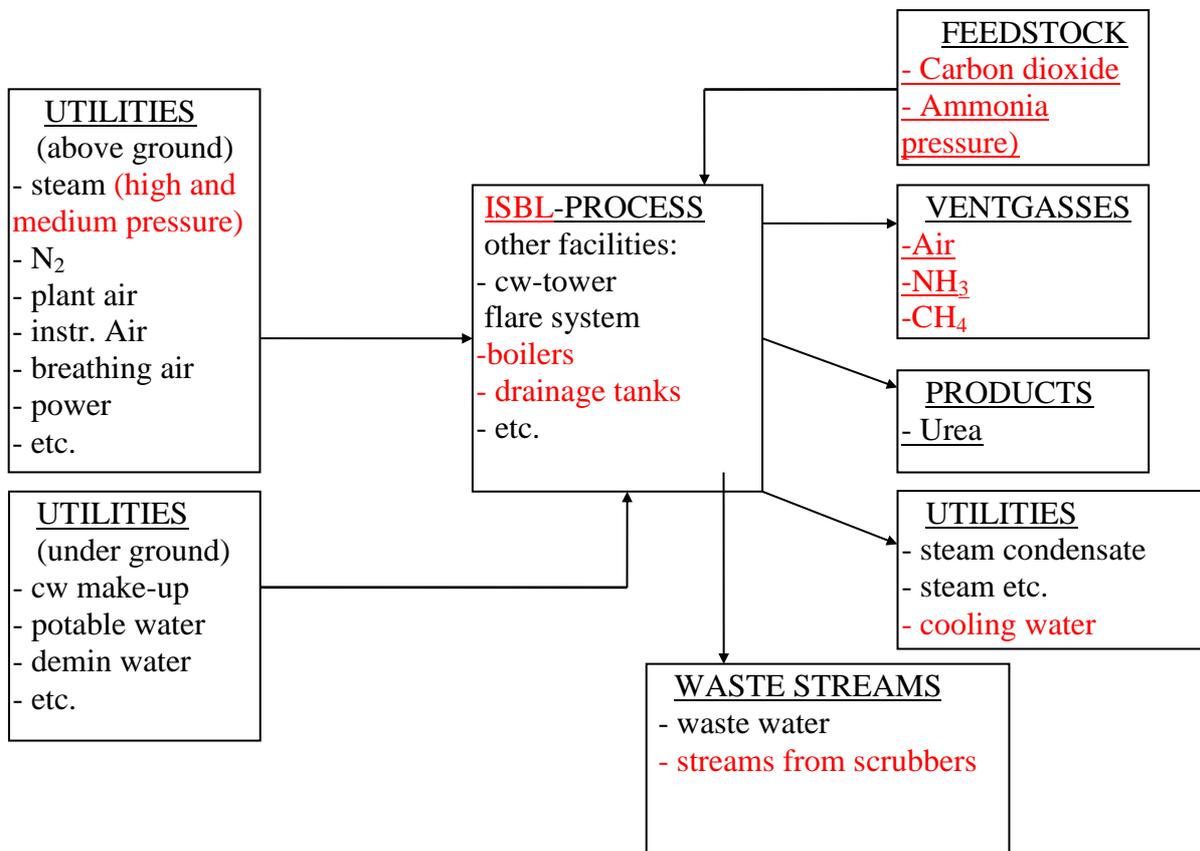
1. SCOPE

1.1. Function of the facilities

- 1.1.1. The function of the facilities designated as the **urea** plant is to produce **100 kt/a** of **urea** from **ammonia** and **carbon dioxide** as a feedstock.
- 1.1.2. The **urea** plant will be close to the existing **ammonia** plant **the Netherlands**. Feed will be made available from **an ammonia plant**. Products will be sent to **a melamine plant**. Byproducts will be **biuret and isocyanic acid**. **Biuret having a small concentration in the product and isocyanic acid won't be present.**
- 1.1.3. **A tank will be constructed for the storage of the product line before the preheater. The solution won't be too rich in urea so temperature can be kept at reasonable levels. The capacity of this tank will be for 2 days production.**
- 1.1.4. Waste water **of the process will be sent to a waste water treatment section**. All waste streams (gas, liquid or solid) should be dealt with in agreement with governmental laws, permit requirement, and corporate requirements and guidelines.
Vent gasses will be routed through a vent gas scrubber. A stack will be installed from which the gasses are sent to atmosphere.
Gases that are released in emergency situations are sent to flare systems.
- 1.1.5. The utilities will be available at battery limits, see also stream summary 1.1.9.
- 1.1.6. On stream time basis **8000** hours/year. This leads to an **urea** production of **12.5 t/h**.
- 1.1.7. **All pressures referred to in this design basis are absolute pressures.**
- 1.1.8. The facilities of the **urea** plant will be designed with a life time expectancy of **20 years**, where possible.

1.1.9 Stream Summary

This will show a sketch (block flow diagram) of all in and outgoing streams).
An example of such a sketch is given below.



1.2. Description of the facilities

The plant includes the following sections:
(see also PFD's in Attachment 4.1 and Process Description in Attachment 4.4. if applicable)

1.2.1. Tag coding of equipment

Equipment will be tag coded as laid down in the process description section chapter 2 – Process and Technology of the project report.

1.2.2. Production and Utility Facilities

The plant will include the following production sections, this section numbering will form the basis of the PFD's:

Section 1	High pressure and synthesis section
Section 2	Medium pressure section
Section 3	Low pressure section
Section 4	Vacuum evaporation section
Section 5	Waste water treatment section
Section 6	Tank farm
Section 7	Utility

The utilities available at battery limit are specified in Chapter 1.8.

A detailed description of the utility section can be found in the project report, chapter 3 – Utility and Specification.

1.2.3. General facilities

1.2.3.1. Water treating and sewerage

Surface water which can reasonably be expected not to be contaminated shall be collected in a clean water sewer system, which has to be connected to the existing main sewer. The process waste water is rinsed by means of distillation. This is done in two compartments. In the upper part ammonia, carbon dioxide and steam strip off the first part of ammonia and carbon dioxide. The liquid mixture then goes to a hydrolyser where urea is converted to ammonia and carbon dioxide. The gas is fed to the upper part of the column to help stripping and the liquid fraction is fed to the bottom part of the column. In the bottom part the ammonia and CO₂ are stripped from the water. LP steam is used as stripping gas for the lower part. Pure water should come out of the bottom which is cooled by the stream going to the column. The waste water treatment section in new plants should be able to deliver water with a mass fraction of urea and ammonia of 1 ppm. The maximum allowable temperature

of waste water in sewage systems is 30 °C. This means that an extra cooling stage is required.

1.2.3.2. Bleed, relief and disposal systems

- The relief system has to protect equipment and piping against overpressure, and shall be designed in such a way that the maximum credible relief quantity can be handled, regardless of mode of operation. The system shall be designed in such a way that a release cannot upset the operation of other sections in the plant or adjacent installations.
- Gases containing combustible components which are blown off by safety valves shall be relieved to a flare system or to 'safe location'. Calculations on the effects of dispersion can be found in appendix 3 of the process report. A risk assessment study and evaluation will have to be made before the start of the basic engineering. Gases containing non-combustible, non-poisonous or non-odorous components, may be relieved to local vents. The design of these vents must prevent dangerous ground level concentrations of suffocating components (N₂, NH₃, CO₂ etc.) and liquid entrainment. Venting should always be to a safe location.

-

Waste gases produced continuously during normal operation and containing significant amounts of combustible, poisonous or odorous components shall be sent to a scrubber.

- For draining of liquids containing combustible, poisonous or odorous components a closed piping system and/or a slop tank shall be installed. Organic liquids not miscible with water are separated and recovered.

1.2.3.3. Control room, social rooms, offices, workshop

The existing facilities of the ammonia plant will be used as much as possible. It is assumed that the plant will have a mixed crew of operators. For the main facilities reference is made to chapter 2 – Process and Technology of the project report. The erection or expansion of operator- and social rooms, an office, workshop and additive storage is excluded from the project scope of work. This project will only cover the control room.

1.2.4. Outside battery limit (OSBL)

OSBL connections are detailed in the stream summary 1.1.9.

1.2.5. Safety measures and facilities

All UPP and government standards are to be adhered to, see also 2.6.

1.3. Plant site information

The plant will be located in (Geleen) (The Netherlands) on the UPP ammonia location.

The plant will be as indicated in the preliminary lay-out, see Attachment 5. (start basic engineering).

The following details are shown:

- battery limits of the plant
- access and internal roads
- areas designated for construction facilities

A preliminary plot plan is shown in Attachment 5. (start basic engineering)

The site will be flat and free of obstacles and underground cables.

With regard to earthquakes is referred to Government Building Regulations.

A preliminary report of geotechnical survey will be included in the Project specification of the civil department. (start basic engineering)

It will be assumed that the soil at the site is not polluted, and that a so called 'Clean soil statement' will be given ('schone grond verklaring').

1.4. Plant capacity and flexibility

The urea plant will have a production capacity of 100 kt/a urea, with a composition as given in Paragraph 1.5. See also 1.1.1.

The production of 1000 kg of urea will not require more than 736 kg of carbon dioxide and 607 kg of ammonia, based on the normal feedstock specification as per Section 1.6. and not more than 1682 kg/h of LP steam and $1.011 \cdot 10^4$ kg/h of MP steam.

When operating at 40 % of design capacity (turn down ratio)⁸, the plant shall still be able to produce products which meet their specification as given in Section 1.5 and consumption figures of feedstock and/or utilities as agreed upon and listed above.

1.5. Product specifications

1.5.1. Product urea

Purity:	98,5-100%
Weight% Nitrogen:	46-46,5%
Weight% Biuret:	1%
Weight% Moisture:	0,5%
Free NH ₃ :	60-160 ppm
Battery limits conditions	
pressure:	1 bar
temperature:	134°C

Physical data:

The physical data of urea can be found in the project report in appendix 4.

1.6. Feedstock specifications at battery limit

1.6.1. Feed carbon dioxide

Composition: ³⁵

Carbon dioxide: 99.9%v/v

Moisture: 20 ppm

Oxygen: 30 ppm

Carbon monoxide: 5 ppm

NO_x (each): 2.5 ppm

Ammonia: 2.5 ppm

Total hydrocarbons (as methane): 50 ppm

Benzene: 0.02

Acetaldehyde: 0.2

Total sulphur (as S): 0.1 ppm

Non-volatile organic residues: 5 ppm

Non-volatile residues: 10 ppm

Passivation air will be added: 0.25 volume %. It is crucial that any hydrogen or other combustible materials before the compressor. This can be done by for example catalytic combustion.

Battery limits conditions

pressure : 1.9 bar

temperature: 20°C

Physical data:

The physical data of carbon dioxide can be found in the project report in appendix 4a.

1.6.2. Feed ammonia

Composition:

We get ammonia from the ammonia plant which will contain 2 wt.% of methane.

Battery limits conditions

Pressure: 30 bar

Temperature: 20 °C

Physical data:

The physical data of ammonia can be found in the project report in appendix 4a.

1.7. Waste stream specifications

1.7.1. Air pollution

The maximum allowable emissions figures are: 350 mg/m³ ³⁶

The maximum allowable concentrations are: 5000 ppm for carbon dioxide, 50 for ammonia

The expected emissions are: 4 to 6 kg/hr of ammonia from vents. ²¹

Remark: The maximum allowable emissions figures and concentrations mentioned here are the figures mentioned in the 'Wet Milieubeheer'.

The emissions include the total of:

- normal and continuous vent and purge losses
- normal leakage from flanges, pumps, valves
- the losses during cleaning and/or repair of equipment

Not included are:

- the expected losses due to blow-off of relief valves
- other losses which are not normal but can be expected (start-up and shut-down losses)

1.7.2. Water pollution

The water flow to the process sewer should be as minimal as feasible. The quantity of organic and inorganic components in the water should be known for normal operating conditions as well as special cases e.g. start-up, shut-down, blow-down and grade change. The temperature is typically 25 °C and shall not exceed 30 °C, see the waste water section in chapter 5 – Process and technology for details. A weight fraction of urea and ammonia of around 1 ppm should be feasible with this plant.

1.7.3. Soil pollution

The soil should be protected to prevent possible pollution.

1.8. Utility specifications at battery limits

The utility data as well as the statement that the total capacity will be available at Battery Limits will be confirmed and approved by **UPP** Utility department (*or other utility supplier*). All utility figures mentioned in this chapter shall be verified and adapted if necessary and have to be approved by the Utility Supplier and the client.

1.8.1. Electric power

For the power requirement of the pumps and compressors see the equipment list in chapter 5 of the project report. For preliminary Conceptual engineering, the following information can be used.

STANDARDIZED VOLTAGE

Alternating current: 50 Hz

1.8.1.1. 10,000 VOLT - 3 PHASE - 50 CYCLES

Derived from the utilities system outside battery limits. The system is or shall be neutral grounded by an 8 Ohm resistance. The maximum short circuit level may be 250 up to 500 MVA. For motors above 400 kW.

1.8.1.2. 690/400 VOLT - 3 PHASE + NEUTRAL - 50 CYCLES

This system shall be derived from the 10 kV system with delta-star (DYN) connected transformers. The secondary starpoint of the feeding transformers shall be solidly grounded in the low voltage main switchboard.

690 V main switchboard:

motors from 55 kW with a maximum power (in kW) equal to 17 % of the rated power of one transformer feeder (in kVA).

690 V MCC:

motors from 15 kW up to and including 90 kW.

1.8.1.3. 400/230 VOLT - 3 PH + NEUTRAL - 50 CYCLES

This system shall be derived from the 10 kV or 690 V system with DYN-connected transformers. The secondary starpoint of the feeding transformers shall be solidly grounded in the low voltage main switchboard.

400 V main switchboard:

motors from 55 kW with a maximum power (in kW) equal to 17 % of the rated power of one transformer feeder (in kVA).

To a combined main switchboard/MCC all motors up to the above mentioned maximum power may be connected.

400 V MCC:

motors up to and including 55 kW.

In case of variable speed drives, different power ratings can apply for the connection to the switchboards. Proposals have to be discussed with owner.

The motor of a drive and the motor of the spare-drive, e.g. the A and B drive, shall be connected to different sides of the buscoupler or to different MCC's fed from different sides of the buscoupler. All motors which belong to a specific unit, for instance motors and the auxiliary motors of a compressor, shall be connected to one and the same side of the HV and/or LV buscoupler(s) and/or to one and the same MCC.

1.8.1.4. 230 VOLT - 2 WIRE - SINGLE PHASE - 50 CYCLES

This system is derived from a 400 Volt - 3 phase - 4 wire system having the neutral grounded.

1.8.1.5. 42 VOLT - 2 WIRE - SINGLE PHASE - 50 CYCLES

This system is normally derived from local installed 230/42 Volt 100 VA transformers.

1.8.2. Electric Power - Direct Current

1.8.2.1. 110 VOLT DC - non earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up.

1.8.2.2. 110 VOLT DC - earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up. The +pole of the system shall be earthed in the first 110 V DC switchboard.

1.8.2.3. 24 VOLT DC - non-earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up.

1.8.2.4. 24 VOLT DC - earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up. The -pole of the system shall be earthed in the first 24 V DC switchboard

1.8.2.5. Other voltage systems and networks

Other voltage systems and networks can be used for special instruments (e.g. computer systems). This will be subject to owners approval. These voltages shall always be derived from the 400/230 V system by means of transformers or -in case of DC- rectifier(s) with suitable battery back-up.

Equipment other than motors shall be connected to the different voltage systems as mentioned here-under:

- packaged units : 400V or 690V 3 phases
- welding socket outlets : 400V 3 pH
- heat tracing : 230V
- lighting : 230V
- socket outlets : 230V
- computer systems : 230V
- socket outlets or handlamps and portable tools in enclosed spaces : 42V
- control of HV switchgear : 110V DC non-earthed
- control of LV switchgear : 110V DC earthed
- emergency lighting in control room and switch room : 110V DC earthed
- network annunciator systems in switch room : 110V DC earthed
- telephone system : 60V DC
- process control equipment : according to EP 5.6-2.1

The pumps and compressors can be found in Chapter 5 – Equipment list and Specification of the process report

1.8.3. Steam

The situation of the used and/or generated steam should be **checked** carefully because there are many types of steam (check for specific site).
The following steam conditions apply at the battery limit:

For technological design the temperature of the saturated steam will be used at the normal operating pressure minus the pressure drop over the inlet lines and valves.

Boiler

1.8.3.2. 25.5 bar

pressure	: bar	25.5	23	28 (setpoint PSV)
temperature	: °C	225	200	275
design	: 275 °C and 0-13 bar (steam condensate: 225 °C)			
	fouling coeff.	: 10,000 W/m ² K		

1.8.3.3. 4.5 bar

pressure	: bar	4.5		5.5 (setpoint PSV)
temperature	: °C	148	140	200
design	: 250 °C and 0-5.5 bar (steam condensate: 148 °C)			
	fouling coeff.	: 10,000 W/m ² K		

1.8.3.4. Steam condensate return (at B.L.)

Medium pressure condensate

- conductivity max. 50 µS/cm
- iron content max. 0.5 mg/l
- temperature 200-225 °C
- pressure 25.5 bar

Low pressure condensate

- conductivity max. 50 µS/cm
- iron content max. 0.5 mg/l
- temperature 100-148 °C
- pressure 4.5 bar

The steam condensate return will be free of oil, poisonous components and volatile combustible components.

1.8.4. Water

1.8.4.1. Canal water

The cooling tower make - up water is flocculated water from the *Canal*.

pressure (at ground level)	average	: 7.5	bar
	max. and design	: 16	bar

	minimum	: 6	bar
temperature	average	: 14	°C
	max. and design	: 25	°C
	minimum	: 4	°C

Quality of flocculated canal water:

Component	Unit	average value	maximum value	minimum value
chloride (as Cl ⁻)	mg/l	60	130	20
Sulphate	mg/l	60	90	35
Nitrate	mg/l	10	15	3
Bicarbonate	mg/l	180	245	120
Active SiO ₂ (silicagel)	mg/l	6	15	2
Inactive SiO ₂ (silicagel)	mg/l	0.3	0.8	0.1
Calcium	mg/l	75	105	45
Magnesium	mg/l	7	12	3
Sodium	mg/l	35	90	13
Potassium	mg/l	5	7	3
Ammonium	mg/l	2	4	<1
Total iron	mg/l	≤0.2	0.2	<0.2
KMnO ₄ -number	mg/l	7	10	5
pH	-	7.7	8.0	7.4
suspension of SiO ₂	mg/l	1	2	0.6
suspended components	mg/l	1.2	3	0.7
conductivity	:S/cm	500	850	300
total hardness	mg eq/l	4.3	5.8	2.8

Maximum values are based on a dry summer with low water levels in the river Maas and adjacent Julianakanaal. The above shown figures for maximum and minimum values do not necessarily occur simultaneously.

1.8.4.2. Cooling water

Cooling water is a factor 3 concentrated from the make-up water for this plant

pressure	pump discharge	: 5 bar
	design	: 7 bar
temperature	minimum	: 5 °C
	design	: 80 °C
Maximum allowable temperature increase	of the total return	: 10 °C
for individual pieces of equipment		: 17 °C
Maximum allowable pressure drop for individual equipment		: 0.7 bar
Maximum allowable pressure drop for equipment in series		: 1.0 bar

The cooling water system will be designed for a cooling water system inlet temperature of 35 °C, outlet temperature 25 °C at a wet bulb temperature of 18 °C. This situation will be exceeded on average 2 % per year.

For cooling water based on concentrated and fully conditioned canal water, the design film temperature of the water film in coolers shall not exceed 60 °C for new equipment. The maximum outlet temperature for a new individual cooler must not exceed 42 °C.

For fouling factors to be used in the design reference is made to section 1.8.3 of this document.

1.8.4.3. Inhibitor and conditioning system

The same conditioning system as used for the ammonia/melamine plant will be used,. *This is a 5-10 % solution of acetodiphosphonic acid, CAS-number 2809-21-4.) Acetodiphosphonic acid is a detergent used in the plant for conditioning the cooling water. This prevents the solidification of calcium carbonate and the growth of bacteria.*³⁷

1.8.4.4. Demineralised water at battery limits

Quality		average	max.	min.
active SiO ₂	mg/l	0.03	0.05	0.02
inactive SiO ₂	mg/l	0.04	0.08	0.01
total SiO ₂	mg/l	0.07	0.10	0.03
Total Fe	mg/l	0.02	0.05	0.01
conductivity	µS/cm	0.2	0.5	0.1
pH	-	7	6.5	
oxygen	mg/l	10	12	8
total hardness	mg eq/l	0.001	0.001	0.001
temperature	°C	15	30	4
pressure	bar	4.5	7.5	3.0

For fouling factors to be used see section 1.8.3.

1.8.4.5. Potable water at battery limits

Pressure	minimum	: 3 bar
	normal	: 4.5 bar
	max. and design	: 6 bar (set pressure for safety valve)
Temperature	minimum	: 10 °C
	maximum	: 14 °C

1.8.4.6. Fire fighting water

See canal water. In case of fire the pressure will be boosted up to 16 bar, which is the design pressure of the system.

1.8.5. Air

1.8.5.1. Instrument air

Pressure min.	: 4.5 bar	max. and design	: 8 bar (setpoint PSV)
norm.	: 5.8 bar		
Temperature norm.		: ambient	
design	: 50 °C		
dew point		: -30 °C	
quality	: free of oil and dust		

A filter shall be installed ISBL to free the air of oil and dust.

1.8.5.2. Plant & Breathing air

Pressure min.	: 5.5 bar for plant air		
	: 4.5 bar for breathing air		
max. and design	: 8 bar (setpoint PSV)		
norm.	: 5.5 bar		
Temperature norm.		: ambient	
design	: 50 °C		
dew point		: ambient	

An ISBL filter for breathing air will be installed.

1.8.6. Nitrogen (oxygen free)

Pressure min.	: 4.0 bar		
max. and design	: 7.0 bar (setpoint PSV)		
norm.	: 5.0 bar		
Temperature min.		: 10 °C	
max. and design	: 50 °C		
dew point	: -60 °C		

composition

nitrogen	min.	: 99.9 % (vol.)
hydrogen	max.	: 3 ppm
oxygen	max.	: 5 ppm
carbon dioxide	max.	: 5 ppm

1.8.7. Natural gas This plant is located in the Netherlands. Low caloric gas will therefore be available.

1.8.7.1. Low caloric

type	: Low calorific without odorant
temperature	: 15 °C
pressure typical	: 17 bar (reduced ISBL to approx. 2 bar)
Composition	: typical
saturated hydrocarbons	: vol. % 85
N ₂	: vol. % 14

CO ₂		: vol. %	0.9
UHV	: MJ/Nm ³		35
LHV	: MJ/Nm ³		32
Wobbe no.		: MJ/Nm ³	45
Wobbe no.		: MJ/kg	31
Total sulphur content		: mg/Nm ³	0.4
density at T=273 K		: kg/Nm ³	0.83

1.9. Existing ISBL utility data

For the utility section of the plant see chapter 3 – Utilities and Specification in the project report.

2. DESIGN CRITERIA AND POLICIES

2.1. Design consideration

- The plant shall be designed as a commercial unit for the performance as listed in 1.1.1.
- Where possible inherently safe design shall be applied.
- Where possible the design shall have a minimum impact on the environment and shall be as energy efficient as possible.
- Establish project key criteria and objectives.
- Establish design life time of the total installations and/or individual pieces of equipment.
- Determine which process parameters should be defined, taken into account the limitations of the technologies selected.
- Assess the significance of the process parameters.
- Identify the basic design parameters (key process parameters).
- Assure that the requirements of all key parties (operation, maintenance, marketing, finance, management, safety, quality) are recognised and presented so as to facilitate prioritisation and resolution of conflicts.
- Mention the design criteria references and assumptions (test results, R & D reports, licence package etc.).
- All relevant design criteria of each piece of equipment have to be motivated in a separate document (e.g. Design Condition Analysis).

2.1.1. State of the art of the technologies and process

- The plant and equipment design shall, where possible, incorporate only those modern (state of the art), available and proven technologies that are consistent with highly reliable, low SHE (safety, health, environmental) risk plant design and with the Corporate Requirements and Guidelines.
- The technologies shall be evaluated with 'state of the art' knowledge from inside and outside UPP. The benchmarking position shall be indicated with an approximate technical/economical evaluation of the considered process.
- Any contractor is expected to consider recent developments of the technologies during design and consult Engineering-Stamicarbon before these are incorporated or rejected.
- The implications of the technologies on equipment design and selection shall be assessed.

2.1.2. Operational requirements

- During process engineering the operating procedures are translated into process design. Operating philosophy must be defined before basic engineering to assure that the designed plant can be operated according to these instructions.

- The degree of atomisation and controlling of the plant is determined by the operating philosophy. Atomisation and control system choice should lead to minimum manning.
- Main and by-product logistics (storage, transport etc.), interference with other plants; off-spec routing shall be indicated.
- Indicate the auxiliary requirements (catalyst, inhibitors, etc.) including handling aspects.
- Operational flexibility shall be assessed in accordance with ideas of the client.
- The installation has to meet the highest performance criteria during transitions: for instance feed composition changes, throughput variations, start up and shut down.
- The design shall be based on maximum and minimum operating conditions including, start up, shut down and cleaning or maintenance procedures, unless otherwise is specified.
- Specify required regeneration equipment (catalyst, adsorbent regeneration etc).

2.1.3. Maintenance requirements

- The specific maintenance philosophy shall be determined by client and Engineering-Saipem.
- The plant equipment and materials of construction shall be consistent with a high service factor and low maintenance cost.
- Preventive, predictive maintenance and regular revision and maintenance intervals should be taken into account.
- The plant design shall allow carrying out as much routine maintenance as possible during operation or during downtime inherently necessary for process reasons.

2.1.4. Allowances for future extension and/or product upgrading

- Allowances for future extension and installation of equipment for product upgrading and off spec routing have to be determined in consultation with client.
- In case of constructing an additional line, the plot-plan of the first line must be designed in such a way that operation of the lines gives synergistic effects.
- In production plants with expected future expansion the capacity of special equipment may be over-designed. This shall be mentioned in the Design Basis and determined by the client.

2.1.5. Project and Technological risks

- The following major technological and project risks and uncertainties are present during the conceptual engineering phase of this project: (kinetics, crystallization characteristics and thermodynamics partly unknown etc.)
- The investigation of risk reduction options and remedial actions are part of this project.
- Indicate with sensitivity analysis the economics of the considered risk options.
- After approval of the owner, the contractor is allowed to use other technologies than mentioned in the design.
- Experiences of UPP with vendors are reflected in the preferred vendor-list.

- Appreciation's of client can also determine the choice between several alternatives.
- The choice between a commercially proven, pilot plant proven, and a recently developed technology is complex and shall be assessed and agreed by Engineering-Saipem and client.

2.1.6. Equipment including package units

Package units are equipment and/or process systems, which are purchased from specialised vendors in order to obtain the necessary performance integrity.

Package units include:

- Pumps, compressors, blowers, centrifuges, mixers, extruders, granulators and other rotating equipment
- Cooling towers, refrigeration equipment, cooling belts
- All fired equipment, incinerators and flares, hot oil furnaces
- Solid handling equipment including storage, filters, sieves, pneumatic transport, dosing units
- Hoisting equipment, bagging, debugging and packing equipment

Design, manufacturing and erection of package units shall comply with:

- Dutch national and local codes
- International design standards and specifications
- Additional requirements as mentioned in owners dedicated project specifications
- Additional requirements according to owners standard specifications as mentioned in the dedicated project specifications
- The UPP Corporate Requirements and Guidelines and Operational Requirements.

Equipment, lines, valves etc. shall be designed according to ANSI/DIN specifications where possible.

The scope of supply shall at least include the design, manufacturing, delivery and, when applicable, erection of equipment and or parts, necessary to achieve the required duty and safe operations.

The contractor remains fully responsible for a good design and the fitness for successful operation of the equipment and package units. The contractor remains also fully responsible for delivery in time of documents, services and materials.

In principle, only equipment, components and constructions, which have been proven during at least two years successful operation in similar process conditions, are acceptable.

The contractor makes sure, that at least the following guarantees (by Vendor) are incorporated in the agreements with Vendors:

- The compliance of the units, the components and the performance of the installation with the applicable technical specifications.

- That the installation and its individual parts function properly in all respects and that they are free from defects and sound in terms of design, workmanship and fabrication.
- Specific performance guarantees with regard to consumptions, capacities and quality of products; these specific performance guarantees shall be described as detailed as possible in figures which are easily measurable in the installation while operating.

In principle the Owner will provide a 'Vendor list'. The contractor is allowed to add other vendors to the list, resulting in the 'proposed Vendor list'. The Owner has the right to make modifications to this list. After Owner's approval, the modified/approved Vendor list will be appointed as the 'project Vendor list'. In case no Vendor list is provided by the Owner, the contractor shall compose and provide a 'project Vendor list'. The Owner has the right to make modifications to this list.

2.2. Total Quality Management Aspects

The contractor shall demonstrate that its organisation is supported by a Quality System, which preferably meets the requirements mentioned in ISO9001, in order to achieve quality of engineering. The organisation and procedures of the contractor can be assessed by means of a quality audit. This audit gives information about the deviations between ISO9001 and the contractor's activities. The contractor shall prepare a project quality plan to demonstrate that engineering is executed according to ISO9001. This plan is to be regarded as the translation of the quality system in working procedures during the project. The same applies in rough outlines for the construction phase.

The contractor shall demonstrate a SHE project plan according to UPP and government standards and requirements.

2.3. Design standards and codes

The facility shall be designed in accordance with:

- UPP -design specifications and Process Design Guides (if applicable) as defined in the Project specification have to be used.
- Recommended practices as laid down in API reports and bulletins shall be adhered to.
- For the design or rating of shell and tube heat exchangers, the design methods of HTRI, or on contractors request HTFS, are strongly recommended.
- For heat exchanger types different from shell and tube, the design methods of HTFS are recommended or the design methods of approved vendors.
- For the design of fractionators the design methods of FRI are strongly recommended or for specific types of packing or tray types, the design methods of approved vendors.
- For the earthing of equipment the LP3 or LP4 safety measures shall be taken, in compliance with NEN1014.

2.4. Plant availability and sparing policies

2.4.1. Availability

The plant shall be designed for an annual availability of 8000 hours (12.5 tons per h) on-stream time. Availability should be read as availability for starting, stopping, production and regular cleaning procedures (e.g. Cleaning in Place). While the planned shut-down of the whole plant for maintenance and 'Stoomwezen' inspection might take place every 2 years for 2-3 weeks, the unexpected plant outages may add up to approximately 20 days per year. Regular maintenance or inspection shall not entail the total shut-down of the plant. It should be noted that the plant gets its feed directly from the ammonia plant, a shutdown of the latter will generate a shutdown of the subject plant. This effect has been taken into account in the annual availability.

2.4.2. Sparing policy

2.4.2.1. Vital services

Vital services are those which in the event of failure could cause an unsafe condition of the installation, jeopardising life and/or equipment. Running equipment in vital service shall be 100 % spared with one of the power sources being electric drive whilst the other motive source should be steam, diesel or gas turbine. The spare equipment shall always be available for operation and therefore a third facility should be available to allow essential maintenance to be carried out while the plant remains onstream. Vital services will include:

- Safeguarding devices (XPV's) for S1 situations
- Pressure relief systems (two PSV's which must be cleaned after use)
- Instrument air supply (ring line)
- Firewater supply (ring line)
- Electrical supply to control room
- Electrical supply to instruments being part of S1 safety loop

Note: In general there will not be installed two pressure relieving devices, the second being a back-up for the first. However this is required when it is expected that the relief valve will not re-open easily after closure, this may be caused by a sticky product. A second relieving device may be dictated by risk analysis.

2.4.2.2. Essential services

The essential services are those which, in the event of their failure, would result in the plant not being available to operate at 100% capacity and make it impossible to obtain the required availability between planned shut-downs.

Normal running equipment in essential service shall be 100 % spared. The spare unit driver does not require an alternative power source. If more than one piece of

equipment, say n units, are required to obtain 100% design capacity, n+1 units shall be installed.

- It may be agreed upon not to install a second pump, but have a complete spare pump and spare motor in stock. This can be done when it is guaranteed that the change can be made in a couple of hours.

Other equipment in essential service shall have adequate provision to ensure operation in accordance with the above definition.

- In some cases, however, i.e. sparing of expensive equipment, the economics may be overriding in sparing policy decisions. (e.g. extruders, compressors)

Essential services include:

- Boiler feed water treating and steam generation facilities
- Seal oil/Lube oil systems of major equipment
- Effluent treatment facilities
- All process unit feed, reflux and product pumps
- Fuelgas supply
- Cooling water supply

2.4.2.3. Non-essential services :

Non-essential services are those which, in the event of failure for a limited time, would not impair production. Rotating equipment in non-essential service need not be spared. Non-essential equipment shall not have provisions for performing essential services.

2.5. Legal requirements and company requirements

The complete list of legal requirements applicable to this project will be defined in the Project specification. It will include requirements derived from the following laws:

- 'Wet Milieubeheer' (Environmental Protection Law)
- 'Stoomwet' (Rules for Pressure Vessels)
- 'Arbeidsomstandighedenwet' (Occupation Safety and Hazard Act)
- 'Wet verontreiniging oppervlaktewateren' (Water pollution Act)
- 'Bouwvergunning' (Building Permit)

Policies of **UPP** management:

- Corporate Requirements and Guidelines and Operational Requirements
- 'Beleidsverklaring' (**UPP** Policy Statement)

2.6. Safety, health and environmental considerations

Careful consideration must be given to operability and safety under normal operation, turn down, start up, shutdown and emergency conditions.

2.6.1. Corporate Standards

Translate the Corporate Safety and Environmental policies into key design features. Anticipation of the likely Safety, Health and Environment (SHE) restrictions of the permit and UPP corporate standards is made in the process design. UPP requirements are among others the Corporate Requirements and Guidelines.

The major potential hazards will be identified using the following methods:

- Systematic process safety analysis (PSA: 'Process Safety Analysis') (Proces Veiligheids Analyse)).
- MCA analyses (Max. Credible Accident) to be based on plot plan, lay out and site.
- Risk analyses, effect calculations and damage calculations.
- DOW F&E Index

The following design standards are to be met:

- Process Design Guide 3.1 "Pressure relieving devices" latest revision.
- For venting requirements, fire protection, evaporation losses, protection against ignitions (several sources), personal protection and design see relevant API-recommendations.

Designing for external fire condition shall be determined by mutual agreement between Engineering-Stamcarbon and owner. According to Corporate Requirements and Guidelines and API-reports all equipment shall be protected against overpressure i.e. also caused by external fire. However indiscriminately designing for external fire conditions has to be avoided by: Thorough analysis of the cause and the source of the fire. Calculations must be made if the maximum pressure increase, due to external fire, may exceed the design pressure regarding the amount of burning component present.

The contractor shall establish the scope and standard in co-operation with UPP for:

- * drain systems
- * fire protection
- * fire proofing, insulation and/or coating
- * emergency showers, eye showers

2.6.2. Asbestos

Asbestos or composites containing asbestos will not be used in this plant.

2.6.3. Noise

The maximum allowable noise level of individual pieces of equipment shall be according to DIN 80 dB(A) at 1 meter distance, under all circumstances. However a noise level of less than 75 dB(A) at 1 meter is strongly preferred. The total noise level shall not exceed the so called site noise 'Contours'.

2.6.4. Energy conservation

- Energy and thermal integration aspects should be considered in relation with corporate philosophy and client standpoint or view.
- Pinch Analysis and Exergy Analysis might be applied to check the energy efficiency.

2.7. Process control philosophy

- For the key process parameters (only 5 to 10) 'Statistical Process Control' (SPC) must be applied when agreed upon with the client.
- DCS, model based process control, advanced process control systems should be assessed with regard to process optimisation, environmental pollution and product quality.
- Local panel, centralised or decentralised control of the plant must be considered.
- In an early design phase (feasibility/conceptual) the control philosophy should be regarded in respect with efficiency, quality and Safety, Health and Environmental requirements.

2.8. Overdesign factors

In the design of process-equipment, uncertainty factors in thermodynamic properties, design correlations and calculation methods are historically compensated for by 'overdesign factors'.

Overdesign should be used with caution, the use of indiscriminative arbitrary safety factors should be avoided.

The magnitude of the risk and consequences involved in a certain application will be reflected in the value of the appropriate safety factor. The justification of the overdesign of individual pieces of equipment will be made on the datasheets/duty-specifications.

- For several streams in the material balance more than one condition will be shown for 'normal operation', and for 'design conditions'. In this latter balance overdesign factors have been applied on process uncertainties.

2.9. Fouling resistances for design

Fouling resistances shall be recorded explicitly, and shall be agreed with the client. The resistance values have to be selected according to the following priority schedule:

1. In the field measured specific values, under identical conditions;
2. Idem, under comparable conditions (c.q. same medium, different velocity, etc.);
3. Values based on guidelines applicable to a class of comparable media:

- from corporate database or inhouse literature;
- from preferred design standards i.e. HTRI, HTFS;
- from different sources i.e.: TEMA, HEDH, VDI, other references.

For cooling water based on conditioned canalwater (viz. concentrated flocculated canalwater, full-conditioned with biofouling, corrosion and phosphate inhibitors) resistance values have to be taken from the report 'Richtwaarden voor vervuiling-coëfficiënten van behandeld koelwater', PT-RU/ RESEARCH N90.9397, oct.31 1990, grafiek bijlage 1C. The selected resistance value shall be in compliance with the cooling water conditioning programme and the effective linear velocity.

The conditioned cooling water shall be connected preferably to the tube side; the preferred velocity is 1.5 - 2 m/s and within this range as high as possible. If cooling water has to be connected to the shell-side, then an effective velocity, for definition see above mentioned report 'RESEARCH', of at least 0.7 m/s has to be pursued. According to report Research 91.9489 a fouling layer has to be taken into account when designing a shell-side cooling water heat exchanger.

In case of the conditioned river water, no flow-reducing control device(s) nor a bypass shall be installed in the cooling water stream. Throttling of the water flow can lead to:

- corrosion of carbon steel because of lack of corrosion inhibitors
- solid deposition and subsequent severe irreversible fouling;
- too high film temperatures and subsequent hydrolysis of phosphate, resulting in sludge deposition. The maximum allowed film temperature for this project is 50°C, this number should be used for a clean heat exchanger.
- chloride stress corrosion of austenitic stainless steel at elevated wall temperatures (>60 °C).

Use of coating at the tube side, to prevent fouling or corrosion, has to be checked with UPP.

The following fouling resistances will be used in this project:

Liquid process stream:urea	5,000	W/m ² K
Vapour distillation column (clean)	6,700 - 10,000	W/m ² K
Steam	10,000	W/m ² K
Condensate, hot water	10,000	W/m ² K
Chilled water	10,000	W/m ² K
Brine	10,000	W/m ² K
Untreated flocculated river water	12000	W/m ² K
- Treated flocculated river water depends on method of treatment:		
e.g. Cooling water	v = 1 m/s	1667 W/m ² K
v = 1.5 m/s		3333 W/m ² K
v = 2 m/s		5000 W/m ² K

2.10. Corrosion allowance

Basically corrosion allowance shall be granted in case of general corrosion attack. For critical process equipment, Engineering-Saipem has to be consulted on this subject. Generally the allowance shall not exceed 3 mm, for economical reasons. A more resistant construction material shall be selected when required, also considering the design lifetime. No corrosion allowance with respect to ambient (atmospheric) conditions shall be used.

All materials to be used for piping and equipment will be detailed in the Construction Material report, which is part of the Conceptual Process Design Package.

The corrosion allowance for utilities (equipment and piping):³⁸

instrument air, mat. CS	: 1 mm
breathing air, mat. galvanised CS	: 1 mm
plant air, mat. CS	: 1 mm
nitrogen, mat. SS	: 0 (zero) mm
steam, mat. SS	: 0.8 mm
condensate, mat. SS	: 0.8 mm
cooling water, mat. SS	: 0.8 mm
demineralized water, mat. SS	: 0.8 mm

The corrosion allowance for process streams will be 0 (zero) mm except for:

Fluid A, mat. SS with a layer of zirconium : 3 mm

Fluid A: solutions in the process containing a high concentration of ammonium carbamate. These will be highly corrosive liquids. The zirconium is used for protecting the stainless steel and a passivation layer will be formed with the added passivation air. It is estimated that a large corrosion allowance is still required here.

2.11. Economic criteria for optimisation of sub-systems

- An estimate of the production cost and preliminary economic analysis (pay-out time) including sensitivity analysis should be made in co-operation with the client.

For feasibility studies during the design the following prices (in euro) will be used:

- (see editions of 'variabele verrekenprijzen Utilities' in order to obtain the prices).³⁹

Power:	0.07	€/kWh
LP steam (4.5 bar)	: 15.00	€/t variable cost
MP steam (25 bar)	: 20.00	€/t variable cost
natural gas	: 1.90	€/GJ
Potable water	: 0.65	€/t
demin. water	: 1000	€/t
nitrogen	: 65.35	€/t ⁴⁰

2.12. Temperatures and pressures for mechanical design

Regarding temperatures and pressures for mechanical design of plant piping (excluding transmission lines outside battery limits) and equipment, reference is made to the latest revision of Process Design Guide 1.15: 'Determination of the design pressures and design temperatures'. The design conditions will be reported on the Equipment Design Condition Forms which are a part of the Conceptual Process Design Package.

3. GENERAL DESIGN DATA

3.1. Units of measurement

SI units shall be adhered to, and the use of the following specific units is preferred.

- pressure : bar (10^5 N/m^2) absolute pressure unless stated otherwise
- flow : kg/s, kg/h, m^3/s , m^3/h , Nm^3/s
- viscosity : mPa.s
- power and heat flow : Watt (W, kW)
- energy : Joule (J, kJ)
- Nm^3 are defined at 0 °C and 1.01325 bar

3.2. Meteorological data (Limburg)

3.2.1. Wind conditions

Prevailing wind : South West (see figure 3.1)

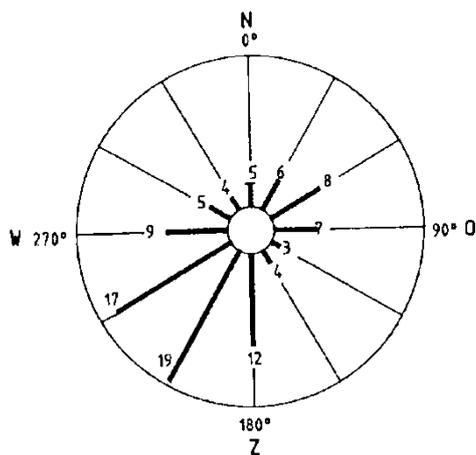


Figure 3.1 Compass-card for Beek (the Netherlands) detailing the occurrence of wind directions (in percentages). Data averaged over the period 1949 - 1970. Fluctuating wind conditions 1 %, no wind 2 %.

3.2.2. Wind speed

- For the design of structures, buildings etc. see the Project Specification.
- For the calculation of heat losses 10 m/s.
- For the calculation of gas dispersion in the atmosphere min. 2 m/s (Pasquill class F) for the MCA calculations.

3.2.3. Temperatures

- In tanks, as caused by the radiation of the sun : 50 °C
- In tanks surrounded by a wall at approximate 2 m : 60 °C

3.2.4. Air temperatures

Extreme max. dry bulb : 35 °C
Minimum dry bulb : -20 °C.
35 °C is exceeded during 10 minutes/year
30 °C is exceeded during 10 hours/year

3.2.5. Design air temperatures for equipment:

- Air compressor - dry bulb 25 °C
 - wet bulb 18 °C
- Cooling tower - dry bulb 25 °C
 - wet bulb 18 °C
- Minimum air temperature -20 °C
- air conditioning : according to HVAC specification.

3.2.6. Relative humidity

Average, summer 75 %
Design - summer 85 %
- winter 100 %

3.2.7. Barometric pressure

Maximum 1050 mbar
Minimum 950 mbar
Design 1030 mbar

3.2.8. Rain- and snowfall

Rain, maximum 0.8 mm/minute during 15 minutes (135 l/s/10.000 m² for 15 minutes)
Run off: 90 % on paved roads and roofs, 50% on unpaved roads.
Average annual rainfall 670 mm/year.
Average annual snowfall 300 mm/year.

3.2.9. Environmental conditions

The installations will be erected on UPP site at Geleen, close to ammonia/melamine plants. The ambient air is polluted with NH₃, SO₂, CO₂, nitrate, nitrous vapours and industrial dust. Copper or its alloys shall not be used, unless stated otherwise.

Appendix 2. Aspen Model

The original Aspen model

The Aspen model of the Snamprogetti urea manufacturing plant can be found in chapter 4 (Figure 23, Figure 24, Figure 25). And a detailed description of each section is given below.

A2.1 Stream Summary Aspen file

- The stream results below are listed in alphabetical order
- The flow rates have been rounded to the nearest full number
- The mass fractions have been given in scientific form to allow the identification of small fractions of components (important to assess the purity, in ppm and ppb, of emitted streams)
- Some recycle streams were not connected in the Aspen model. To achieve a correct mass balance, the incoming streams of the recycles were disregarded, and are shown in red.

	Units	AMMHOT	AMMLI Q	AMMLI Q2	AMMRC YC	AMMRCY C2	AMMSC RB	AMMSCR B1	AMMSCR B2
From		C1202-2	E1202		AMMSPL T	P1102	C1203-2	B7	
To		E1202		V1201-2	P1102	P1101	P1202		C1202-2
Phase:		Vapor	Mixed	Mixed	Mixed	Liquid	Mixed	Mixed	Mixed
Component Mass Flow									
UREA	KG/HR	0	0	0	0	0	0	0	0
CARB	KG/HR	0	0	0	0	0	0	0	0
CO2	KG/HR	0	0	0	0	0	0	0	0
NH3	KG/HR	6957	6957	6941	10232	10232	178	178	177
H2O	KG/HR	0	0	0	0	0	699	699	699
N2	KG/HR	12	12	13	1	1	0	0	0
O2	KG/HR	12	12	13	4	4	0	0	0
CH4	KG/HR	25	25	24	19	19	0	0	0
Component Mass Fraction									
UREA		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CARB		5,13E-12	5,13E-12	5,12E-12	2,51E-12	2,51E-12	0,00E+00	0,00E+00	0,00E+00
CO2		9,63E-10	9,63E-10	9,62E-10	4,85E-10	4,85E-10	5,02E-13	5,02E-13	9,74E-13
NH3		9,93E-01	9,93E-01	9,93E-01	9,98E-01	9,98E-01	2,03E-01	2,03E-01	2,02E-01
H2O		1,87E-08	1,87E-08	1,88E-08	9,20E-09	9,20E-09	7,97E-01	7,97E-01	7,98E-01

N2		1,78E-03	1,78E-03	1,82E-03	1,27E-04	1,27E-04	1,63E-06	1,63E-06	1,73E-06
O2		1,66E-03	1,66E-03	1,86E-03	3,68E-04	3,68E-04	9,46E-06	9,46E-06	1,27E-05
CH4		3,56E-03	3,56E-03	3,38E-03	1,83E-03	1,83E-03	1,20E-04	1,20E-04	1,18E-04
Mass Flow	KG/HR	7006	7006	6991	10256	10256	877	877	876
Volume Flow	CUM/HR	523	30	30	19	19	1	1	1
Temperature	C	45	40	40	40	55	65	65	65
Pressure	BAR	18	18	18	18	200	18	18	18
Vapor Fraction		1	0	0	0	0	0	0	0
Liquid Fraction		0	1	1	1	1	1	1	1
Mass Enthalpy	KJ/KG	-2711	-3811	-3810	-3853	-3788	-13415	-13414	-13425
Enthalpy Flow	KW	-5276	-7416	-7398	-10975	-10790	-3269	-3268	-3268
Mass Density	KG/CUM	13	236	236	539	552	902	902	902

	Units	AMMTOD IS	CARBMR C1	CARBMR C2	CARBR 1	CARBR 2	CARBRC CL	CARBRCY C	CO2
From		V1201-2	C1202-2	C1202-1	V1101			P1201	
To		P1203	C1202-1	P1201		P1101	E1101		R1101
Phase:		Liquid	Liquid	Liquid	Liquid	Mixed	Liquid	Liquid	Vapor
Component Mass Flow									
UREA	KG/HR	0	0	4	14	14	4	4	0
CARB	KG/HR	0	608	4990	7765	7761	4990	4990	0
CO2	KG/HR	0	11	9	28	28	9	9	9185
NH3	KG/HR	14211	2847	4058	5457	5432	4058	4058	0
H2O	KG/HR	0	704	2661	2866	2863	2661	2661	0
N2	KG/HR	2	0	0	7	7	0	0	11
O2	KG/HR	5	0	0	16	18	0	0	5
CH4	KG/HR	26	0	0	28	27	0	0	0
Component Mass Fraction									
UREA		0,00E+00	0,00E+00	3,52E-04	8,80E-04	8,82E-04	3,52E-04	3,52E-04	0,00E+00
CARB		2,51E-12	1,46E-01	4,26E-01	4,80E-01	4,81E-01	4,26E-01	4,26E-01	0,00E+00
CO2		4,85E-10	2,59E-03	7,46E-04	1,71E-03	1,72E-03	7,45E-04	7,46E-04	9,98E-01

NH3		9,98E-01	6,83E-01	3,46E-01	3,37E-01	3,36E-01	3,46E-01	3,46E-01	0,00E+00
H2O		9,20E-09	1,69E-01	2,27E-01	1,77E-01	1,77E-01	2,27E-01	2,27E-01	0,00E+00
N2		1,27E-04	1,36E-06	2,88E-07	4,36E-04	4,48E-04	2,89E-07	2,88E-07	1,14E-03
O2		3,68E-04	4,89E-06	1,36E-06	1,01E-03	1,12E-03	1,36E-06	1,36E-06	5,08E-04
CH4		1,83E-03	1,04E-05	2,40E-06	1,74E-03	1,66E-03	2,40E-06	2,40E-06	0,00E+00
Mass Flow	KG/HR	14244	4171	11722	16181	16150	11722	11722	9200
Volume Flow	CUM/HR	26	6	13	20	20	13	13	43
Temperature	C	40	54	71	155	155	72	78	160
Pressure	BAR	18	18	18	150	150	150	150	150
Vapor Fraction		0	0	0	0	0	0	0	1
Liquid Fraction		1	1	1	1	1	1	1	0
Mass Enthalpy	KJ/KG	-3854	-6558	-8384	-7718	-7723	-8371	-8352	-8877
Enthalpy Flow	KW	-15248	-7597	-27300	-34692	-34644	-27260	-27196	-22685
Mass Density	KG/CUM	550	712	901	811	812	907	900	213

	Units	CONDOU T	EXTRA WA T	EXTR WAT 2	INERTS	LIQREC	LIQREC2	LP1	LP2
From		E1101			V1101	R1501-2	E1502-2	C1301-3	
To		V1101	V1401	V1402	C1201-1	E1502-2	C1501-2		C1301-1
Phase:		Mixed	Vapor	Vapor	Vapor	Liquid	Mixed	Vapor	Vapor
Component Mass Flow									
UREA	KG/HR	14	0	0	0	0	0	1	1
CARB	KG/HR	7765	0	0	0	0	0	0	0
CO2	KG/HR	32	0	0	4	7	7	253	256
NH3	KG/HR	5579	0	0	122	158	158	380	376
H2O	KG/HR	2869	140	110	4	8091	8091	299	291
N2	KG/HR	19	0	0	12	0	0	0	0
O2	KG/HR	27	0	0	10	0	0	0	0
CH4	KG/HR	46	0	0	18	0	0	0	0
Component Mass Fraction									
UREA		8,71E-04	0,00E+00	0,00E+00	2,13E-06	5,41E-06	5,41E-06	1,28E-03	1,30E-03
CARB		4,75E-01	0,00E+00	0,00E+00	2,52E-04	7,04E-06	7,04E-06	2,00E-07	2,07E-07
CO2		1,95E-03	0,00E+00	0,00E+00	2,51E-	8,13E-	8,13E-	2,72E-	2,77E-

					02	04	04	01	01
NH3		3,41E-01	0,00E+00	0,00E+00	7,19E-01	1,92E-02	1,92E-02	4,07E-01	4,07E-01
H2O		1,75E-01	1,00E+00	1,00E+00	2,16E-02	9,80E-01	9,80E-01	3,20E-01	3,14E-01
N2		1,17E-03	0,00E+00	0,00E+00	7,06E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00
O2		1,63E-03	0,00E+00	0,00E+00	5,98E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CH4		2,79E-03	0,00E+00	0,00E+00	1,03E-01	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Mass Flow	KG/HR	16351	140	110	170	8256	8256	933	924
Volume Flow	CUM/HR	21	58	46	1	10	17	332	328
Temperature	C	155	150	150	155	203	150	138	138
Pressure	BAR	150	5	5	150	20	6	5	5
Vapor Fraction		0	1	1	1	0	0	1	1
Liquid Fraction		1	0	0	0	1	1	0	0
Mass Enthalpy	KJ/KG	-7669	-13212	-13212	-2944	-14895	-15130	-7644	-7617
Enthalpy Flow	KW	-34831	-514	-404	-139	-34158	-34697	-1981	-1955
Mass Density	KG/CUM	762	2	2	113	796	480	3	3

	Units	LPCARB	LPLIQ	LPOFFGAS	LPPURGE	MP1	MPCARB	MPDECVA	MPLIQ
From		V1301	C1301-3	C1301-1	V1301	C1201-3	P1301	C1201-1	C1201-3
To		P1301	C1302-3	E1301		C1201-1	PREHMX	PREHMX	C1301-1
Phase:		Liquid	Liquid	Vapor	Vapor	Vapor	Liquid	Vapor	Liquid
Component Mass Flow									
UREA	KG/HR	1	12963	1	0	3	1	3	12965
CARB	KG/HR	1107	50	0	0	0	1107	0	498
CO2	KG/HR	0	4	278	12	1600	0	2197	27
NH3	KG/HR	1008	327	1191	297	2131	1008	7546	1326
H2O	KG/HR	1376	5507	446	2	486	1376	586	5961
N2	KG/HR	0	0	0	0	0	0	12	0
O2	KG/HR	0	0	0	0	0	0	10	0
CH4	KG/HR	0	0	0	0	0	0	18	0
Component Mass Fraction									
UREA		4,10E-04	6,88E-01	7,25E-04	2,07E-09	7,08E-04	4,10E-04	2,59E-04	6,24E-01
CARB		3,17E-01	2,64E-03	9,17E-07	1,42E-08	1,83E-06	3,17E-01	3,64E-06	2,40E-02
CO2		9,50E-	1,89E-04	1,45E-01	3,99E-02	3,79E-	9,50E-	2,12E-01	1,29E-

		05				01	05		03
NH3		2,89E-01	1,74E-02	6,21E-01	9,55E-01	5,05E-01	2,89E-01	7,28E-01	6,38E-02
H2O		3,94E-01	2,92E-01	2,33E-01	5,14E-03	1,15E-01	3,94E-01	5,65E-02	2,87E-01
N2		6,14E-14	0,00E+00	1,28E-09	7,91E-09	1,33E-06	6,14E-14	1,16E-03	1,18E-10
O2		1,26E-11	0,00E+00	2,73E-08	1,68E-07	5,85E-06	1,26E-11	9,79E-04	2,52E-09
CH4		1,49E-11	0,00E+00	3,98E-08	2,45E-07	9,31E-06	1,49E-11	1,69E-03	3,67E-09
Mass Flow	KG/HR	3493	18851	1916	311	4219	3493	10371	20776
Volume Flow	CUM/HR	4	17	726	100	352	4	921	20
Temperature	C	40	138	124	40	155	41	131	155
Pressure	BAR	5	5	5	5	18	18	18	18
Vapor Fraction		0	0	1	1	1	0	1	0
Liquid Fraction		1	1	0	0	0	1	0	1
Mass Enthalpy	KJ/KG	-10040	-8013	-5920	-2983	-6112	-10035	-4458	-7935
Enthalpy Flow	KW	-9740	-41957	-3151	-257	-7164	-9736	-12843	-45795
Mass Density	KG/CUM	948	1097	3	3	12	947	11	1035

	Units	MPPREH	NH3	NH3PURE	PREHCARB	PREHCRB1	PRODUCT	PUREWA T	PUREWAT 2
From		PREHMX		AMMSPLT	C1302-2	E1201	V1402	C1501-2	E1501-2
To		C1302-1	V1201-1	C1202-2	E1201	C1202-1		E1501-2	
Phase:		Mixed	Liquid	Mixed	Mixed	Mixed	Liquid	Liquid	Liquid
Component Mass Flow									
UREA	KG/HR	4	0	0	4	4	12516	0	0
CARB	KG/HR	1107	0	0	3446	4382	2	0	0
CO2	KG/HR	2197	0	0	879	352	0	0	0
NH3	KG/HR	8553	7450	3979	7533	7125	0	0	0
H2O	KG/HR	1962	0	0	1962	1962	47	8153	8153
N2	KG/HR	12	0	1	12	12	0	0	0
O2	KG/HR	10	0	1	10	10	0	0	0
CH4	KG/HR	18	149	7	18	18	0	0	0
Component Mass Fraction									
UREA		2,97E-04	0,00E+00	0,00E+00	2,97E-04	2,97E-04	9,96E-01	5,48E-06	5,48E-06
CARB		7,99E-02	0,00E+00	2,51E-12	2,49E-01	3,16E-01	1,98E-04	7,13E-06	7,13E-06
CO2		1,58E-01	0,00E+00	4,85E-10	6,34E-02	2,54E-02	7,98E-15	1,82E-43	1,82E-43

NH3		6,17E-01	9,80E-01	9,98E-01	5,43E-01	5,14E-01	1,55E-09	5,71E-06	5,71E-06
H2O		1,42E-01	0,00E+00	9,20E-09	1,42E-01	1,42E-01	3,77E-03	1,00E+00	1,00E+00
N2		8,65E-04	0,00E+00	1,27E-04	8,65E-04	8,65E-04	0,00E+00	0,00E+00	0,00E+00
O2		7,32E-04	0,00E+00	3,68E-04	7,32E-04	7,32E-04	0,00E+00	0,00E+00	0,00E+00
CH4		1,27E-03	1,96E-02	1,83E-03	1,27E-03	1,27E-03	0,00E+00	0,00E+00	0,00E+00
Mass Flow	KG/HR	13864	7599	3988	13864	13864	12566	8153	8153
Volume Flow	CUM/HR	857	13	7	580	423	10	9	8
Temperature	C	106	20	40	87	75	134	148	90
Pressure	BAR	18	30	18	18	18	0	5	1
Vapor Fraction		1	0	0	1	0	0	0	0
Liquid Fraction		0	1	1	0	1	1	1	1
Mass Enthalpy	KJ/KG	-5863	-3964	-3853	-6340	-6588	-5078	-15365	-15609
Enthalpy Flow	KW	-22579	-8368	-4268	-24415	-25370	-17725	-34798	-35352
Mass Density	KG/CU M	16	581	539	24	33	1244	892	967

	Units	RCVRV	RCVRV1	RCYCIN	REACTOUT	S1	S11	S13	S14
From		V1201-2		P1101	R1101	C1302-3	C1301-2	C1201-1	E1301
To			V1201-1	R1101	E1102	MIX1	C1301-3	C1201-2	V1301
Phase:		Vapor	Vapor	Liquid	Mixed	Vapor	Mixed	Liquid	Mixed
Component Mass Flow									
UREA	KG/HR	0	0	14	12977	5	12964	12968	1
CARB	KG/HR	0	0	7761	5617	0	50	3318	1107
CO2	KG/HR	0	0	28	921	30	257	37	13
NH3	KG/HR	428	426	15664	9247	347	707	2226	1305
H2O	KG/HR	0	0	2863	6751	3604	5806	6446	1377
N2	KG/HR	13	13	9	19	0	0	0	0
O2	KG/HR	13	14	22	27	0	0	0	0
CH4	KG/HR	40	39	46	46	0	0	0	0
Component Mass Fraction									
UREA		0,00E+00	0,00E+00	5,39E-04	3,64E-01	1,37E-03	6,55E-01	5,19E-01	3,77E-04
CARB		3,57E-19	3,56E-19	2,94E-01	1,58E-01	6,51E-08	2,52E-03	1,33E-01	2,91E-01
CO2		2,55E-09	2,98E-09	1,05E-	2,59E-02	7,58E-03	1,30E-02	1,47E-	3,35E-

				03				03	03
NH3		8,68E-01	8,67E-01	5,93E-01	2,60E-01	8,71E-02	3,57E-02	8,91E-02	3,43E-01
H2O		1,77E-11	1,79E-11	1,08E-01	1,90E-01	9,04E-01	2,93E-01	2,58E-01	3,62E-01
N2		2,55E-02	2,58E-02	3,23E-04	5,35E-04	0,00E+00	0,00E+00	2,24E-07	6,46E-10
O2		2,58E-02	2,84E-02	8,29E-04	7,46E-04	0,00E+00	0,00E+00	9,90E-07	1,38E-08
CH4		8,06E-02	7,90E-02	1,73E-03	1,28E-03	0,00E+00	0,00E+00	1,57E-06	2,01E-08
Mass Flow	KG/HR	494	492	26406	35606	3987	19784	24995	3803
Volume Flow	CUM/HR	36	36	39	49	19395	349	24	103
Temperature	C	40	40	115	188	86	138	134	40
Pressure	BAR	18	18	150	150	0	5	18	5
Vapor Fraction		1	1	0	0	1	0	0	0
Liquid Fraction		0	0	1	1	0	1	1	1
Mass Enthalpy	KJ/KG	-2738	-2727	-6194	-7029	-12336	-7995	-7987	-9464
Enthalpy Flow	KW	-375	-372	-45434	-69516	-13663	-43938	-55453	-9998
Mass Density	KG/CUM	14	14	681	724	0	57	1043	37

	Units	S15	S16	S19	S2	S20	S21	S22	S3
From		C1201-2	V1201-1	P1203	MIX1	B4	P1202	R1501-1	C1202-1
To		C1201-3	V1201-2	B4	E1403	AMMSPL T	B7	R1501-2	C1202-2
Phase:		Mixed	Liquid	Liquid	Mixed	Mixed	Liquid	Mixed	Vapor
Component Mass Flow									
UREA	KG/HR	12968	0	0	50	0	0	0	0
CARB	KG/HR	498	0	0	0	0	0	0	0
CO2	KG/HR	1626	0	0	30	0	0	329	354
NH3	KG/HR	3457	7698	14211	348	14211	178	347	5914
H2O	KG/HR	6446	0	0	4955	0	699	9698	5
N2	KG/HR	0	2	2	0	2	0	0	12
O2	KG/HR	0	5	5	0	5	0	0	10
CH4	KG/HR	0	42	26	0	26	0	0	18
Component Mass Fraction									
UREA		5,19E-01	0,00E+00	0,00E+00	9,22E-03	0,00E+00	0,00E+00	4,31E-06	1,05E-19
CARB		1,99E-02	0,00E+00	2,51E-12	1,28E-07	2,51E-12	0,00E+00	5,60E-06	3,23E-08
CO2		6,51E-02	1,85E-10	4,85E-10	5,61E-03	4,85E-10	5,02E-13	3,17E-02	5,60E-08

		02							02
NH3		1,38E-01	9,94E-01	9,98E-01	6,46E-02	9,98E-01	2,03E-01	3,35E-02	9,37E-01
H2O		2,58E-01	1,14E-12	9,20E-09	9,21E-01	9,20E-09	7,97E-01	9,35E-01	7,86E-04
N2		2,24E-07	2,13E-04	1,27E-04	0,00E+00	1,27E-04	1,63E-06	0,00E+00	1,90E-03
O2		9,90E-07	6,40E-04	3,68E-04	0,00E+00	3,68E-04	9,46E-06	0,00E+00	1,61E-03
CH4		1,57E-06	5,46E-03	1,83E-03	0,00E+00	1,83E-03	1,20E-04	0,00E+00	2,78E-03
Mass Flow	KG/HR	24995	7747	14244	5383	14244	877	10374	6312
Volume Flow	CUM/HR	372	14	26	30218	26	1	206	475
Temperature	C	155	29	40	100	40	65	203	54
Pressure	BAR	18	18	22	0	18	22	20	18
Vapor Fraction		0	0	0	1	0	0	0	1
Liquid Fraction		1	1	1	0	1	1	1	0
Mass Enthalpy	KJ/KG	-7628	-3910	-3853	-12492	-3853	-13414	-14206	-3044
Enthalpy Flow	KW	-52958	-8413	-15243	-18679	-15243	-3268	-40939	-5337
Mass Density	KG/CUM	67	571	550	0	539	906	50	13

	Units	S4	S5	S6	S7	S8	S9	SCRBOU T	SCRBVA P
From		C1302-3	C1302-4	C1302-5	V1201-1	C1302-1	C1301-1	C1203-1	C1203-1
To		C1302-4	C1302-5	C1302-3	C1203-1	C1302-2	C1301-2	C1203-2	
Phase:		Liquid	Mixed	Vapor	Vapor	Mixed	Liquid	Liquid	Vapor
Component Mass Flow									
UREA	KG/HR	12975	12975	17	0	4	12964	0	0
CARB	KG/HR	50	2	0	0	3446	498	0	0
CO2	KG/HR	0	27	27	0	879	4	0	0
NH3	KG/HR	14	34	34	178	7533	512	178	0
H2O	KG/HR	4604	4604	2701	0	1962	5806	699	1
N2	KG/HR	0	0	0	11	12	0	0	11
O2	KG/HR	0	0	0	9	10	0	0	9
CH4	KG/HR	0	0	0	146	18	0	0	145
Component Mass Fraction									
UREA		7,35E-01	7,35E-01	6,11E-03	0,00E+00	2,97E-04	6,55E-01	0,00E+00	0,00E+00
CARB		2,82E-03	1,41E-04	3,20E-08	0,00E+00	2,49E-01	2,52E-02	0,00E+00	0,00E+00
CO2		4,25E-07	1,51E-03	9,59E-03	9,42E-11	6,34E-	2,23E-	5,02E-13	1,92E-10

						02	04		
NH3		7,82E-04	1,95E-03	1,21E-02	5,18E-01	5,43E-01	2,59E-02	2,03E-01	5,29E-04
H2O		2,61E-01	2,61E-01	9,72E-01	1,39E-20	1,42E-01	2,93E-01	7,97E-01	4,13E-03
N2		0,00E+00	0,00E+00	0,00E+00	3,22E-02	8,65E-04	1,50E-25	1,63E-06	6,65E-02
O2		0,00E+00	0,00E+00	0,00E+00	2,63E-02	7,32E-04	5,01E-21	9,46E-06	5,42E-02
CH4		0,00E+00	0,00E+00	0,00E+00	4,24E-01	1,27E-03	4,30E-21	1,20E-04	8,75E-01
Mass Flow	KG/HR	17642	17642	2779	343	13864	19784	877	166
Volume Flow	CUM/HR	15	14104	14092	25	979	18	1	14
Temperature	C	86	105	105	20	160	126	108	36
Pressure	BAR	0	0	0	18	18	5	18	18
Vapor Fraction		0	0	1	1	1	0	0	1
Liquid Fraction		1	1	0	0	0	1	1	0
Mass Enthalpy	KJ/KG	-7830	-7455	-13054	-3424	-5863	-8116	-13229	-4133
Enthalpy Flow	KW	-38370	-36534	-10076	-327	-22579	-44599	-3223	-191
Mass Density	KG/CUM	1171	1	0	14	14	1100	853	12

	Units	STACK	STACK2	STRPR1	STRPRLI Q	TOHYDR O	TOTOPOF C	TOWAST E	UREASLU 2
From		C1501-1	P1502	E1102	E1102	E1502-1	C1501-2	MIX2	E1401-1
To		P1502	E1502-1	E1101	C1201-1	R1501-1	C1501-1	E1501-1	V1401
Phase:		Liquid	Liquid	Vapor	Liquid	Liquid	Vapor	Mixed	Mixed
Component Mass Flow									
UREA	KG/HR	447	447	10	12967	447	0	447	12958
CARB	KG/HR	0	0	1	3318	0	0	0	2
CO2	KG/HR	1	1	1587	630	1	7	30	0
NH3	KG/HR	94	94	2731	7519	94	158	348	1
H2O	KG/HR	7832	7832	208	6543	7832	1438	5710	1903
N2	KG/HR	0	0	19	0	0	0	0	0
O2	KG/HR	0	0	27	0	0	0	0	0
CH4	KG/HR	0	0	46	0	0	0	0	0
Component Mass Fraction									
UREA		5,34E-02	5,34E-02	2,19E-03	4,19E-01	5,34E-02	3,91E-09	6,84E-02	8,72E-01
CARB		6,37E-07	6,37E-07	2,61E-04	1,07E-01	6,37E-07	8,26E-11	8,15E-07	1,67E-04
CO2		1,32E-04	1,32E-04	3,43E-01	2,03E-02	1,32E-04	4,19E-03	4,62E-03	4,49E-07

NH3		1,12E-02	1,12E-02	5,90E-01	2,43E-01	1,12E-02	9,86E-02	5,32E-02	4,68E-05
H2O		9,35E-01	9,35E-01	4,49E-02	2,11E-01	9,35E-01	8,97E-01	8,74E-01	1,28E-01
N2		0,00E+00	0,00E+00	4,12E-03	2,19E-10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
O2		0,00E+00	0,00E+00	5,74E-03	3,29E-08	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CH4		0,00E+00	0,00E+00	9,86E-03	4,70E-08	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Mass Flow	KG/HR	8374	8374	4629	30977	8374	1603	6535	14864
Volume Flow	CUM/HR	9	9	38	37	10	669	10887	7483
Temperature	C	142	143	193	201	198	144	10	130
Pressure	BAR	5	20	150	150	20	5	0	0
Vapor Fraction		0	0	1	0	0	1	0	0
Liquid Fraction		1	1	0	1	1	0	1	1
Mass Enthalpy	KJ/KG	-14701	-14696	-5258	-7088	-14465	-12142	-14492	-6186
Enthalpy Flow	KW	-34197	-34187	-6760	-60993	-33648	-5405	-26306	-25539
Mass Density	KG/CUM	907	907	122	828	825	2	1	2

	Units	UREASL U3	UREASL U4	UREAS OL	VAPREC	WASTEI N2	WATCON D1	WATCON D2	WATER 2
From		V1401	E1402-1	C1302-5	R1501-2	E1501-1	E1403	E1404	
To		E1402-1	V1402	E1401-1	C1501-1	C1501-1	MIX2	MIX2	C1203-1
Phase:		Liquid	Mixed	Liquid	Vapor	Mixed	Mixed	Liquid	Liquid
Component Mass Flow									
UREA	KG/HR	12914	12914	12958	0	447	50	398	0
CARB	KG/HR	2	2	2	0	0	0	0	0
CO2	KG/HR	0	0	0	322	30	30	0	0
NH3	KG/HR	0	0	1	189	348	348	0	0
H2O	KG/HR	692	692	1903	1607	5710	4955	754	700
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
CH4	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		9,49E-01	9,49E-01	8,72E-01	7,83E-09	6,84E-02	9,22E-03	3,45E-01	0,00E+00
CARB		1,83E-04	1,83E-04	1,67E-04	6,68E-10	8,15E-07	1,28E-07	4,03E-06	0,00E+00
CO2		1,64E-10	1,64E-10	4,49E-07	1,52E-01	4,62E-03	5,61E-03	1,93E-09	0,00E+00

NH3		7,91E-07	7,91E-07	4,68E-05	8,93E-02	5,32E-02	6,46E-02	9,32E-06	0,00E+00
H2O		5,08E-02	5,08E-02	1,28E-01	7,59E-01	8,74E-01	9,21E-01	6,55E-01	1,00E+00
N2		0,00E+00							
O2		0,00E+00							
CH4		0,00E+00							
Mass Flow	KG/HR	13608	13608	14864	2119	6535	5383	1152	700
Volume Flow	CUM/HR	11	46111	12	195	14	108	1	1
Temperature	C	130	134	105	203	105	30	26	25
Pressure	BAR	0	0	0	20	5	0	0	18
Vapor Fraction		0	0	0	1	0	0	0	0
Liquid Fraction		1	1	1	0	1	1	1	1
Mass Enthalpy	KJ/KG	-5565	-5436	-6408	-11523	-14186	-14995	-12140	-15879
Enthalpy Flow	KW	-21036	-20547	-26458	-6781	-25752	-22421	-3885	-3088
Mass Density	KG/CUM	1224	0	1208	11	462	50	1110	1038

	Units	WATEV AP3	WATV AP	WWRC YC	WWRCY C2	WWRE C	WWREFL UX	WWSTEAM1	WWSTEAM2	WWV AP
From		V1402	V1401	WWSP LIT		E1503	WWSP LIT			C1501-1
To		E1404	MIX1		E1301	WWSP LIT	C1501-1	R1501-1	C1501-2	E1503
Phase:		Vapor	Vapor	Mixed	Mixed	Mixed	Mixed	Vapor	Vapor	Vapor
Component Mass Flow										
UREA	KG/HR	398	44	0	0	0	0	0	0	0
CARB	KG/HR	0	0	0	0	0	0	0	0	0
CO2	KG/HR	0	0	358	359	716	358	0	0	716
NH3	KG/HR	0	1	601	597	1203	601	0	0	1203
H2O	KG/HR	754	1351	922	932	1845	922	2000	1500	1845
N2	KG/HR	0	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0	0
CH4	KG/HR	0	0	0	0	0	0	0	0	0
Component Mass Fraction										
UREA		3,45E-01	3,17E-02	2,31E-05	2,37E-05	2,31E-05	2,31E-05	0,00E+00	0,00E+00	2,31E-05
CARB		4,03E-06	3,09E-07	3,86E-12	4,02E-12	3,86E-12	3,86E-12	0,00E+00	0,00E+00	3,86E-12
CO2		1,93E-09	4,78E-06	1,90E-01	1,90E-01	1,90E-01	1,90E-01	0,00E+00	0,00E+00	1,90E-01
NH3		9,32E-06	4,91E-	3,20E-	3,16E-	3,20E-	3,20E-01	0,00E+00	0,00E+00	3,20E-

			04	01	01	01				01
H2O		6,55E-01	9,68E-01	4,90E-01	4,94E-01	4,90E-01	4,90E-01	1,00E+00	1,00E+00	4,90E-01
N2		0,00E+00								
O2		0,00E+00								
CH4		0,00E+00								
Mass Flow	KG/HR	1152	1396		1887	3763	1882	2000	1500	3763
Volume Flow	CUM/HR	53990	8336	80	67	159	80	161	630	1369
Temperature	C	134	130	30	30	30	30	225	148	129
Pressure	BAR	0	0	5	5	5	5	26	5	5
Vapor Fraction		1	1	0	0	0	0	1	1	1
Liquid Fraction		0	0	1	1	1	1	0	0	0
Mass Enthalpy	KJ/KG	-10026	-12937	-10789	-10842	-10789	-10789	-13123	-13215	-8973
Enthalpy Flow	KW	-3208	-5016	-5639	-5684	-11278	-5639	-7290	-5506	-9380
Mass Density	KG/CUM	0	0	24	28	24	24	12	2	3

A2.2 Aspen Model Description

A2.2.1 The HP section

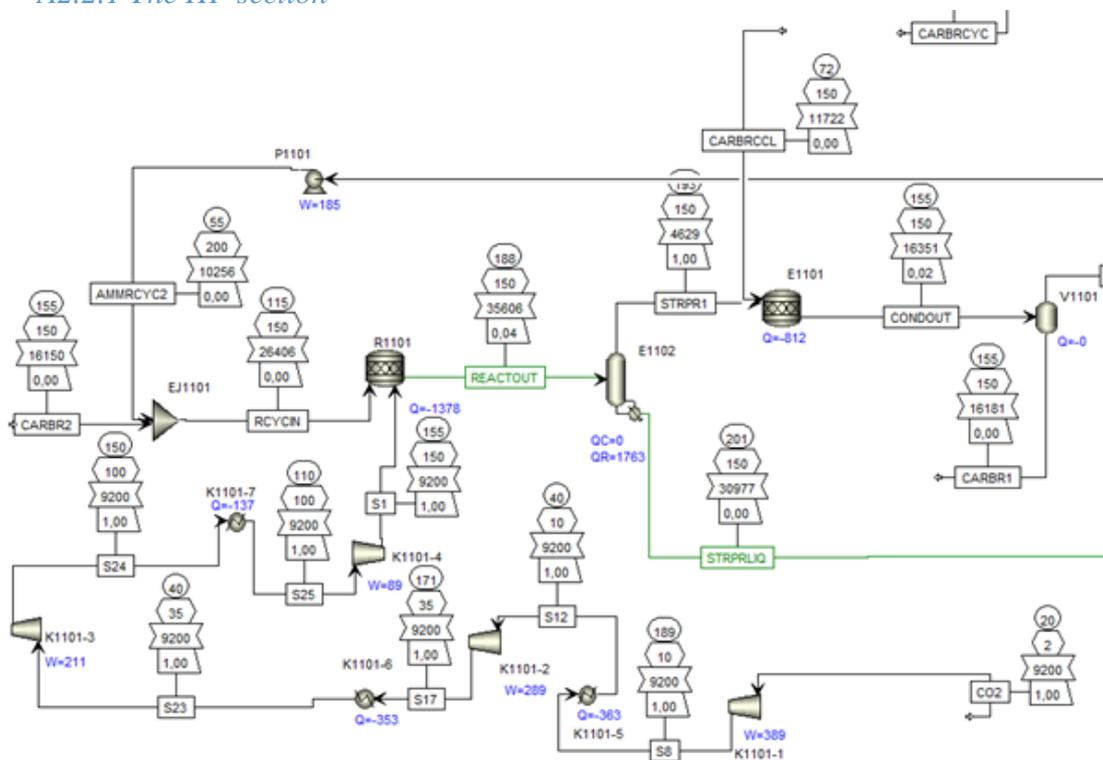


Figure 39: Overview of HP section

The CO₂ compressor (K1101)

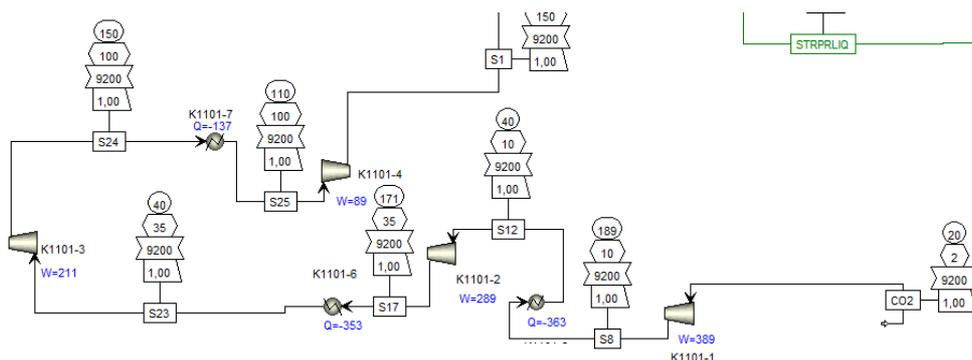


Figure 40: The CO₂ compressor

The CO₂ compressor consists of four stages with intercooling, so instead of using a single compressor model four compressors with heat exchangers were used. The CO₂ is specified to enter the compressor at 20°C and 1.9 bar (CO₂) and is compressed to 10 bar in the first stage (K1101-1). The CO₂ is cooled to 40°C (K1101-5) before it enters the second stage (K1101-2) where it is compressed to 35 bar. Before entering the third stage (K1101-3), where it is compressed to 100 bar, the CO₂ is cooled to 40°C (K1101-6) yet again. The CO₂ is then

cooled to 110°C (K1101-7) and compressed to 150 bar(K1101-4) so it enters the reactor at 155°C (S1). The intercooling helps reduce the workload on the compressor because it decreases the volume of the CO₂ making it more easy to compress. This reduces the energy requirement of the compressor to 978 kW with regards to electricity and 853 kW with regards to cooling.

The high pressure ammonia pump, the ejector and the reactor

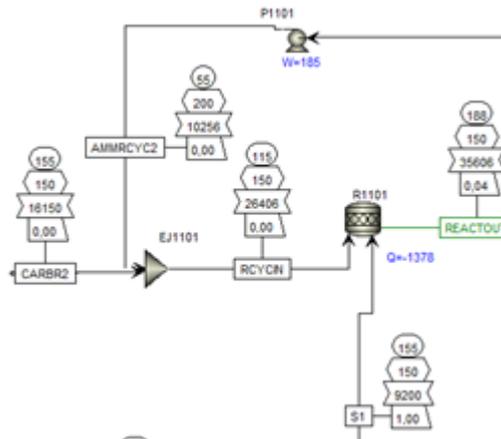


Figure 41: high pressure ammonia pump, the ejector and the reactor

The high pressure ammonia pump (P1101) is modeled as a simple pump that raises the pressure to 200 bar. The ammonia recycle (AMMRCYC2) enters the ejector (EJ1101) where it is mixed with the carbamate recycle coming from the separator (CARBR2). Since Aspen lacks a suitable model for an ejector a simple mixer was used, this works fine because it reduces the pressure to 150 bar and mixes the flows. The combined flow (RCYCIN) enters the reactor (R1101) at 150 bar and 115°C together with the compressed CO₂ (S1). The reactor is specified to operate at a temperature of 188°C and 150 bar to facilitate the reactions to carbamate and urea. The reaction from ammonia and CO₂ to carbamate has a conversion of 90% and the reaction from carbamate to urea has a conversion of 75%, this brings the overall conversion of CO₂ to carbamate in the reactor to 67.5%.

The stripper, the carbamate condenser and the carbamate separator

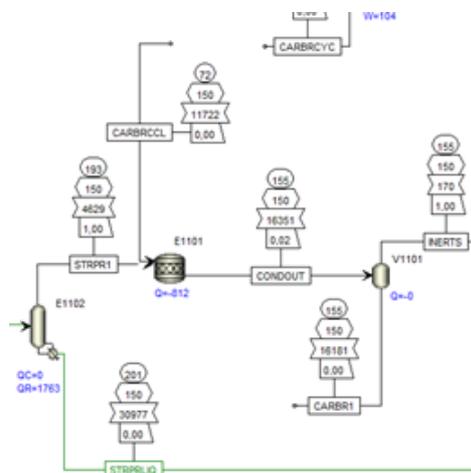


Figure 42: The stripper, the carbamate condenser and the carbamate separator

The liquid coming from the reactor (REACTOUT) enters the top of the stripper (E1102) and flows down. In reality the stripper is a falling film heat exchanger, however it had to be modelled as a radfrac with 5 stages to ensure that enough carbamate is decomposed. The temperature of the liquid outlet is supposed to be 205°C as specified by Saipem so a bottoms to feed ratio of 0.87 was specified. This resulted in a outlet temperature of 201°C however an increase of this temperature led to problems in the separation column (C1201), so the temperature was compromised to be 201°C. The resulting liquid (STRIPLIQ) is sent to the medium pressure decomposer (C1201), while the off-gas (STRPR1) is sent to the high pressure carbamate condenser (E1101) where it is mixed with the carbamate solution (CARBRCCCL) coming from the separation column (C1202). In the high pressure carbamate condenser the ammonia and CO₂ react to form carbamate with an efficiency of 98%. The heat supplied by this reaction is used to from low pressure steam and raises the temperature of the solution to 155°C at 150 bar. The outgoing stream (CONDOUT) contains both liquid and vapour and it is undesirable to feed gasses back to the reactor, so the stream is sent to the carbamate separator (V1101) where the gasses are flashed of and the liquid is fed into the ejector. The carbamate separator operates at the same temperature and pressure as the carbamate condenser. Therefore, it only serves to separate the gasses from the liquid and modelling it as a flash vessel will suffice.

A2.2.2 MP section

MP decomposer (C1201)

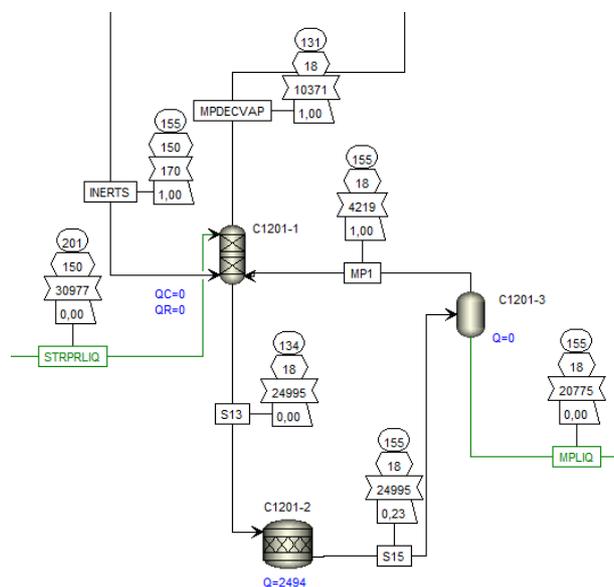


Figure 43: MP decomposer (C1201)

The MP decomposer was modelled in Aspen as three units to best replicate the different function each section of the column performs (refer to MP theory section in chapter 2). The top separator (C1201-1) was modeled as a packed column, the heat exchanger section was modeled as a reactor (C1201-2) and the bottom holding section was modeled as a flash vessel (C1201-3).

It should be noted that as the first unit downstream of the HP section, the letdown in pressure was modeled inside the decomposer (by specifying the pressure of the units to be 18 bar) rather than by a let-down valve, as is the case in reality.

The 42 wt% urea solution (STRPRLIQ) coming from the HP stripper enters the top of the column and the free gases (mainly NH₃), which flash upon letting down the pressure from 150 to 18 bar, exit the top of the column (MPDECVAP). The remaining solution runs through the column encountering a counter-current stream of rising vapours (INERTS), coming from the HP carbamate separator (V1101). The vapours preheat the descending solution before it reaches the reactor (heat exchanger section). The duty of the reactor was not greatly affected by feeding the INERTS stream into the column rather than in the reactor however, the composition could be altered. Thus, to achieve a model closer resembling reality, the INERTS stream should be fed into C1201-2 in future.

The stream (S13) then enters the reactor. This unit was required to simulate the heat exchanger section, as the decomposition of carbamate to NH₃ and CO₂ needed to take place. By specifying the endothermic reaction and an outlet temperature of 155°C, as found in literature⁴¹, the required steam supply could be evaluated from the duty (2494 kW) calculated by Aspen (see utility section for details).

The decomposed solution (S15) then flows to the flash vessel (bottom holder) and the rising action of the decomposed vapours is simulated by returning the vapour fraction from the flash to the bottom of the column. The urea solution (MPLIQ) now concentrated to 62 wt% urea, as specified in literature, exits the bottom of the flash and is transferred to the LP decomposer (C1301)⁴¹.

Pre-heater shell (C1302-1)

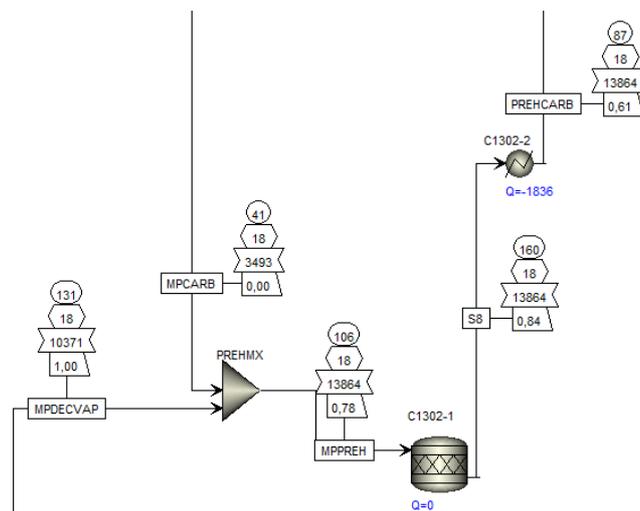


Figure 44: Pre-heater shell (C1302-1)

The pre-heater (C1302), found at the beginning of the vacuum section, is a unit similar to the decomposers. However, instead of steam supplying the heat for the decomposition of carbamate, Saipem has saved utility costs by condensing the vapours of the MP decomposer (MPVAP) and the bottoms flow out of the LP carbamate receiver (MPCARB) in the shell of the pre-heater. This action provides the necessary heat due to the simultaneous absorbing,

condensing and reacting of the vapours and the carbamate solution resulting in an increased volume of carbamate solution⁸.

This situation was modelled in Aspen as a reactor, where the reaction and condensation could be specified by setting an appropriate operating temperature. However, due to the lack of information on the degree of conversion and condensation, the shell was split into two units, a reactor (C1302-1) and a condenser (C1302-2). The reactor was modeled as zero duty, to get an idea of the heat the reaction would produce ($S8 = 160^{\circ}\text{C}$), then a condenser was installed and the conversion in the reactor and the outlet temperature of the condenser were altered to achieve the duty required by the pre-heater (1836 kW). This arrangement gave an idea of the heat generated in the shell, which came in useful for equipment sizing (see equipment sizing derivations in appendix 5).

The carbamate solution (PREHCARB) produced in the shell of the pre-heater and still consisting of 61% vapours at 87°C was thus transferred to the MP carbamate condenser for further condensing.

MP carbamate condenser (E1201)

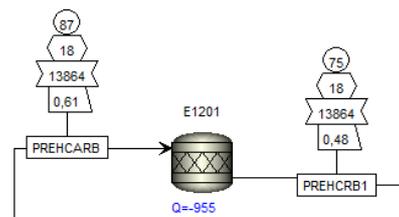


Figure 45: MP carbamate condenser (E1201)

The carbamate condenser was modelled as a reactor operating at 75°C . A reactor was again required as the solution (PREHCARB) still contained NH_3 and CO_2 gases, which react to form carbamate upon condensing. Thus, the solution was condensed from 87°C to 75°C .

Ammonia-Carbamate separation column (C1202)

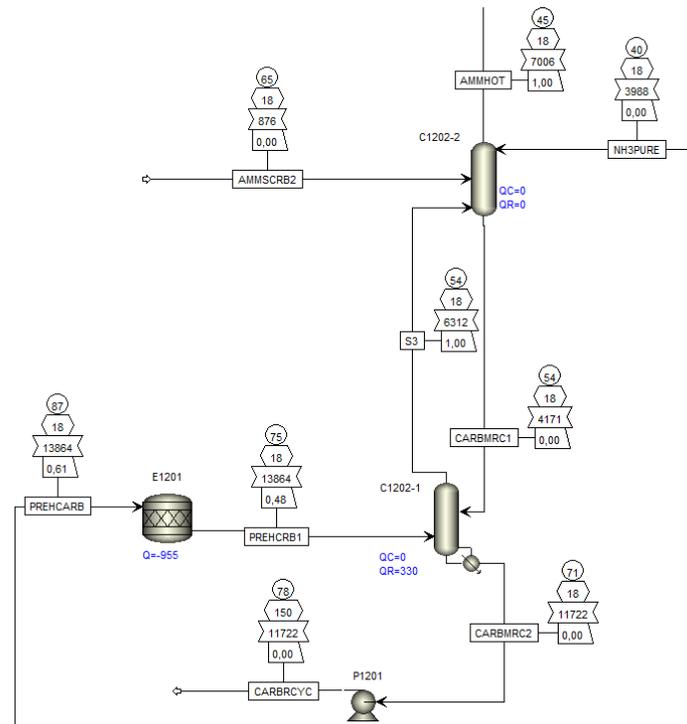


Figure 46: Ammonia-Carbamate separation column (C1202)

This column had several requirements which needed to be fulfilled. Firstly, the separation of CO_2 and NH_3 needed to be complete, such that only NH_3 and inerts (and ppm levels of CO_2) exit in the vapour stream (AMMHOT).⁴² Secondly, from literature, the bottoms solution was known to be within $70^\circ\text{C} - 90^\circ\text{C}$.⁴¹ These specifications were met by modelling the column in Aspen as two radfracs. The model was based on two patents (see Figure 47 in the manufacture of urea' Figure 48), which described the recovery of ammonia in the urea process^{42,43}.

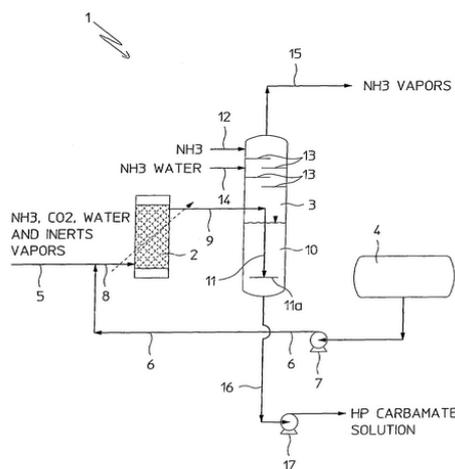


Figure 47: Patent for the 'treatment of unreacted ammonia in the manufacture of urea'

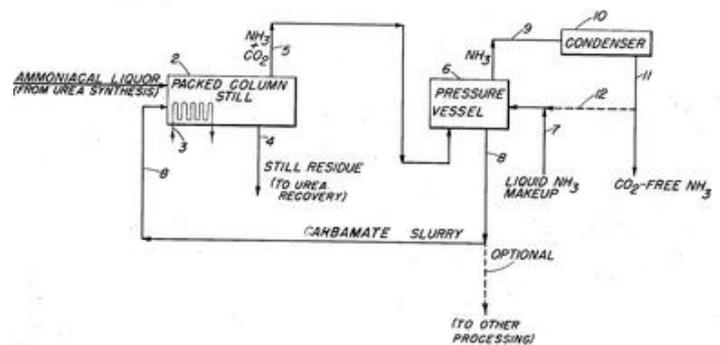


Figure 48: Patent of 'process for urea production and plant'

The carbamate solution (PREHCRB1) was transferred above stage four of the bottom column (C1202-1). This column was set to have a kettle type reboiler, which required the specification of a bottoms to feed mass flow rate: 0.65. This specification allowed the control of the bottoms temperature. The resulting gases (S3) thus ascended the column, through three stages before entering the second column (C1202-2).

In this column the ascending vapours were met by two liquid solutions flowing down the column. Pure liquid nitrogen (NH3PURE) from the ammonia receiver (V1202) at 40°C was fed into the top of the column, whilst aqueous ammonia (AMMSCRB2) from the scrubber (C1203) entered just below, on stage three (Figure 46). These streams serve the purpose of ‘washing down’ and condensing the rising vapours. Due to the contact of CO₂ and ammonia liquid in this column, carbamate particles form and as such, the exothermic carbamate forming reaction was specified in this column.

The vapourized ammonia which leaves the column (AMMHOT) is 99 wt% NH₃ and 0.007 wt% inerts. The remaining carbamate, NH₃ and water solution (CARBMRC1) descending the top column, is returned to the bottom column, to simulate that the two columns are in reality one unit.

An important aspect of the solution (CARBMRC1) exiting the bottom column is that it is of an appropriate composition for the temperature it is at. This is a requirement as the solution contains a large amount of carbamate (43 wt%), which must be dissolved within the column to avoid clogging the trays, and must be below its crystallization point upon exiting the unit to avoid clogging the downstream pipes and pumps.

As the crystallization temperature is a complex relationship between NH₃, CO₂ and water in the solution, a carbamate crystallization temperature calculator was used to determine whether the conditions set were safe for operation¹⁸. With the composition modelled in Aspen the crystallization temperature was found to be around 55°C (see Figure 31) thus, the outflow temperature of 71°C is safe. If this were not the case, the water feed to the scrubber (C1203) could be increased to increase the water flow rate of AMMSCRB2 and thus the water content of the column, or the inflow in ammonia from the receiver (V1201) could be increased.

Ammonia condenser (E1202)

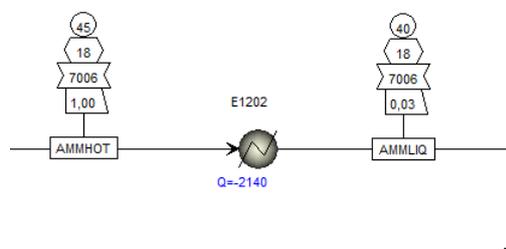


Figure 49: Ammonia condenser (E1202)

The ammonia condenser (E1202) serves the purpose of condensing the ammonia vapours (AMMHOT) exiting the ammonia-carbamate separation column, in order to feed liquid

ammonia (AMMLIQ) to the receiver (V1201). As the condenser is operating at 18 bar (as is the rest of the MP section), the temperature of the unit was set to 40°C to condense ammonia. The 3% vapours left in the stream are inerts (CH_4 , O_2 , N_2).

Ammonia receiver (V1201)

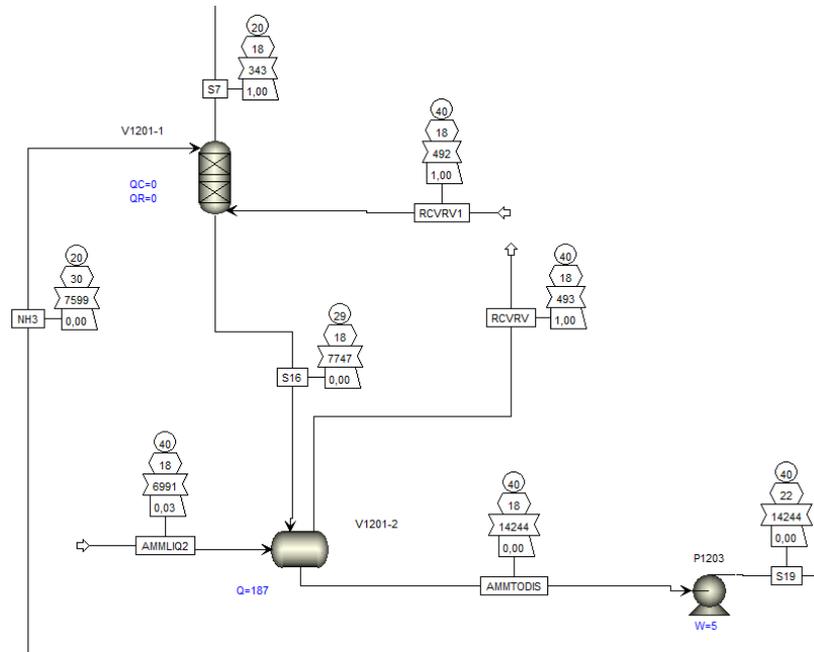


Figure 50: Ammonia receiver (V1201)

The ammonia receiver (V1201) was modelled as two units. A packed column (V1201-1) represents the ammonia recovery tower and a horizontal flasher (V1201-2) simulates the horizontal collection vessel (see theory section Figure 12).

The AMMLIQ2 coming from the ammonia condenser enters the flash vessel, where the gases (RCVRV) are separated from the liquid ammonia (AMMTODIS). In Aspen the flasher was set to 40°C, which resulted in a duty of 187 kW to maintain the vessel temperature. This duty was ignored in later utility calculations as it could have been prevented by taking a different approach to modelling. For example, the vessel could have been modeled as zero duty, which would have decreased the efficiency of ammonia-inerts separation but would have perhaps better modeled reality as literature, which was later found, suggested sending the hot cooling water past the receiver to maintain its temperature (suggesting the vessel is in fact operating around 35-40°C)¹⁶. Another option would be to regulate the ammonia condenser to condense the AMMHOT stream only so far to achieve the desired 40°C in the receiver (this temperature control was specified in the P&ID of the MP section).

The fresh ammonia feed (NH_3 , 7600 kg/h of ammonia with 2% CH_4) is first introduced into the process at the recovery tower of the receiver. It is pumped from an ammonia storage tank and fed into the top of the packed column. The tank and pump were not modelled in Aspen, instead the stream was set at the conditions required to transport the ammonia from the tank to the receiver. The descending liquid ammonia comes into contact with the ascending gases (RCVR1) from the flash and serves to condense some of the ammonia which escaped the

receiver along with the inerts. The bottom stream (S16) is therefore fed into the flash vessel, whilst the top stream (S7) is transferred to the scrubber (C1203).

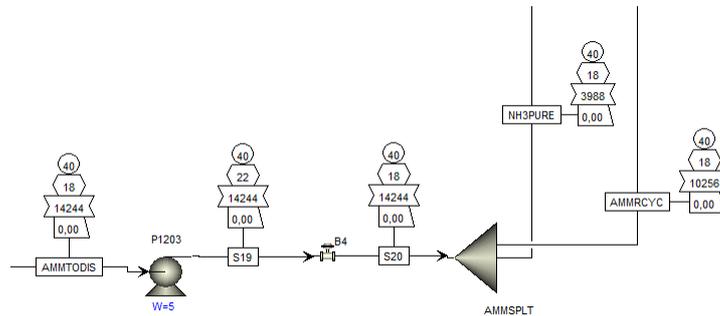


Figure 51: The ammonia liquid leaving the receiver

The liquid stream exiting the horizontal flash (AMMTODIS) is pumped to 22 bar, to move the liquid through the pipes, before being split; 72 reactor (AMMRCYC): 28 ammonia-carbamate separation column (NH3PURE). This ratio was chosen as it led to the desired temperatures in C1202, whilst maintaining the requirement found in literature (less than half to be recycled)⁴¹.

The pump (P1203) was added in order to get an idea of the head it was required to deliver however, as the entire medium pressure section was modelled at 18 bar an expansion valve was added to return to 18 bar for the purposes of this model.

Scrubber (C1203)

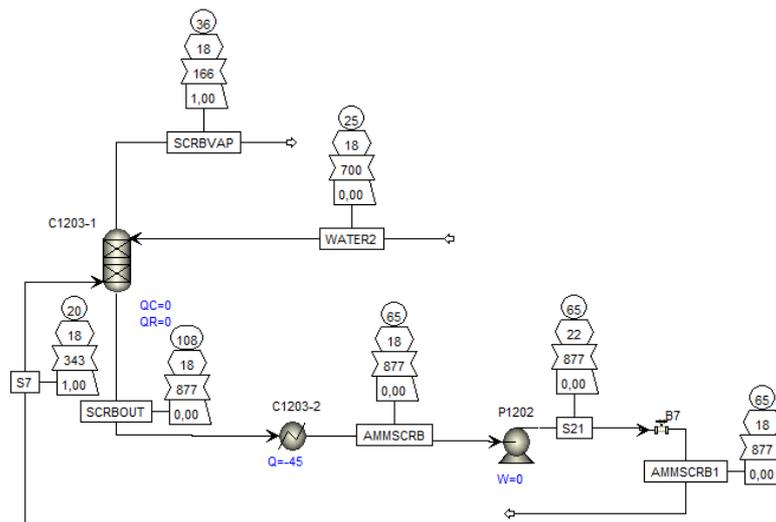


Figure 52: Scrubber (C1203)

The scrubber (C1203) was modeled as a four stage Nutter-float valve trayed column (C1203-1) and a heat exchanger (C1203-2). The vapour stream out of the ammonia receiver (S7) is fed to the bottom of the column (above stage 5) and 700 kg/h of scrubbing water is fed to the top. The scrubbing water absorbs 177 kg/h of ammonia and exits the bottom of the column (SCRBOU) at 108°C, due to the heat of absorption of ammonia.

In reality, the bottom section of the scrubbing column is a heat exchanger and is thus cooled by cooling water. To simulate this in Aspen, the heat exchanger was added to the model to cool the stream of aqueous ammonia to 65°C, before it is fed back to the ammonia-carbamate separation column (C1202). The pump (P1202) was added to give an indication of its power requirements, after which the pressure was returned to 18 bar, as described for P1203.

The inert vapours (SCRBVAP) exiting the top of the column thus contain only around 530ppm or 0.09 kg/h of ammonia, ensuring the ammonia emission regulations (4 kg/h out of vents) are conformed with²¹.

Although the scrubber was initially modeled to achieve the specified emission targets, such that the stream could simply be purged, due to the large amount of methane in the vapours (145 kg/h), the stream is sent to be flared before release to the environment.

A2.2.3 LP section

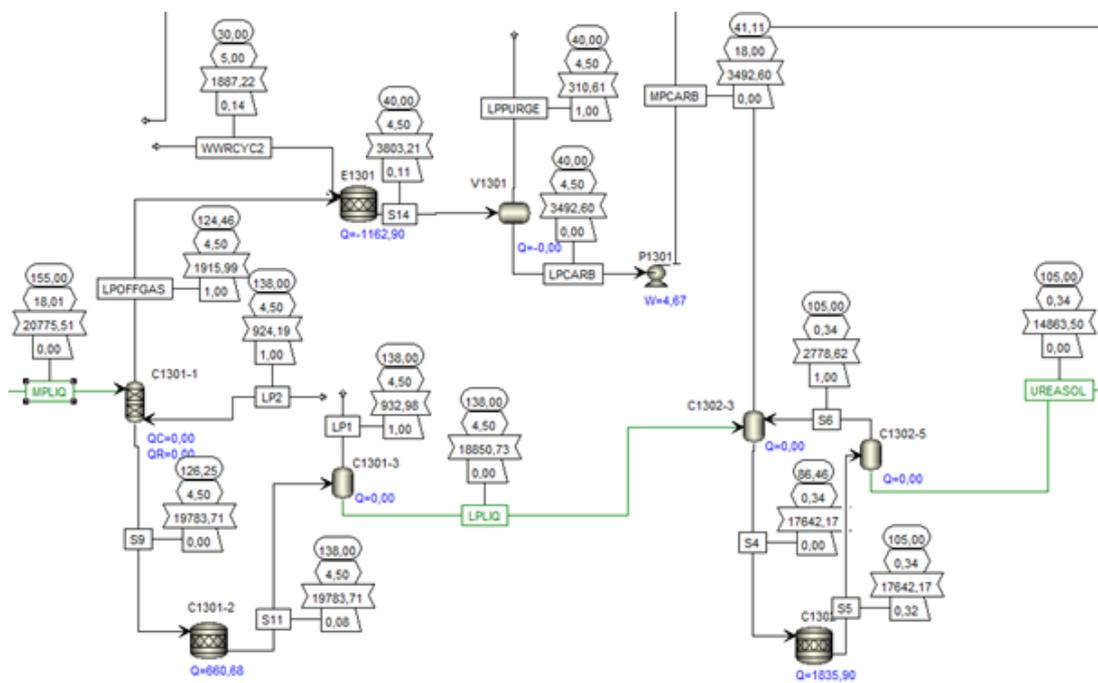


Figure 53: Overview of LP section

The solution coming from the medium pressure decomposer and rectifier called MPLIQ contains 62wt% urea, 2.4wt% ammonium carbamate, 6.4wt% ammonia, 29wt% water and very small amount of inerts. This mixture is then fed to the low pressure decomposer and rectifier, which was modeled as three pieces of equipment instead of one. C1301-1 represents the top part of the actual low pressure decomposer, meaning that its function is to separate the off gasses. Then, the liquid effluent is fed to C1301-2, which is a reactor. Here, the decomposition of ammonium carbamate, which in reality happens in the tube side of the falling-film heat exchanger, takes place. The product is then fed to C1301-3, where gasses are separated from the mixture, just as in C1301-1.

The stream LPOFFGAS, which consists of 15wt% carbon dioxide, 62wt% ammonia and 23wt% water is fed to E1301 together with the stream coming from the waste water treatment called WWRCYC2. This should be a heat exchanger, but since a condensation reaction between carbon dioxide and ammonia takes place, it was modelled as a reactor instead of a heat exchanger. The carbamate solution, which contains 29wt% ammonium carbamate, 34wt% ammonia and 36wt% water is then led to the carbamate receiver V1301. For simplicity, this was modelled as a regular flasher, where off gasses containing 96wt% ammonia (297kg/hr) were purged instead of cleaned. In reality, it is not allowed to purge such amount of ammonia, so the gasses are first scrubbed and then purged to atmosphere.

The liquid coming from V1301 is first pumped to 18 bar by P1201 and then led to C1302-1, which represents the shell side of the preheater. Here, the condensation reaction between ammonia and carbon dioxide takes place, supplying the heat necessary for the decomposition of ammonium carbamate in the tube side of the preheater (for further explanation on C1302-1 & C1302-2, see MP section).

The stream LPLIQ, which represents the liquid effluent of the low pressure decomposer and rectifier flows to the tube side of the preheater, which was modelled as three pieces of equipment instead of one. The principles the same as for the low pressure decomposer: the first vessel (C1302-3) separates the released flash gasses and sends them to a condenser. The bottom stream, which contains 74wt% urea and 26wt% water with some small carbamate, ammonia and carbon dioxide impurities is fed to C1302-4, where further decomposition of ammonium carbamate, as well as heating of the solution takes place. Again, this should be a falling film type heat exchanger, but since a reaction is taking place, it was modelled as a reactor.

The product is then led through another flasher, where the flash gasses are separated and fed to C1302-3 and subsequently condensed. The liquid stream UREASOL is then fed to the vacuum section. This stream consists of 87wt% urea and 13wt% water.

WWVAP is condensed in E1503, which is modelled to have a temperature of 30°C. Half of the condensed stream (WWREC) is recycled to E1301 (WWRCYC), the other half is refluxed back to the column (WWREFLUX).

The effluent of the top of the column (STACK) consists of 5.3 wt% urea and 1.1 wt% ammonia. This is pumped up to 20 bar in P1502 and preheated in E1502 before entering the hydrolyzer (R1501). E1502 consist of two parts: E1502-2 cools down the effluent of the hydrolyzer (stream LIQREC), which is modelled to have an output of 150°C. The heat of E1502-2 is the input of E1502-1, which results in an output of 198°C of TOHYDRO.

In the hydrolyzer (R1501) urea is hydrolyzed to carbamate and carbamate is decomposed in ammonia and CO₂. First the reactor was modelled as a REquil with zero duty, which calculate the equilibrium composition of the reactor. To achieve a urea concentration below 10 ppm in the effluent, the temperature should be 200°C or higher. This temperature is achieved by adding MP steam (WWSTEAM1), which was found to be 2000 kg/h resulting in a temperature of 203°C in R1501. Later R1501 was modeled as a RStoic with the same conversion of urea and carbamate is in REquil, making modeling calculations easier. The conversion of urea was modelled at 0.9999 and the conversion of carbamate was also at 0.9999.

A flash (R1501-2) was modelled to separate the vapor from the liquid at zero duty. The vapor (VAPREC) consists of 83% water, 10% ammonia and 7% CO₂, which is used as stripping agent in C1501-1. The effluent of R1501 (LIQREC) consist of water with 5 ppm urea, 7 ppm carbamate and 1.9 wt% ammonia.

The effluent of R1501 is cooled down in E1502-2 and enters the top of C1501-2 as LIQREC2. In C1501-2 the ammonia is stripped out by LP steam (WWSTEAM2).

C1501-2 is the bottom part of C1501. It is modeled to have 17 stages, with LIQREC2 entering at stage 1 and WWSTEAM2 entering at stage 17. It has no reboiler or condenser and it is calculated at equilibrium. It was found that 1500 kg/h of LP steam was needed to have a ammonia concentration of the effluent below 10 ppm.

The top vapors (TOTOPOFC) consist of water vapor with 9.9 wt% of ammonia and 0.4 wt% of CO₂, which is used as stripping agent in C1501-1. The effluent (PUREWAT) consists of water with 5 ppm urea, 7 ppm carbamate and 6 ppm ammonia.

Appendix 3. Hazard Analysis

A3.1 Hazop Study

A3.1.1 The HP section

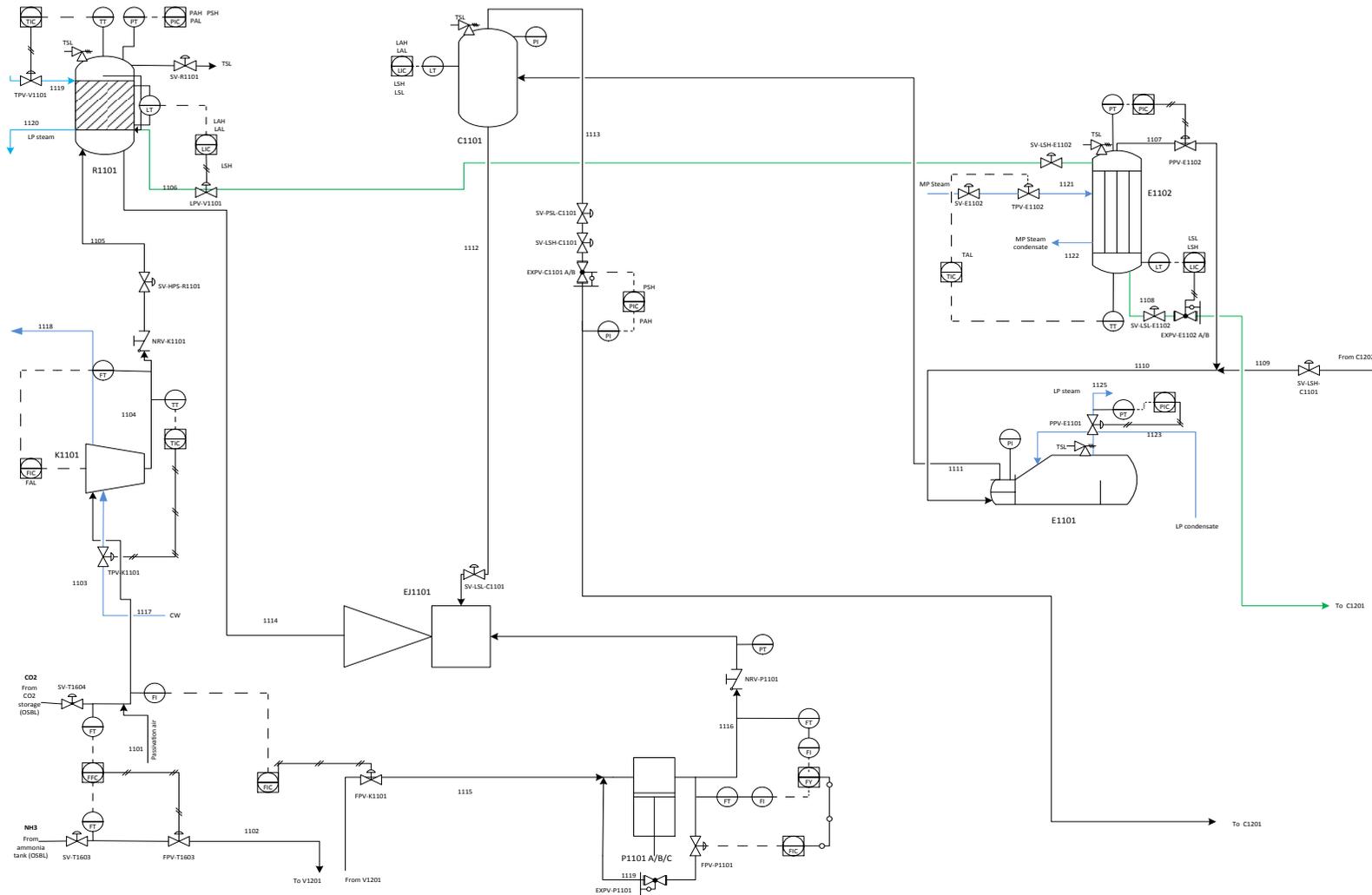


Table 8: HP Hazop report

Vessel CO2 Compressor K1101			
Intention Compression of CO2 to reactor conditions(150 bar)			
Guide Word	Guide Word	Guide Word	Guide Word
Line No. 1101 15.17kg/hr 2 bar 20 °C Intention: Supplying passivation air to the process			
No	No air flow	Valve stuck closed	Corrosion might occur Choose suitable MOC for the all equipment(zirconium lining)
More	More air flow	Valve stuck open	Potential build-up of inerts in the system.
Less	Less air flow	Valve partially closed	Corrosion might occur Choose suitable MOC for the equipment(zirconium lining)
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1103 9200kg/hr 1,9 bar 20 °C Intention: Supplying CO2 to the compressor			
No	No CO2 flow	Valve stuck closed	Loss of flow to the compressor Installed FI-K1101 and FIC-K1101 to stop the flow of ammonia to P1101 and the reactor.
More	More CO2 flow	Valve stuck open	Lower pressure and temperature in the compressor. Installed FT-K1101 and FIC-K1101 to regulate the speed of the compressor
Less	Less CO2 flow	Valve partially closed	Increase of pressure and temperature in the compressor
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1104 9200kg/hr 150 bar 160 °C			

Intention: Supplying compressed CO2 and passivation air to the reactor			
No	No flow	Valve stuck closed/compressor broken	Loss of flow to the reactor
More	More flow	Valve stuck open	Level and pressure increase in the reactor
Less	Less flow	Valve partially closed	Level and pressure decrease in the reactor
Reverse	Reverse flow	Compressor broken/ sudden reduction of line pressure	Reverse flow of corrosive reactor liquid into the compressor. Installed NRV-K1101
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1117 Intention: Supplying cooling water to the compressor for the intercooling			
No	No flow	Valve closed or non-functioning pump	The temperature of the gas and energy consumption of the compressor will increase Installed TT-K1101 and TIC-K1101 to regulate the flow of cooling water in line 1117 using TPV-K1101
More	More flow	Valve stuck open	The temperature of the gas and energy consumption of the compressor will decrease
Less	Less flow	Valve stuck closed	The temperature of the gas and energy consumption of the compressor will increase
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1118 Intention: Transporting the cooling water from the compressor			
No	No flow	Valve closed or non-functioning pump	Temperature in the compressor will increase
More	More flow	Valve stuck open	The intercooling will run dry

			and the temperature in the compressor will increase
Less	Less flow	Valve stuck closed	Build-up of water and the temperature of the gas will increase
Vessel Ammonia receiver			
Intention Retain/collect ammonia for further use in the process			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1102 7599kg/hr 30 bar 20 °C Intention: Supplying fresh ammonia to the ammonia receiver			
No	No flow	Valve stuck closed or ratio control failure	Loss of flow to the receiver Installed level control and made sure the receiver contains a reserve to keep the process running for up to an hour.
More	More flow	Valve stuck open or ratio control failure	Higher level in the receiver
Less	Less flow	Valve partially closed or ratio control failure	Lower level in the receiver
Vessel Reactor R1101			
Intention Facilitating the reaction between ammonia and CO2 to form carbamate and the reaction from carbamate to urea forming a liquor with 34wt% urea.			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1105 9200kg/hr 150 bar 155 °C Intention: Relieving pressure from the reactor into the vent system			
No	No flow	Valve stuck closed	Pressure decrease in the reactor and a disturbed NH3:CO2 ratio
More	More flow	Valve stuck open or high pressure inside the reactor	Pressure build-up in the reactor Installed PT-R1101 and PIC-R1101 with high and low pressure alarms and a high

			<p>pressure switch to stop the inflow of CO₂ and ultimately the compressor using a high pressure switch.</p> <p>Installed a line to an emergency scrubber with SV-R1101 to allow for depressurisation during shutdown without loss of containment</p> <p>Installed PSV-R1101 A/B/C</p>
Guide Word	Deviation	Cause	Consequences and Action
<p>Line No. 1106 34321kg/hr 150 bar 188 °C Intention: Transporting the urea liquor to the stripper</p>			
No	No flow	Valve stuck closed or high level safety valve in stripper closed	<p>Build-up in the reactor.</p> <p>Installed LT-R1101 and LIC-R1101 to control LPV-R1101</p>
More	More flow	Valve stuck open	Level decrease in the reactor
Less	Less flow	Valve partially closed	Level increase in the reactor
Guide Word	Deviation	Cause	Consequences and Action
<p>Line No. 1116 25121kg/hr 150 bar 15 °C Intention: Supplying carbamate/ammonia solution to the reactor</p>			
No	No flow	Valve stuck closed	Build-up and level decrease in the reactor and changed reactor ratio
More	More flow	Valve stuck open/more flow from rectifying column and subsequently the ejector	Level increase and changed reactor ratio
Less	Less flow	Less flow through ejector due to low level in the carbamate separator	Level decrease and changed reactor ratio
Guide Word	Deviation	Cause	Consequences and Action
<p>Line No. 1119 Supplying cooling water to the reactor</p>			

No	No flow	Valve stuck closed or non-functioning pump	Temperature increase in the reactor Installed TT-V1101 and TIC-V1101 to control the flow of cooling water using TPV-V1101
More	More flow	Valve stuck open	Temperature decrease in the reactor
Less	Less flow	Valve partially closed	Temperature increase in the reactor
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1120 Transporting low pressure steam from the reactor			
No	No flow	Valve stuck closed or non-functioning pump	Temperature increase in the reactor
More	More flow	Valve stuck open	Temperature decrease in the reactor
Less	Less flow	Valve partially closed	Temperature increase in the reactor
Vessel Stripper E1102			
Intention Decompose carbamate and remove ammonia and CO ₂ from the product			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1106 34321kg/hr 150 bar 188 °C			
Intention: Transporting the urea liquor to the stripper			
No	No flow	Valve stuck closed or low level in the reactor	Level will decrease and temperature will increase causing more gas- and biuret formation Installed LT-E1102 and LIC-E1102 to control EXPV-E1101A/B and a low level switch controlling SVLL-E1102.
More	More flow	Valve stuck open	Level will increase and temperature will decrease

			lowering urea purity Installed a high level switch controlling SVLH-E1102
Less	Less flow	Valve partially closed	Level will decrease and temperature will increase
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1107 4629kg/hr 150 bar 193 °C Intention: Transport the stripping gasses to the carbamate condenser			
No	No flow	Valve stuck closed	Pressure increase in stripper Installed PT-E1102 and PIC-E1102 to control PPV-E1102. Installed PSV-E1102 A/B
More	More flow	Valve stuck open or temperature increase	Pressure decrease in stripper
Less	Less flow	Valve partially closed or temperature decrease	Pressure increase in stripper
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1108 30977kg/hr 150 bar 201 °C Intention: Transport the urea liquor to the medium pressure decomposer			
No	No flow	Valve stuck closed	Level increase in stripper and lower temperatures
More	More flow	Valve stuck open	Level decrease in stripper and higher temperatures
Less	Less flow	Valve partially closed	Level increase in stripper and lower temperatures
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1121 Transport high pressure steam to the stripper			
No	No flow	Valve stuck closed or non-functioning compressor	Temperature decrease in stripper and no decomposition leading to a pressure decrease
More	More flow	Valve stuck open	Temperature increase and more decomposition and higher

			<p>pressure</p> <p>Installed TT-E1102 and TIC-E1102 to control the flow of medium pressure steam using TPV-E1102</p> <p>Installed a line with SV-E1102 to a back-up condenser to reduce steam flow to the stripper without disturbing the overall steam flow</p>
Less	Less flow	Valve partially closed	Temperature decrease in stripper and less decomposition
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1122 Transport the condensed steam to the shell of the carbamate condenser			
No	No flow	Valve stuck closed	Temperature decrease in stripper and no decomposition + pressure decrease
More	More flow	Valve stuck open	Temperature increase and more decomposition and higher pressure
Less	Less flow	Valve partially closed	Temperature decrease in stripper and less decomposition
Vessel Carbamate condenser E1101			
Intention Form carbamate from ammonia and CO ₂ and use the reaction heat to form low pressure steam			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1110 16351kg/hr 150 bar 135 °C Intention: Transport the ammonia and CO ₂ solution to the condenser			
No	No flow	Valve stuck closed or no flow from the stripper and separation column	No low pressure steam formation and no flow to the separator
More	More flow	Valve stuck open or more gas from stripper/liquid from separation column	More carbamate formation and higher temperatures causing more low pressure steam formation and flow to the separator

Less	Less flow	Valve partially closed or less gas from stripper/liquid from column	Less carbamate formation and lower temperatures causing less low pressure steam formation and flow to the separator
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1111 16351kg/hr 150 bar 155 °C Intention: Transport the carbamate solution to the separator			
No	No flow	Valve stuck closed or no flow from the stripper and separation column or clogging	No flow to separator causing a level decrease in the separator and no low pressure steam formation
More	More flow	Valve stuck open or more gas from stripper/liquid from column	More flow to separator causing a level increase in the separator and more low pressure steam formation
Less	Less flow	Valve partially closed or less gas from stripper/liquid from column	Less flow to separator causing a level decrease in the separator and less low pressure steam formation
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1123 Transport the condensed steam to the condenser			
No	No flow	Valve stuck closed or no steam flow from medium pressure decomposer	Temperature increase in the condenser and no low pressure steam production
More	More flow	More steam coming from medium pressure decomposer	Level increase in the shell of the condenser lowering the temperature and the low pressure steam production
Less	Less flow	Less steam coming from medium pressure decomposer or partially closed valve	Level decrease in the shell of the condenser increasing the temperature and the low pressure steam production
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1125 Transport the low pressure steam from the condenser			
No	No flow	No steam formation or valve stuck closed	Temperature and pressure increase in the shell of the

			condenser Installed PT-E1101 and PIC-E1101 to control the outflow of low pressure steam using PPV-E1101
More	More flow	Higher temperatures in the condenser due to more carbamate formation	More steam production and a potential increase steam pressure
Less	Less flow	Lower temperatures in the condenser due to less carbamate formation or valve partially closed	Less low pressure steam available for the rest of the plant or steam with a different pressure reaching the rest of the plant
Vessel Carbamate separator C1101			
Intention To separate the liquid carbamate solution from the gasses			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1111 16351kg/hr 150 bar 155 °C Intention: Transporting the carbamate solution from the condenser to the separator			
No	No flow	No flow to the carbamate condenser	Level decrease in the separator Installed level control with LT-C1101 and LIC-C1101 with high and low level alarms and switches controlling SV-LSH-C1101 and SV-LSL-C1101
More	More flow	More flow to the carbamate condenser	Level increase in the separator
Less	Less flow	Less flow to the carbamate condenser	Level decrease in the separator
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1112 16181kg/hr 150 bar 155 °C Intention: Transporting the liquid carbamate solution to the ejector			
No	Flow	No level in separator	Gasses entering the ejector and the reactor
More	More flow	More flow coming	Level decrease due to increased

		from the ammonia receiver	outflow
Less	Less flow	Less flow coming from the ammonia receiver	Level increase due to decreased outflow
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1113 170kg/hr 150 bar 155 °C Intention: Transporting the hot gasses to the medium pressure decomposer			
No	Flow	No gas formation or separator filled with liquid	Carbamate solution entering the medium pressure decomposer
More	Flow	Lower conversion in the carbamate condenser	Less carbamate solution entering the separator and more gas leading to a level decrease
Less	Flow	Higher conversion in the carbamate condenser	The medium pressure decomposer will require additional steam because of the less flow of hot gases from the separator
Vessel Ejector EJ1101			
Intention Transport the liquid ammonia and carbamate solution to the reactor			
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1112 16150kg/hr 150 bar 155 °C Intention: Transporting the liquid carbamate solution to the ejector			
No	Flow	No level in separator	Gasses entering the ejector and the reactor
More	More flow	More flow coming from the ammonia receiver	Increased flow to the reactor leading to an increased level and a disturbed ratio in the reactor
Less	Less flow	Less flow coming from the ammonia receiver	Decreased flow to the reactor leading to a decreased level and a disturbed ratio in the reactor
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1114 26406kg/hr 115 bar 155 °C Intention: Transporting the ammonia/carbamate solution to the reactor			
No	Flow	No flow from the	No flow to the reactor leading to

		ammonia receiver or pump failure(P1103 A/B/C)	a decreased level and a disturbed ratio in the reactor
More	More flow	Higher pressure from the ammonia pump (P1103) causing more flow to the reactor	Increased flow from the carbamate separator and thus to the reactor leading to an increased level and a disturbed ratio in the reactor
Less	Less flow	Lower pressure from the ammonia pump (P1103) causing less flow to the reactor	Decreased flow from the carbamate separator and thus to the reactor leading to a decreased level and a disturbed ratio in the reactor
Guide Word	Deviation	Cause	Consequences and Action
Line No. 1116 10256kg/hr 200 bar 155 °C Intention: Transporting the liquid ammonia to the ejector			
No	Flow	No flow from the ammonia receiver or pump failure(P1103 A/B/C)	No flow through the ejector and to the reactor leading to an decreased level and a disturbed ratio in the reactor
More	More flow	Higher pressure from the ammonia pump (P1103) causing more flow to the reactor	Increased flow from the carbamate separator and thus to the reactor leading to an increased level and a disturbed ratio in the reactor
Less	Less flow	Higher pressure from the ammonia pump (P1103) causing more flow to the reactor	Decreased flow from the carbamate separator and thus to the reactor leading to a decreased level and a disturbed ratio in the reactor

Table 9: Hazop report of MP section

<p>Vessel – MP Decomposer (C1201)</p> <p>Intention – To purify the urea solution (30977 kg/hr, 42 wt% urea) coming from the HP stripper (E1102) to 62 wt% urea. This is achieved by decomposing residual carbamate, at 18 bar and 155°C, and separating the resulting gases from the purified urea stream.</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1215</i></p> <p>Intention: transfers the urea solution (30977 kg/hr, 42 wt% urea) from the HP Stripper (150 bar) to the MP decomposer (18 bar).</p>			
MORE	Concentration of carbamate	Low temperatures in the HP stripper (possibly due to HP steam failure).	<p>A higher carbamate concentration would require more heating to decompose and achieve desired urea purity.</p> <p>The initial decrease in temperature in the column is registered by the TIC measuring the temperature of line 1217 thus, regulating (increasing) steam flow (line 1219) to deal with higher required carbamate decomposition.</p> <p>Initially a lower pressure will be indicated in the decomposer and the pressure valve on line 1218 will decrease flow until pressure restored upon increase in decomposition.</p>
MORE	Flow	Failure of HP-MP expansion valve (EXPV-E1102A) open.	<p>HP urea solution (150 bar) entering vessel designed for MP (18 bar) could cause equipment failure. PSV opens TSL (emergency absorber).</p> <p>Increase in level in MP decomposer, could lead to Biuret formation (unwanted).</p> <p>Higher pressure will also lead to higher concentration of NH₃ and CO₂ in exiting urea solution (line 1217), ie. desired urea purity not achieved.</p> <p>To prevent this, the LIC on</p>

			<p>the HP stripper will register the changing level, upon failing to rectify the situation by controlling the HP-MP expansion valve (EXPV-E1102), the low level safety valve (SV-LSL-E1102) of stripper would stop flow to MP decomposer.</p> <p>Make use of backup expansion valve on line 1215 (EXPV-E1102B). If this is not immediately possible, emergency shutdown, whilst valve replaced.</p>
NO	Flow	Failure of HP-MP expansion valve (EXPV-E1102A) closed.	<p>Decrease of level in vessel could lead to possible escape of gases through bottoms line 1217 to LP section. LIC on line 1217 prevents this by closing MP-LP expansion valve (EXPV-C1201A) to maintain level in MP decomposer.</p> <p>Bypass faulty expansion valve on line 1215, by activating backup valve (EXPV-E1102B).</p> <p>If this doesn't occur quickly the urea solution will be stagnant in the decomposer and temperatures will rise once endothermic carbamate decomposition reaction complete. The TIC measuring temperature of line 1217 will regulate (decrease) steam flow with valve (TPV-C1201) correspondingly. The excess steam will be redirected to an emergency condenser (in the utility section) to not disturb the steam supply system of the entire plant.</p> <p>The residence time must be kept as short as possible due to an increase in residence time favouring biuret formation.</p>
<p><i>Line No. 1217</i> Intention: transfers 20775 kg/hr urea solution (62 wt% urea) at 155°C from the MP decomposer (18 bar) to the LP decomposer (4.5 bar).</p>			

NO	Flow	<p>Failure of MP-LP expansion valve (EXPV-C1201A) closed.</p> <p>Failure of low level safety valve (SV-LSL-C1201) closed.</p> <p>Clogging of pipe due to solid carbamate formation because of low temperatures in the column, possible if no steam supply or TIC failure.</p>	<p>Build-up of urea solution in line 1217, causing level and pressure increase in column and could lead to biuret (undesired) formation.</p> <p>PIC controls release of pressure with PPV-C1201 however, if situation not rectified, PSV will open TSL to relieve built-up pressure.</p> <p>The LIC would register high levels and activate the high level switch (LSH) to close the safety valve (SV-LH-C1201) on line 1215. This action would affect the HP section, where same action would be triggered to prevent flooding of HP stripper.</p> <p>Along with the high level alarm, the FI downstream of valve will indicate to operators no flow. The backup valve (EXPV-C1201B) to be implemented immediately, or else emergency shutdown.</p> <p>If due to clogging of pipes, plant shut down, including draining and washing of column and pipes TSL (aqueous urea holding tank) before pipe section is replaced.</p>
MORE	Flow	<p>MP-LP expansion valve (EXPV-C1201A) fails/stuck open.</p> <p>Steam failure leading to more bottoms product (unsatisfactory purity) and less top gas stream.</p>	<p>Decrease of level in vessel, leading to possible escape of gases through bottoms line 1217 to LP section.</p> <p>LIC on line 1217 prevents this by sounding low level alarm (LAL), thus notifying controllers to close the low level valve (SV-LSL-C1201) or else switch will close valve to maintain level.</p> <p>Replace faulty expansion valve on line 1217 by activating backup valve (EXPV-C1201B).</p> <p>Higher pressure will be entering LP decomposer until safety valve closed,</p>

			causing same issues and same controls to be activated in LP decomposer as 'failed open' HP-MP expansion valve causes in MP decomposer (explained above).
<p><i>Line No. 1218</i> Intention: transfers the flash gases and NH₃ and CO₂ from decomposed carbamate 10371 kg/hr, at 131°C, to shell of preheater, to be partially absorbed, condensed/reacted and recycled.</p>			
MORE	Flow	<p>High temperatures in C1201, possibly due to steam control failure leading to excess steam supply.</p> <p>Higher concentration of NH₃, CO₂ or carbamate in urea solution coming through line 1215, possible if steam failure and TIC failure in HP stripper.</p>	<p>Higher temperatures cause more water to vapourise, leading to more water being recycled to the reactor (lower conversion).</p> <p>Upon failure of the TIC or the steam control valve (TPV-C1201) the high temperature alarm will sound and the SV-TSH-C1201 on line 1219 will close (the steam production in the utility section will be redistributed by use of an emergency condenser to avoid steam failures in rest of plant).</p> <p>Higher concentration of free NH₃ and CO₂ will immediately cause higher flow, whereas a higher carbamate concentration will first actuate TIC to increase steam flow (line 1219) to provide the required energy for the endothermic reaction, thereby also leading to an increase in gases leaving through line 1218.</p> <p>The pressure will be measured by the PI and the valve on line 1218 adjusted accordingly.</p>
LOW	Flow	Steam valve failure (TPV-C1201) closed.	Low temperatures in MP decomposer will cause problems in the shell side of preheater (C1302), a low flow of gases leaving line 1218 means not enough heat of condensation, reaction and absorption to provide enough heat for preheater tubes, which will lead to lower than required urea composition out of preheater (LP section).

			<p>The FI on line 1218 will indicate the situation and PPV-C1201 will close to increase the pressure in the decomposer.</p> <p>Low temperatures will be registered by bottoms flow TIC, upon no change in reading due to failed control valve (TPV-C1201), low temperature alarm will be activated, so steam valve is replaced.</p>
NO	Flow	Pressure controlled valve (PPV-C1201) failure (closed)	<p>Pressure in MP and LP decomposer will rise, PSV will vent TSL if TIC fails to rectify situation by steam control.</p> <p>The upstream flow indicator, reading no flow and the TAH sounding will indicate the failure of PPV-C1201.</p> <p>As with LESS flow, preheater will not receive required heating.</p> <p>Composition of product stream (line 1217) also affected as higher concentration of NH₃ and CO₂ remains in solution.</p> <p>Valve to be immediately replaced.</p>
<p><i>Line No. 1216</i> Intention: transfers 170 kg/hr of inerts along with NH₃ and CO₂ at 155°C and 150 bar to MP decomposer (18 bar) to aid in heating and decomposing the residual carbamate.</p>			
NO	Flow	Valve failure (EXPV-C1101A) closed	<p>Endothermic decomposition of carbamate would not be efficient, without first increasing steam supply steam. The TIC would record lower temperatures and would increase steam flow.</p> <p>Pressure decrease in decomposer will activate PIC on line 1218.</p> <p>Bypass faulty expansion valve by activating backup valve (EXPV-C1101B).</p>
MORE	Flow	Valve failure	HP gases (150 bar) entering vessel

		(EXPV-C1101A) stuck open	<p>designed for 18 bar could cause equipment failure.</p> <p>PSV will relieve pressure TSL in case pressure reaches extreme values.</p> <p>TIC on line 1217 would record increased temperatures and would regulate steam flow accordingly.</p> <p>Bypass faulty expansion valve by activating backup valve (EXPV-C1101B).</p>
<p><i>Line No. 1219 (utility: steam)</i> Intention: heats decomposer with 4750 kg/h MP steam (225 °C, 25.5 bar).</p>			
NO	Flow	Valve failure (TPV-C1201) closed.	<p>Endothermic decomposition of carbamate would not be satisfactory, resulting in incorrect bottoms composition out of the vessel and low gas flow to preheater (as described above).</p> <p>The TIC on the bottoms line will actuate alarm (TAL) upon failure of TIC to control an increase in temperature, and faulty steam valve should be replaced.</p> <p>A decrease in temperature in the vessel could also lead to carbamate and urea crystallization and clogging of lines, depending on the duration of steam failure (If short, not likely as incoming HP flows are high temperature and equipment is insulated)</p> <p>As the solution exiting MP decomposer is 62 wt% urea, operators must fix the problem before temperatures drop below 50°C – the saturation temperature of a urea-water solution of this composition (see appendix 4 for urea data).</p>
MORE	Flow	Valve failure (TPV-C1201) open.	<p>Temperature in vessel could build up, TIC will register change TAH will sound and TSH will close safety valve (SV-</p>

			TSH-C1201) to redirect steam in utility section to emergency condenser.
Vessel – Ammonia-carbamate separation column (C1202)			
Intention – This column separates NH ₃ from the rest of the recycle (carbamate, CO ₂ , water), to achieve a pure NH ₃ gas stream (with inerts) of 7006 kg/hr at 45°C. The CO ₂ level in the gas stream must be kept below 200 ppm.			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1209</i> Intention: To carry 877 kg/h of ammonia/water mixture at 65°C from scrubber (C1203) to separation column			
NO	Flow	Pump failure (P1202A)	<p>Level in C1202 will decrease, which will be corrected for by LIC controlling LPV-LL-C1202 on line 1205.</p> <p>Unsatisfactory separation of CO₂ and NH₃ in column. CO₂ in gas stream (line 1206) could result in carbamate formation in condenser (E1202) thus clogging condenser, necessitating shutdown.</p> <p>Temperature will increase in column so TIC will initiate an increase in reflux ammonia, to ensure correct composition of gas stream, by controlling three-way valve (TPV-C1202) accordingly. If this measure does not decrease temperature sufficiently in line 1206 and thus improve separation of CO₂ sufficiently, TSH will control heat to column with SV-TSH-C1202.</p> <p>No flow of aqueous ammonia to the column will also effect the concentration of water in the bottoms solution (line 1205), if the wt% water becomes too low (modelled: 23 wt% water gives carbamate crystallization temperature of 54°C) to successfully dissolve and carry carbamate to HP condenser, crystallization of carbamate will cause clogging of lines and HP pump (P1201)</p>

			<p>failure to occur.</p> <p>Level in scrubber (C1203) will also be increasing and LAH will indicate to controllers the connection between changing column (C1202) conditions and pump (P1202) failure.</p> <p>Start-up of backup pump (P1202B) required immediately. An emergency water flow can also be manually opened (SV4-C1202) to feed directly into the column (C1202) to avoid crystallization during hazardous period. If issue not solved, emergency shut down.</p>
<p><i>Line No. 1204</i></p> <p>Intention: To carry ammonia liquid 3988 kg/hr at 40°C from ammonia receiver (V1201) to ammonia-carbamate separation column</p>			
NO	Flow	<p>Pump failure (P1203A)</p> <p>Valve failure (closed) LPV-T1201 or FPV-C1202</p>	<p>Temperature in column would increase, unsatisfactory separation of CO₂ and NH₃. CO₂ in gas stream could result in carbamate formation in downstream condenser (E1202).</p> <p>The TIC to activate increase reflux of ammonia (controlling valve TPV-C1202) due to high temperatures, will try to make up for the lack of new ammonia feed.</p> <p>No flow would also cause level in rectifying column to drop, LAL would sound and valve (LPV-LSL-C1202) on line 1205 would close.</p> <p>Level in ammonia receiver (T1201) would increase, LAH would sound and automatic backup pump (P1203B) should be started or faulty valve replaced.</p> <p>In case this is not possible immediately, SV-LH-T1201 will need to be shut to stop NH₃ feed to system.</p>
<p><i>Line No. 1203</i></p>			

Intention: To transfer ammonia liquid, 10256 kg/hr at 40°C, to reactor (R1101)			
NO	Flow	<p>Pump failure (P1203A)</p> <p>Control valve failure (LPV-T1201) or three-way valve failure (FPV-C1202 closed to only line 1203, or closed to both 1203 and 1204).</p>	<p>No ammonia feed to the ejector and subsequently no feed to the reactor.</p> <p>Level in ammonia receiver would increase, LAH would sound and NH₃ supply reduced with SV-LH-T1201.</p> <p>FI on both lines 1203 and 1204 would indicate if valve and pump failure. By checking both indicators operators may also identify if issue due to partial three-way valve failure rather than pump or complete valve failure.</p> <p>If pump failure, backup pump (P1203B) should be started immediately.</p> <p>In case of partial three-way valve failure, flow in line 1203 would decrease whilst flow to the C1201 would increase.</p> <p>High level alarm on C1202 would sound and SV2-LSH-C1202 would be opened to direct excess flow through line 1213 to carbamate receiver (V1301).</p> <p>The reactor would no longer receive ammonia feed therefore, carbamate solution still being pumped to HP section, which is dependent upon the ammonia feed to be ejected into reactor, will also stop feeding the reactor. This situation requires immediate valve replacement or emergency shutdown.</p> <p>The FI on line 1203 would show partial valve failure and to avoid above-mentioned situations operators could open safety valve (SV-FL) to bypass three-way valve to avoid immediate shutdown. The faulty valve (FPV2-C1202) would then need to be replaced.</p>
<p><i>Line No. 1206</i></p> <p>Intention: To transfer ammonia gas and inerts, 7006 kg/hr at 45°C, to ammonia condenser</p>			

(E1202)			
MORE	Flow	High temperatures in C1202 due to steam control failure or cooling water failure in E1202	<p>Gas will be at higher temperatures and contain greater levels of CO₂ which could cause carbamate crystallization in condenser.</p> <p>A TIC will register increase in temperature and activate increase reflux of ammonia (line 1212).</p> <p>If temperature not brought under control by reflux, TAH will sound and the kettle temperature will be reduced by safety valve SV-TSH-C1202. The excess steam will be condensed in utility section to avoid disturbing steam supply to rest of process.</p>
<p><i>Line No. 1214</i> Intention: To carry 13864 kg/hr, 75 °C carbamate solution and residual vapours from condenser (E1201) to column (C1202).</p>			
More	Temperature	Failure of CW supply pump for condenser (E1202)	<p>Desired condensation will not occur. Temperature in C1202 will increase (same problems with CO₂ and NH₃ separation as explained above).</p> <p>TIC will increase ammonia reflux from line 1212.</p>
<p><i>Line No. 1205</i> Intention: To carry carbamate solution 11722 kg/hr at 71°C from C1202 to HP carbamate condenser (E1101).</p>			
NO	Flow	<p>If high level on HP carbamate separator (C1101) is reached, safety valve shut on line 1205.</p> <p>Failure of pump P1201A</p>	<p>Increase of level in C1202. Upon reaching HL, LAH alerts operators that stream 1205 will be directed through line 1213, by opening of SV2-LSH-C1202 to carbamate receiver (V1301), where safe storage of solution is possible. Operators should close SV1-LH-C1202.</p> <p>If cause is failure of pump, instigate use of backup P1201B.</p>
LESS	Temperature	Failure of CW recycle pump for	Temperature in C1202 will decrease, bottoms temperatures may reach

		condenser E1202 causing too much cooling.	<p>carbamate crystallization temperatures (54°C). Leading to clogging and potential failure of pump 1201. The TI on cw (line 1222) will indicate increasing temperatures of cooling water and operators should cross-check TI on line 1205.</p> <p>Cw situation must be immediately rectified, SV-TSH-C1202 could be manually adjusted to increase heat to column or plant shutdown.</p>
<p>Vessel – MP carbamate condenser (E1201)</p> <p>Intention – This MP condenser serves to further condense the solution coming from the shell of the preheater (line 1229) to 75°C and to feed the 13864 kg/hr to the bottom of the ammonia-carbamate separation column.</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1221 (Utility, CW)</i></p> <p>Intention: To cool carbamate solution running through condenser from 87°C to 75°C with 8.2×10^4 kg/h of cooling water.</p>			
MORE	Flow	Failure of control in utility section	The temperature of the carbamate solution in stream 1214 will decrease, the TI on line 1222 will register change from norm and will recycle the warm cw to ensure carbamate solution is not cooled to point of crystallization.
LESS	Flow	Failure of cw supply pump	Same as MORE temperature for line 1214 (see above)
<p><i>Line No. 1222 (Utility, CW)</i></p> <p>Intention: 8.2×10^4 kg/h of cooling water leaving condenser (E1201) after being heated from 25°C to 35°C.</p>			
MORE	Temperature	Failure of TIC, valve (LPV-E1201) or pump on cw recycle	A higher temperature of cw coming out of E1201 indicates the temperature of the carbamate stream through E1201 will be cooled further than desired, possibly creating crystallization of carbamate. This could lead to pipe clogging and thus NO flow situation through line 1214. Operators should be aware of failure due

			to TAH, then cw equipment to be fixed or plant shut-down.
<p><i>Line No. 1229</i> Intention: transfers carbamate solution from preheater shell (C1302) to condenser (E1201) to be further condensed from 87°C to 75°C.</p>			
LESS	Flow	<p>Low temperatures in MP decomposer leading to less gases being fed to preheater shell.</p> <p>Failure of P1301A.</p>	<p>Lower flow would result in lower temperatures in line 1214 until cw recycle system rectifies situation.</p> <p>The low flow would cause level in C1202 to decrease, and subsequently less recycle to reactor. The LIC on C1202 would close LPV-LSL-C1202.</p> <p>Pump to be bypassed with P1301B.</p> <p>If issue is in MP decomposer see description of line 1218.</p>
<p>Vessel – MP ammonia condenser (E1202)</p> <p>Intention – This MP condenser serves to condense the 7006 kg/hr of ammonia and inert vapours, from 45°C to ammonia liquid at 40°C, before being fed into the ammonia receiver (V1201).</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1207</i> Intention: transfers ammonia liquid (40°C, 7006 kg/hr) to ammonia receiver (V1201).</p>			
MORE	Temperature	Cw supply failure	<p>Ammonia will not be condensed and will escape receiver (V1201) more readily along with the inerts, leading to greater demand on scrubber.</p> <p>PIC will register increase in pressure in V1201 and will control PPV-V1201 accordingly. If pressure increase is too great, SV-V1201 could be opened TSL (emergency absorber), bypassing the scrubber to release release pressure.</p>
<p><i>Line No. 1224 (Utility, CW)</i> Intention: supplies $1.8 \times 10^5 \frac{kg}{h}$ of cooling water to ammonia condenser (E1202).</p>			
MORE	Flow	Failure of control in utility section	Excessive cooling in ammonia condenser will lead to low temperatures (below 40

			°C) in ammonia receiver and reduced removal of inerts from the vessel. The TI on the receiver will register decrease in temperature and TIC will rectify cw situation with the cw recycle control system, as explained above for line 1221.
<p><i>Line No. 1225 (Utility, CW)</i> Intention: $1.8 \times 10^5 \frac{kg}{h}$ cooling water coming out of ammonia condenser (E1202), after being heated from 25°C to 35°C.</p>			
MORE	Temperature	Failure of TIC, valve (TPV-E1202) or pump on cw recycle	<p>The temperature alarm (TAH) should indicate to operators a problem with the utility equipment.</p> <p>In this situation there is more time to replace the faulty equipment as carbamate crystallization is not a direct consequence.</p>
<p><i>Vessel – Ammonia receiver (V1201)</i></p> <p>Intention – This MP ammonia reservoir (40 °C and 18 bar) serves to collect feed ammonia (7600 kg/hr) and recycled ammonia (7006 kg/hr) and distributes it to the reactor and the ammonia-carbamate separating column.</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1201</i> Intention: To carry ammonia liquid (7600 kg/hr) from ammonia storage tank (OSBL) to ammonia receiver.</p>			
NO	Flow	No raw material supply from ammonia plant (possibly due to NH ₃ supply pump failure)	<p>Ammonia receiver is able to supply process without dependency on raw material for one hour. As the level decreases, the LAL will sound and LPV-V1201 (line 1202) will be shut however, in this emergency circumstance, the level control will need to be manually overridden to continue to supply the process with ammonia.</p> <p>If failure not repaired within the hour, plant shutdown.</p>
<p><i>Line No. 1202</i> Intention: To carry ammonia liquid (14244 kg/hr) from ammonia receiver to ammonia rectifying column and reactor</p>			

NO	Flow	Pump failure (P1203A) Valve (LPV-V1201) failed closed	No flow to reactor, level in receiver (V1201) will increase, LAH will activate and NH ₃ supply must be shut off (SV-LH-V1201). Equipment must be immediately replaced (pump bypassed with P1203B) or emergency shutdown.
<p><i>Line No. 1208</i> Intention: To transfer inerts and ammonia gas (343 kg/hr) from ammonia receiver to MP scrubber (C1203)</p>			
NO	Flow	Failure of PIC valve (closed)	Pressure increase in receiver vessel and PSV opens TSL. To avoid the opening of the PSV, SV-V1201 can be opened to control the feed of gases TSL (emergency absorber), after which they will be stored in the emergency aqueous ammonia tank (OSBL).
MORE	Flow	High temperatures in V1201 due to cw failure in E1202 Releasing pressure of MP section to achieve safe shutdown	More ammonia will flow to scrubber, this will be registered by FI on line 1208, which will actuate FFC to increase H ₂ O feed by opening of LPV-C1203 (this control ensures safe levels of ammonia in line 1210). The ratio of flow in line 1208 and 1211 will be controlled and H ₂ O feed adjusted, to achieve an approximate flow ratio of 1m ³ /h gases out of receiver to 0.03 m ³ /h of water. In the case that the urea plant is shutdown, the ammonia liquid which has been collected in the ammonia receiver will vapourize if the pressure is quickly let down and could cause the PSV to blow. To ensure the vessel can be emptied safely and the contents collected (rather than being sent to flare through scrubber, line 1208), the safety valve SV-V1201 is opened TSL (emergency absorber) thus, allowing the safe collection and storage of aqueous ammonia at atmospheric pressure

			(aqueous ammonia tank, OSBL).
Vessel – Ammonia scrubber (C1203)			
Intention – This unit (18 bar) separates ammonia from inerts by scrubbing with water (700 kg/hr), thus allowing 166 kg/hr of inerts (and largely methane) to be sent to flare with safe levels of ammonia present (530ppm). The scrubbing water is also necessary in other parts of the process to ensure safely dissolved carbamate compositions.			
<i>Line No. 1211</i> Intention: To transfer scrubbing water (700kg/hr at 25°C) to scrubber for ammonia absorption			
NO	Flow	Valve (FPV-C1203) failure, closed Fresh water feed pump failure (OSBL)	Absorption of ammonia in water will not take place, dangerous ammonia emission levels in vapour outflow (however, as all inerts are sent to flare due to large methane content, it will lead to increased NOx emissions, not direct ammonia emissions) . Analyzers installed in line 1210 will detect unacceptable NH ₃ concentrations and LAH alarm will sound and switch (ASH) will open valve SV-ASH-C1203 and close SV-ASH-C1203 to send stream TSL (emergency absorber) . Level in scrubber will also drop, which will be regulated by LPV-C1203. Thus, there will be no feed to C1202 (actions described above, line 1209).
LESS	Flow	FFC failure	Low water:ammonia ratio thus, vapour flow not at safe emission levels, same actions as above. If only a failure of the FFC system, the valve (FPV-C1203) should be manually adjusted until controller fixed.
<i>Line No. 1209</i> Intention: To transfer ammonia-water solution (877 kg/hr) at 65 °C from scrubber to ammonia-carbamate separation column.			
Less	Flow	Failure of water feed pump (no flow in line 1211)	Not enough water fed to rectification column, thus lower CO ₂ absorption and possibly too low water concentration to move carbamate solution to reactor (as

			explained above, for C1202 line 1209, again emergency water feed SV4-C1202 could be introduced to C1202).
More	Flow	Faulty FFC, causing too much H ₂ O into scrubber	<p>Too high water supply could result in too high water concentration in rest of system, eventually leading to lower conversion in reactor.</p> <p>Level increase in scrubber will activate LAH and LPV-C1203 is adjusted. FPV-C1203 on water feed should be closed manually to desired flow.</p>

A3.1.3 The LP section

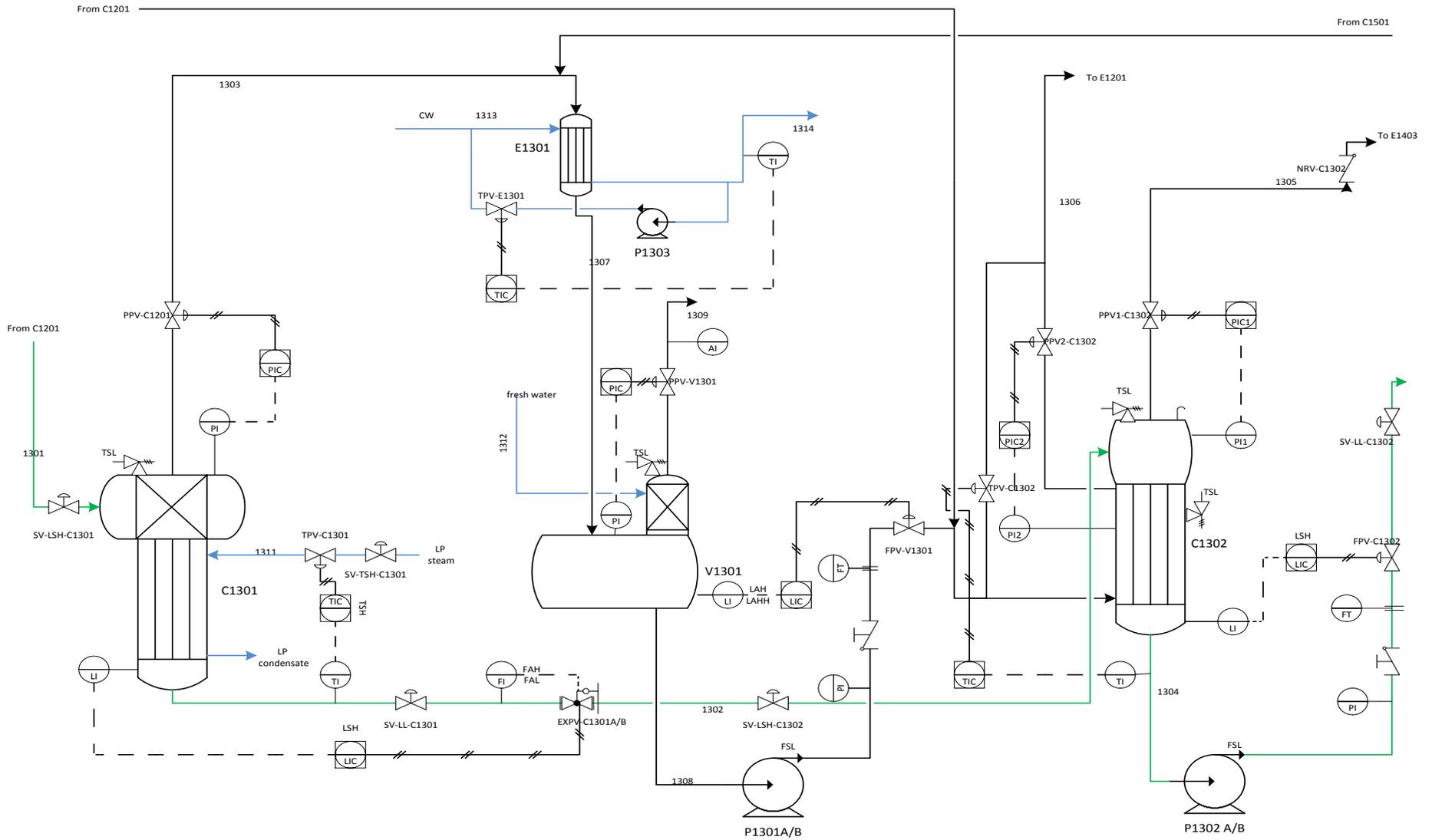


Figure 58: P&ID of LP section

Table 10: Hazop report of LP section

Vessel – LP decomposer and rectifier			
Intention – Removal of released flash gasses and decomposition of ammonium carbamate			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1301</i>			
Intention: Transport liquid effluent from MP decomposer and rectifier to LP decomposer and rectifier Mass flow: 20775 kg/hr Temperature: 155°C Pressure: 4.5 bar			
NO/NONE	Flow	Low or no liquid level on C1201 and subsequent closing of SV-LL-C1201	Level falls in C1301; Use a level indicator connected to a level indicator controller which operates EXPV-C1301
MORE	Pressure	Malfunctioning of EXPV-C1201	Pressure build-up in C1301; fit a pressure safety valve
LESS	Flow	Low liquid level on C1201	As NO flow
<i>Line No. 1302</i>			
Intention: Transport of the product line to the preheater. Mass flow: 18851 kg/hr Temperature: 138°C Pressure: 0.34 bar			
NO/NONE	Flow	Low or no liquid level in C1301 and subsequent closing of SV-LL-C1301	Low liquid level in C1302; use a low level safety valve on C1302
MORE	Pressure	Malfunctioning of EXPV-C1301	Pressure build-up in C1302; use a pressure safety valve
	Temperature	Excessive heating	Use a temperature indicator connected to a temperature indicator controller to regulate the flow of low pressure steam
	Level	Valve failure	Use a high level switch connected to the level indicator to operate SV-LSH-C1301 and lessen or stop the inlet flow

LESS	Flow	Low liquid level in C1301	As NO Flow
	Temperature	Not enough heating	As MORE Temperature
	Level	No inlet flow	Use a low level safety valve
<p><i>Line No. 1303</i> Intention: Transport of released flash gasses to the condenser Mass flow: 1916 kg/hr Temperature: 126°C Pressure: 4.5 bar</p>			
MORE/LESS	Pressure		Use a pressure indicator as well as a pressure indicator controller to regulate the flow
<p><i>Vessel – Preheater/ preconcentrator</i></p> <p>Intention – To pre-concentrate the product before entering the vacuum purification and recovery section. Mass flow: 14864 kg/hr Temperature: 105°C Pressure: 0.34 bar</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1304</i> Intention: To transport the product line to the vacuum purification and recovery section.</p>			
NO/NONE	Flow	Low or no liquid level on C1302 and subsequent FPV-C1302 or pump failure	Use a low flow alarm connected to a flow transmitter
MORE	Flow	Pump tripping	Use high flow alarm connected to a flow transmitter
	Temperature	Excessive heating	Use a temperature indicator connected to a temperature indicator controller to regulate the inlet flow of heating medium coming from V1301 and C1201
	Level	Valve failure	Use a high level switch connected to a level indicator to regulate the inlet flow to C1302
LESS	Flow	Low liquid level	Same as NO Flow

		in C1301	
	Temperature	Insufficient heating	Same as MORE temperature
	Level	No inlet flow	Use a low level safety valve
<p><i>Line No. 1305</i> Intention: To transport the released flash gasses to the condenser E1403 Mass flow: 3987 kg/hr Temperature: 87°C Pressure: 0.34 bar</p>			
NO/NONE	Flow	Valve failure	Pressure build-up in the vessel; use a pressure safety valve
MORE/LESS	Pressure		Use a pressure indicator with a pressure indicator controller to regulate PPV1-C1302
REVERSE	Flow	Pressure loss in the vessel due to malfunctioning	Contamination due to addition of water; use a check valve
<p><i>Line No. 1306</i> Intention: To transport the released gasses to the condenser E1202 Mass flow: 13864 kg/hr Temperature: 87°C Pressure: 18 bar</p>			
NO/NONE	Flow	Valve failure	Pressure build up in the shell side of the heater; use a pressure safety valve
MORE/LESS	Pressure		Use a pressure indicator connected to a pressure indicator controller to regulate PPV2-C1303
<p><i>Vessel – Low pressure carbamate condenser (E1301)</i> Intention – To condensate the off gasses from C1301 and V1401</p>			
Guide Word	Deviation	Cause	Consequences and Action
<p><i>Line No. 1307</i> Intention: Transport the off gasses from C1301 and C1501 to the condenser. Mass flow: 3803 kg/hr Temperature: 40°C Pressure 4.5 bar</p>			
MORE	Temperature	Insufficient	Pressure build-up in V1301 due to

		cooling	incomplete condensation of the gasses; use a temperature indicator with a temperature indicator controller to regulate the inlet of cooling water to the condenser
LESS.	Temperature	Excessive cooling	Use a temperature indicator with a temperature indicator controller to regulate the inlet of cooled water
Vessel – Low pressure carbamate receiver (E1202)			
Intention – To store ammonium carbamate solution at low pressure.			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1308</i> Intention: To transport ammonium carbamate solution to the shell side of the preheater Mass flow: 3493 kg/hr Temperature: 40°C Pressure: 4.5 bar			
NO/NONE	Flow	Low level on V1301 and subsequent valve shutdown or pump failure	Insufficient heating medium available for the preheater; use a low flow alarm on the flow transmitter
MORE	Flow	Failure on the pump control	Use a high flow alarm on the flow transmitter
	Level	Valve stuck closed	Use a high level alarm and a high high level alarm connected to a level indicator
LESS	Flow	Low level on V1301	Same as NO Flow
	Level		Use a level indicator and a level indicator controller to regulate the outlet flow
REVERSE	Flow	Malfunctioning of the pump	Contamination of the solution in the vessel; use a non check valve
<i>Line No. 1309</i> Intention: Transport off gasses from the low pressure ammonium carbamate receiver to the atmosphere. Mass flow: 311 kg/hr Temperature: 40°C Pressure: 4.5 bar			

NO/NONE	Flow	PPV-V1301 fails closed	Pressure build-up in the vessel; use a pressure safety valve
MORE	Temperature	Insufficient cooling	Same as MORE Flow
MORE/LESS	Pressure		Use a pressure indicator and pressure indicator controller to regulate PPV-V1301

A3.1.4 The Vacuum section

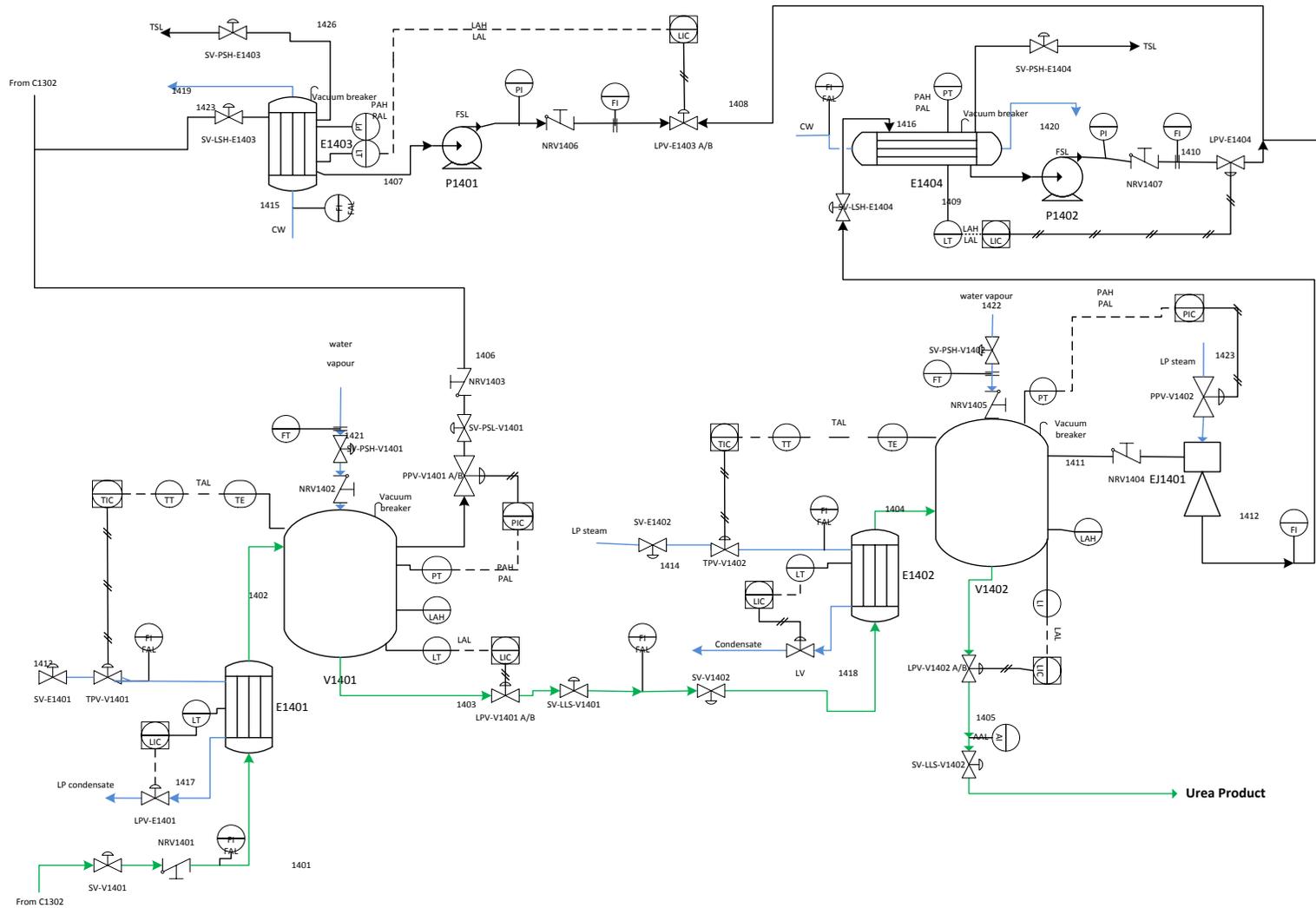


Figure 59: P&ID of vacuum section

Table 11: Hazop report of vacuum section

Vessel - Vacuum separator (VI401)			
Intention - heat up process stream with LP steam			
Guide word	Deviation	Cause	Consequences and action
<i>Line No. 1401</i> Intention : Transfer liquid from the preheater to the vacuum section 1.48*10 ⁴ kg/h, 105°C, 0.34 bar, 87.2 wt.% urea			
no	flow	Clogging, valves stuck closed, control failure in preheater	No feed to apparatus, temperature will keep being regulated as the pressure and the level. This means the steam will all be send back to the backup steam condenser. Level and pressure valves will close due to low flow: flow indicator, low flow alarm, emergency shutdown.
Reverse	flow	pressures around line incorrect for example due to pressure control failure	Flow back to pump, pump will break: add non-return valve NRV1401
more of	flow	level valve preheater stuck open, level control failure	increased level and pressure in the evaporator: flow indicator
<i>Line No. 1402</i> Intention: transfer liquid + gas from heat exchanger to separation vessel 1.48*10 ⁴ kg/h, 130°C, 0.3 bar, 87.2 wt.% urea			
as well as	composition	crystallization in line due to controller failing or a valve stuck in the water vapour line for a long time.	Product will be contaminated: proper maintenance in apparatus will prevent this problem.
<i>Line No. 1403</i> Intention: Transfer liquid urea mixture to next evaporator system. 1.36*10 ⁴ kg/h, 130°C, 0,3 bar, 94.9 wt.% urea			
no	flow	valves on discharge stuck closed, clogging in pipes	No product will leave the evaporator. The level will rise, liquid might reach to the inlet and the vapour outlet.: LAH in LIC, backup level valve, SV-V1401 will switch off if the high level switch is triggered.
less of	flow	control/heating/pressure failure	temperature/pressure wrong, wrong composition, level will rise: LAH, high level switch

			connected to SV-V1401
more of	flow	control/heating/pressure failure	level will drop too much, next evaporator might not be able to handle it, vapour will enter the line.: LAL with low level switch SV-LLS-V1401
as well as	vapour fraction	Control failure in evaporator, wrong composition from preheater	gas will go to pump which breaks the pump: LAL in LIC, low level switch SV-LLS-V1401
<i>Line No. 1406</i>			
Intention: Transport contaminated water to condenser. 1396 kg/h, 130°C, 0.3 bar, 96.8 wt.% water			
less	flow	fouling due to fail in water vapour supply	proper maintenance for fouling and water supply will prevent this problem.
no	flow	valve stuck closed	pressure in evaporator increases, product purity decreases, no flow to heat exchanger: high pressure alarm, backup valve, high pressure switch water vapour input SV-PSH-V1401, high pressure switch in SV-V1401
more	flow	valves stuck open	possible risk of implosion: vacuum breaker, low pressure alarm, low pressure switch SV-PSL-V1401
as well as	liquid fraction	valves on discharge stuck closed, control failure	Liquid will go though the discharge line and might flow back though the inlet. LAH, high level switch in the SV-V1401
as well as	composition	too much co2 and ammonia formation due to control failure	condensation will be harder, might cause gas build up in condenser: release the extra gases in the condenser to a flare system, indicated in the P&ID as to safe location.
Reverse	Flow	Pressure control failure in either the preheater, vacuum condenser or the vacuum evaporator	The flow will reverse stopping the effective separation in the cyclone: NRV1403
<i>Line No.1421</i>			
Intention: Transfer water vapour to separation vessel to reduce fouling. 140 kg/h, 150°C, 4.5 bar			
no/less	flow	Failure in valves or distribution system	Crystals will build up over time, this is not an immediate problem but if it is not treated the product will be contaminated.: Close the line and replace broken equipment. In next shutdown

			it is advised to check equipment carefully for crystals. Mechanical cleaning is required.
Reverse	flow	fail in distribution system, pressure control failure	stream will go in the wrong direction which will disturb the distribution system: non-return valve NRV1402
Line No. 1413 Intention: Transfer low pressure steam to heat exchanger. 1539 kg/h, 25°C, 5 bar			
No	flow	valve stuck closed, failure in distribution system	heating requirements not met, separation insufficient: flow indicator, low flow alarm, this will indicate whether there is a large disturbance in the steam distribution. There is also a low temperature alarm to indicate a problem in the steam supply.
Vessel - Condenser (E1403)			
Intention - Condense contaminated water vapour			
Line No. 1423 Intention: Transfer vapour from the preheater and the first evaporator to the first vacuum condenser E1403. 5383 kg/h, 100°C, 0.304 bar, 92.1 wt.% water			
More	flow	Failure in control in preheater or vacuum evaporators.	Full condensation becomes impossible pressure will build up: high pressure switch SV-PSH-E1403 which will open a line to transport the said gases to a flare system.
Line No. 1407 Intention: Transfer condensed waste water to pump. 5383 kg/h, 30°C, 0.304 bar, 92.1 wt.% water			
no/less	flow	valve stuck closed	build up of liquid in shell: high level alarm, backup valve, high level switch in SV-LSH-E1403, in the pump there is a low flow switch to prevent it sucking cavities.
as well as	vapour fraction	too much co2 and ammonia in feed, not sufficient cooling, pressure control broken	pump will receive vapour, pump will break: low level alarm
more	flow	Pump failure	If the suction from the pump is too big will decrease, risk of implosion: vacuum breaker on shell side of condenser.

Auxiliary E1403			
Intention - Cooling down waste water line to condense the vapour.			
<i>Line No. 1415</i>			
Intention: Transfer of cooling water to heat exchanger. $3.22 \cdot 10^5$ kg/h, 25°C, 5 bar			
no/less	flow	Failure in cooling water distribution system	not enough cooling, which will result in insufficient condensing: flow indicator, equipped with a low flow alarm
Vessel - Second vacuum evaporator V1402			
Intention - Last purification step for the product by evaporating water and possible other volatile materials.			
<i>Line No. 1404</i>			
Intention: Transferring mixture from heat exchanger to separation vessel. $1.36 \cdot 10^4$ kg/h, 134°C, 0.03 bar, 94.9 wt.% urea			
no	flow	Clogging, valves stuck closed, control failure in preheater	No feed to apparatus, temperature will keep being regulated as the pressure and the level. This means the steam will all be send back to the backup steam condenser. Level and pressure valves will close due to low flow: flow indicator, low flow alarm, emergency shutdown.
as well as	composition	crystallization in line due to controller failing or a valve stuck in the water vapour line for a long time.	Product will be contaminated: proper maintenance in apparatus will prevent this problem.
more of	flow	level valve first evaporator stuck open, level control failure	increased level and pressure in the evaporator: flow indicator
<i>Line No. 1405</i>			
Intention: Transferring urea melt to storage/ melamine plant. $1.26 \cdot 10^4$ kg/h, 134°C, 0.03 bar, 99.6 wt.% urea			
no	flow	valves on discharge stuck closed, clogging in pipes	No product will leave the evaporator. The level will rise, liquid might reach to the inlet and the vapour outlet.: LAH in LIC, backup level valve, SV-V1402 will switch off if the high level switch is triggered.
less of	flow	control/heating/pressure failure	temperature/pressure wrong, wrong composition, level will rise: LAH, high level switch connected to SV-V1402
more of	flow	control/heating/pressure failure	level will drop too much, next evaporator might not be able to handle it, vapour will enter

			the line.: LAL with low level switch SV-LLS-V1402
as well as	vapour fraction	Control failure in evaporator, wrong composition from preheater	gas will go to pump which breaks the pump: LAL in LIC, low level switch SV-LLS-V1402
As well as	Composition	Wrong composition in feed, failure in control	Product wont meet the specifications for its use in the melamine plant: analyser with an alarm for the case if the urea concentration is too low.
<i>Line No. 1411</i>			
Intention: Transferring water vapour to steam ejector. 1152 kg/h, 134°C, 0.03 bar, 86.3 wt.% water			
less	flow	fouling due to fail in water vapour supply	proper maintenance for fouling and water supply: flow indicator
no/less	flow	steam ejector failure	pressure in evaporator increases as there is no suction, increased pressure in vessel product purity decreases, no flow to heat exchanger: high pressure alarm, backup valve, high pressure switch on water vapour input and in SV-1402.
Reverse	flow	steam ejector failure	steam might go into separation vessels, which will cause less efficient separation in the evaporator: NRV1404
as well as	liquid fraction	valve stuck closed	level will build up, might cause reverse flow, might cause ejector to fail: backup valve, LAH, high level switch in the feed in SV-1402
more	flow	Control over steam injection in ejector broken, suction from ejector too high	possible risk of implosion: vacuum breaker, low pressure alarm
<i>Line No. 1422</i>			
Intention: Transfer water vapour to separation vessel to reduce fouling. 110 kg/h, 150°C, 4.5 bar			
no/less	flow	Failure in valves or distribution system	Crystals will build up over time, this is not an immediate problem but if it is not treated the product will be contaminated.: Close the line and replace broken equipment. In next shutdown it is advised to check equipment carefully for crystals. Mechanical cleaning is required.

Reverse	flow	fail in distribution system, pressure control failure	stream will go in the wrong direction which will disturb the distribution system: non-return valve NRV1405
Auxiliary	E1402		
Intention	heat product stream before it enters the vacuum evaporator with LP steam		
<i>Line No. 1418</i> Intention: Transferring LP steam to heat exchanger of vacuum evaporator. 839 kg/h, 148°C, 4.5 bar			
no	flow	valve stuck closed, failure in distribution system	heating requirements not met, separation insufficient: flow indicator, low flow alarm, this will indicate whether there is a large disturbance in the steam distribution. There is also a low temperature alarm to indicate a problem in the steam supply.
Vessel - Vacuum condenser 2 E1404			
Intention - Condense contaminated water vapour from the second vacuum evaporator			
<i>Line No. 1412</i> Intention: Transferring contaminated water vapour from second heat evaporator to condenser. 1752kg/h, 140°C, 0.3 bar, 91.9 wt.% water			
More	flow	Failure in control vacuum evaporators, wrong composition in evaporator	Full condensation becomes impossible pressure will build up: high pressure switch SV-PSH-E1404 which will open a line to transport the said gases to a flare system.
<i>Line No. 1409</i> Intention: Transferring water to pump to tank. 1752kg/h, 30°C, 0.3 bar, 91.9 wt.% water			
no/less	flow	valve stuck closed	build up of liquid in shell: high level alarm, backup valve, high level switch in SV-LSH-E1404, in the pump there is a low flow switch to prevent it sucking cavities.
as well as	vapour fraction	too much co2 and ammonia in feed, not sufficient cooling, pressure control broken	pump will receive vapour, pump will break: low level alarm
more	flow	Pump failure	If the suction from the pump is too big will decrease, risk of implosion: vacuum breaker on shell side of condenser.
Auxiliary - E1404			
Intention - Cooling the waste water stream to condense it.			
<i>Line No. 1420</i> Intention: Transferring cooling water. $5.83 \cdot 10^4$ kg/hr, 35°C, 5 bar			

no/less	flow	Failure in cooling water distribution system	not enough cooling, which will result in insufficient condensing: flow indicator, equipped with a low flow alarm

A3.1.5 The Wastewater section

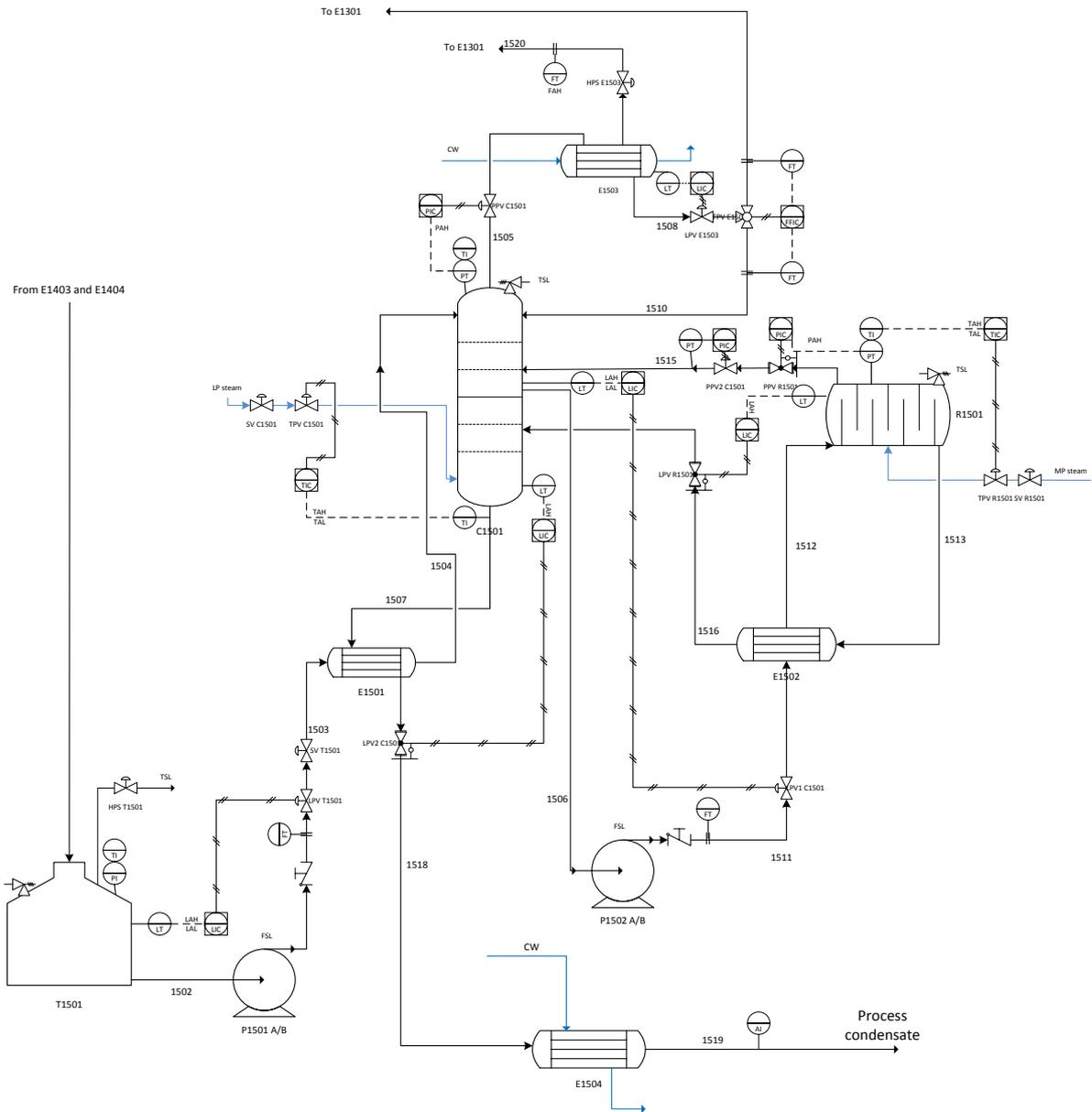


Figure 60: P&ID of wastewater section

Table 12: Hazop report of wastewater section

Vessel – Wastewater tank (T1501)			
Intention – To store the wastewater before treating it at 1 bar and 40°C, 6535 kg/h, 6.8 wt% urea, 5.3 wt% ammonia.			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1501</i>			
Intention: transfer wastewater from vacuum condenser.			
No	flow	Failure in evaporation section	level drops in the tank, which closes LPV T1501. Line 1504 will stop flowing, which decreases the level in the top of C1501, closing LPV1 C1501. With no liquid inflow in R1501, the level will drop, closing LPV R1501. With no decomposition in R1501 the pressure will decrease, closing PPV R1501 and the temperature will increase closing TPV R1501. With no liquid inflow in C1501 the level in the bottom of C1501 will drop, closing LPV2 C1501. With no stripping in C1501 the pressure will decrease, closing PPV C1501 and the temperature will increase closing TPV C1501.
More	flow	More live steam is used in the plant More water is recycled	The level increases, Pump increases flow, more wastewater is entering the column, stripping is less effective and more water leaving plant is more contaminated.
As well as	Vapor fraction	Failure in level valve in vacuum condenser.	Increase of pressure in tank, part of the vapor is absorbed by pressure increase. If pressure is too high the HPS will open and vapor is sent to the scrubber.
<i>Line No. 1502</i>			
Intention: transfer wastewater from tank to the pump to pump it up to 4.5 bar, 6535 kg/h, 6.8 wt% urea, 5.3 wt% ammonia.			
No	flow	P1501 failure	Level increase of the tank, if level is too high, alarm goes off. A backup pump has to be installed before it overflows. When the tank is filling up completely, the plant has to be shut down.
more	flow	Level increase of the tank	Pump increases flow, more wastewater is entering the column, stripping is less effective and more water leaving plant is more contaminated.
Vessel – Heat exchanger E1501			
Intention – to recover heat of the process condensate and preheat the wastewater before entering the top of the column			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1503</i>			
Intention: transfer pumped up wastewater to heat exchanger, in which it is heated to 105°C, 4.5 bar, 6535 kg/h, 6.8 wt% urea, 5.3 wt% ammonia.			

No	flow	P1501 failure, LPV T1501 failure, SV T1501 is activated	The process condensate flow won't be cooled down. The process condensate outflow in line 1518 and thus 1519 will be warmer. Eventually the whole wastewater treatment stops as described in no flow in line 1501.
More	flow	Level increase in tank	The wastewater input of the column will be colder (line 1504) and the process condensate will be hotter (line 1518). The temperature of the column drops, which opens TPV C1501. More steam enters the column, which keeps the temperature the same in the column. Eventually all the streams are increased, which causes a more urea and ammonia in the process condensate.
less	flow	Level decrease in tank	The wastewater input of the column will be hotter and the process condensate will be colder. The temperature of the column increases. Less steam enters the column, which keeps the temperature the same in the column. Eventually all the streams are decreased, which leads to less contamination in the process condensate.
<i>Line No. 1507</i>			
Intention: transfer warm process condensate from the bottom of the column to the heat exchanger in which it is cooled down from 148°C to 90°C, 4.5 bar, 8153 kg/h, pure water.			
more	flow	Increase level of the column	Line 1518 will be warmer, which results in a warmer process condensate. Line 1504 will be warmer. Less steam enters the column.
less	flow	Decrease level of column	Line 1518 will be colder, which results in a colder process condensate. Line 1504 will be colder. More steam enters the column.
<i>Vessel –stripping column C1501</i>			
Intention – to strip the wastewater and the effluent from the hydrolyzer from NH ₃ and CO ₂ at 4.5 bar pressure and a temperature of 128°C at the top and 148°C at the bottom.			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1504</i>			
Intention: Transfer preheated wastewater to the top of the column, 105°C, 4.5 bar, 6535 kg/h, 6.8 wt% urea, 5.3 wt% ammonia.			
more	Flow	More live steam is used in the plant More water is recycled	Level of the top column increases, LPV1 C1501 will open, increase in flow 1506. The temperature in 1512 will be lower, which causes a temperature decrease in R1501. TPV R1501 will open, which counterbalance this with more HP steam. Eventually all the streams will be higher. With a higher flow in the C1501 and a lower residence time in R1501, the ammonia and urea content will be higher

			in the process condensate.
more	NH ₃ concentration	Ratio of NH ₃ /CO ₂ is too high. Stripping in plant was less effective.	The pressure increases in C1501 and PPV C1501 opens. If there is a buildup of ammonia in E1503, it won't condense and the pressure in E1503 and C1501 is still increasing, HPS E1503 will open and vapor is send to the LP carbamate condenser through line 1520. In the LP carbamate condenser it is mixed with line 1509 and the off-gas of the LP decomposer and condensed to flow in the carbamate receiver.
more	Urea concentration	Higher temperature or lower pressure in vacuum evaporators	Higher concentration urea going to the hydrolyser. More urea is decomposed in the hydrolyser. More CO ₂ and NH ₃ is flowing in the column. Which causes the same as for more NH ₃ concentration.
<i>Line No. 1505</i>			
Intention: to transport top vapor of the column to the condenser, 128°C, 4.5 bar, 3763 kg/h, 49 wt% water, 32 wt% ammonia, 19 wt% CO ₂ .			
no	flow	Failure in PPV C1501	The pressure in C1501 will increase. Normally PPV C1501 would open, but this fails. The PAH will ring because the pressure is too high in C1501. SV T1501 has to be closed manually, So there is no wastewater coming in the column and the level in T1501 is rising. The temperature rises in C1501, so TPV C1501 will close, which shut off the steam input and thus the heat supply. Also PPV2 C1501 closes because of the high pressure in C1501, which shuts off the vapor coming from the hydrolyzer. In the hydrolyzer (R1501), the pressure and thus the temperature is rising, closing TPV R1501, which shut off the steam input and thus the heat supply. Because line 1503 stops, 1504 stops. This decreases the level in the top of C1501 closing LPV1 C1501. With no input in R1501 the level decreases, which closes LPV R1501. This shuts off the input in the bottom of the column, decreasing the level, which closes LPV2 C1501. So in every line the flow stops and T1501 is filling up.
<i>Line No. 1508</i>			
Intention: outlet of the condenser E1503, 30°C, 4.5 bar, 3763 kg/h, 49 wt% water, 32 wt% ammonia, 19 wt% CO ₂ .			
No	flow	Cooling water failure	The condenser will heat up and less vapor will be condensed in E1503. The pressure will increase due buildup of vapor in the top of C1501 and in E1503. PAH goes off and HPS E1503 will open and vapor is

			<p>send to the LP carbamate condenser. Also the level in E1503 will drop, because no condensate is formed, which closes the LPV E1503, which stops the flow in 1508, 1509 and 1510. So all the off gas of C1501 will leave through 1520. This triggers a FAH. SV T1501 has to be closed manually and the operator has to check if there is something wrong with cooling water</p> <p>Because there is no reflux in C1501, more water vapor is recycled through 1520 to the carbamate condenser, which increases the water concentration in the plant.</p>
No	flow	LPV E1503 failure FPV E1503 failure	The level in E1503 will rise. The cooling capacity decreases in E1503, which increases the pressure in E1503, as in cooling water failure.
<i>Line No. 1506</i>			
Intention: outlet effluent of the top column, 142°C, 4.5 bar, 8375 kg/h, water with 5.3 wt% urea and 1.1 wt% ammonia.			
no	flow	LPV1 C1501 failure Pump failure p1502	<p>Level in top column increases. LAH goes off. The back-up pump or valve has to be installed manually and SV T1501 has to be closed manually. If the top of C1501 is filling completely to the top the recycle stream in 1509 would be larger and containing more water.</p> <p>Also the liquid input in R1501 will stop, decreasing the level, closing LPV R1501. With no reaction in R1501, the pressure drops, closing PPV R1501 and the temperature will increase, closing TPV R1501.</p>
<i>Line No. 1507</i>			
Intention: outlet effluent of the bottom column, 148°C, 4.5 bar, 8153 kg/h, pure water.			
no	flow	LPV2 C1501 failure	Level in the bottom of the column increases. The LAH goes off. The back-up valve has to be installed manually. SV T1501 has to be closed manually to prevent the column filling up completely.
<i>Line No. LP steam</i>			
Intention: heating C1501 and stripping agent in C1501, 148°C, 4.5 bar, 1500 kg/h.			
no	flow	TPV C1501 failure LP steam system failure	The temperature in C1501 will decrease, which causes a higher concentration of ammonia in the process condensate. The TAL will go off. The SV T1501 has to be closed manually, which shuts down the water treatment section.
<i>Vessel –Hydrolyser R1501</i>			
Intention – to hydrolyze urea to carbamate and decompose carbamate to CO ₂ and NH ₃ at 203°C and 20 bar			
Guide Word	Deviation	Cause	Consequences and Action

<i>Line No. 1512</i>			
Intention: preheated effluent of the top of C1501 entering R1501, 198°C, 20 bar, 8374 kg/h, 5.3 wt% urea, 1.1 wt% ammonia.			
no	flow	P1502 failure LPV1 C1501 failure	Same as no flow in 1506
<i>Line No. 1515</i>			
Intention: off-gas flow of R1501, which is expanded from 20 bar to 4.5 bar, 203°C, 2119 kg/h, 15 wt% CO ₂ , 8.9 wt% ammonia.			
no	flow	Failure in PPV R1501 or PPV2 C1501	The pressure in R1501 will increase, which triggers the PAH at which SV T1501 has to be closed, which causes a shut down in the water treatment section. Because if there is no off-gas in R1501, there is no decomposition, which leads to a higher concentration of urea in the process condensate.
<i>Line No. 1513</i>			
Intention: liquid outflow of R1501, which is cooled down in E1502 from 203°C to 150°C and is expanded in LPV R1501 from 20 bar to 4.5 bar, 8256 kg/h, water with 1.9 wt% ammonia			
no	flow	LPV R1501 failure	The level in R1501 will rise, triggering LAH. SV T1501 has to be closed manually.
<i>Line No. MP steam</i>			
Intention: MP steam input of R1501, providing heat. 225°C, 22.5 bar, 2000 kg/h.			
no	flow	Failure in TPV R1501	The temperature in R1501 will decrease, which triggers the TAL, at which SV T1501 has to be closed, which causes a shut down in the water treatment section. Because if the temperature is too low, there is no decomposition, which leads to a higher concentration of urea in the process condensate.
Vessel –Heat exchanger (E1504)			
Intention – To cool the process condensate down to a temperature which is appropriate to release in the environment.			
Guide Word	Deviation	Cause	Consequences and Action
<i>Line No. 1518</i>			
Intention: outlet of cooled process condensate of E1501 at 90°, which is expanded by LPV2 C1501 from 4.5 to 1 bar and cooled down in E1504 to 30°C, 8153 kg/h, pure water.			
more	flow	High level in bottom of C1501	The process condensate, which will be released in the environment will be warmer. This might cause local environmental problems.

A3.2 Two scenarios with widespread effect

Two scenarios have been considered which will have follow on effects throughout the entire plant. In both cases the shutdown procedure which should be carried out, upon failing to rectify the situation efficiently, has been described. In some of the cases above, the ‘emergency shutdown’ mentioned could be a similar procedure, due to similar causes of failure, as those outline below.

Table 13: Hazard report for 2 specific process failures

Scenario	Consequences	Action
<p>Utility Failure (MP steam failure - possibly due to broken lines)</p>	<p>The pressure in the MP network of the utility system will drop, triggering an alarm to alert operators of the steam failure.</p> <p>Steam failure will result in no MP steam to Stripper and MP section, thus no LP steam produced by carbamate condenser.</p> <p>The reactor will continue to produce steam for LP steam for a limited time.</p> <p>The purity of the urea solution will not be high enough exiting the stripper and MP decomposer.</p> <p>Continuing to run the process without steam will cause cooling of equipment and pipes (as jacket insulation is steam controlled) and eventual crystallization and clogging.</p>	<p>There will be approximately 10-15 minutes (based on reactor residence time of 25 minutes) for the LP requiring sections to be shut off safely before steam production from reactor ends.</p> <p>The ammonia feed will be shut. This will be done by shutting off P1203 and P1103. The safety valve (SV-LH-V1201) must then be closed to shut off ammonia feed to receiver (V1201).</p> <p>The HP carbamate pump (P1201) will be shut to stop carbamate solution feed to HP section.</p> <p>The CO2 compressor (K1101) will be shut off, thereby stopping all feed to reactor.</p> <p>The wastewater section will be isolated from the rest of plant, by shutting off P1501, to make the LP steam usually used for column C1501 available for upstream sections or steam controlled jacketing for process pipes. Tank T1501 is of a volume to be able to contain two days’ worth of feed.</p> <p>The level in the reactor will drop, triggering the EXPV-E1102 to close, isolating product line of the HP section from the MP section. The same will occur between the MP and LP sections and the LP and vacuum sections.</p>

		<p>The level in V1101 will increase and activate FIC on C1202 so safety valve SV2-LSH-C1202 is opened to redirect carbamate solution to carbamate receiver (V1301).</p> <p>Once C1202 is emptied and washed (to avoid crystallization) with scrubber (C1203) feed, P1202 will be shut off.</p> <p>P1301 should be shut off to isolate LP section from MP section.</p> <p>The ammonia receiver is thus isolated and will be kept at pressure until the pressure of the system is released before total shut down.</p> <p>Water must be added to evaporators to prevent crystallization of urea by diluting product (as the concentration of urea is highest and the temperature of the solution is lowest in this part). Ensure product line to melamine plant is shut, to safely drain the solution to the aqueous urea tank.</p> <p>The solutions being held in the remaining sections must then be diluted and the pressure of each section let down to have a complete shutdown.</p> <p>This will be done by feeding emergency water to reactor and the MP decomposer (to ensure dilution in LP section does not take too long) thus, increasing the level and allowing flow through stripper and subsequently through MP decomposer, LP decomposer and preheater, from where the diluted product is drained to the emergency aqueous urea tank (OSBL).</p> <p>The remaining liquid in all tanks and piping, after flushing with water, will be drained to aqueous urea tank.</p> <p>During the draining process the safety</p>
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		<p>valves on this equipment must be opened to the emergency absorber to decrease the system pressure to atmospheric conditions.</p> <p>The emergency absorber will thus dilute the gases and the aqueous stream is sent to an aqueous ammonia storage tank (OBL).</p> <p>The ammonia receiver (V1201) and the carbamate receiver (V1301) must then finally be let down to atmospheric conditions, the resulting vapors will be directed to the emergency absorber and also collected in the aqueous ammonia storage tank.</p>
<p>Instrument air failure</p>	<p>Pressure indicator on instrument air supply indicates failure.</p> <p>Steam valves supplying stripper, MP and LP decomposer fail closed - process temperature is high enough to keep solution from crystallizing for several hours (equipment and pipes are insulated).</p> <p>Steam valves to C1202 and vacuum evaporators fail open - as output carbamate solution is closest to crystallization point. Valves controlling steam in jacketed pipes fail open.</p> <p>Live steam control valves fail closed.</p> <p>Expansion valves on product line fail closed - to isolate each section.</p> <p>Valves controlling raw feed fail closed - to stop supply.</p>	<p>With the valves failed as specified the system has been brought to a standstill. The only unit still receiving an inflow is C1202 and subsequently V1201, as aqueous ammonia from the scrubber (as water supply valve failed open) is still recycling through these units.</p> <p>If the instrument air failure is not immediately resolved operators will need to manually control the shutdown of the system.</p> <p>The difference to the above specified emergency shutdown is that operators are able to manually control temperatures by opening the steam valves which initially failed closed, in case of dangerously low temperatures during shutdown.</p> <p>Upon failure to resolve the instrument air failure water will be added to the vacuum evaporators (which still have steam supply) to dilute the urea solution to 45%, in order to prevent crystallization of urea in the emergency aqueous urea tank (at room temperature). Once this concentration is reached, the LP steam is manually switched off and</p>

	<p>Valves controlling cw recycle system in condensers fail open- to prevent excessive cooling in condensers.</p> <p>Valve supplying water to scrubber fails open.</p> <p>Level control valves fail closed - to maintain levels.</p> <p>Pressure control valves on units fail open- to avoid build-up of pressure.</p>	<p>the evaporators drained to the emergency urea tank.</p> <p>Because of the pressure difference in each section and the greater difficulty of controlling this when flow valves must be manually operated, the sections will be drained and diluted with water independently of one another.</p> <p>Water is added to the LP decomposer (C1301) to dilute the product (from 68% to 45% urea) and the valve between the LP decomposer and the preheater (C1302) is manually opened to allow the aqueous urea to drain to the emergency aqueous urea tank (the aqueous urea tank will have a vapor outlet to the emergency absorber).</p> <p>During draining, the drop in pressure in the LP decomposer, will cause a drop in pressure in the connected carbamate receiver, requiring the operators to open the safety valve to the emergency absorber (to absorb the exiting ammonia and collect it in the aqueous ammonia tank).</p> <p>Water is then added to the MP decomposer C1201 (to dilute urea from 64% to 45%) and the shell side of the preheater (C1302). The diluted solution is drained to the atmospheric aqueous urea tank.</p> <p>The MP separation column C1202 which is diluted by the continuous incoming stream of aqueous ammonia from the scrubber is drained (to aqueous urea tank) and the water to the scrubber will be shut off.</p> <p>The safety valve (SV-V1201) on the ammonia receiver (V1201) will need to be opened to the emergency absorber as the vessel is brought to atmospheric conditions (as before, the vaporized ammonia will thereby be absorbed in</p>
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		<p>water and collected in the aqueous ammonia storage tank).</p> <p>The pressure in the HP section is preferably maintained to avoid the cost and time required to restore these conditions. However, if instrument air failure is not easily repaired, draining of the HP section must proceed.</p> <p>Water is added to the reactor (R1101) and the level valve (LPV-V1101) between the reactor and stripper is opened manually. The stripper (E1102) is then drained to the emergency aqueous urea tank. The remaining dilute liquid in the reactor is then drained directly from the reactor to the aqueous urea tank.</p> <p>Water will be added to the carbamate condenser (E1101) to rinse both the condenser and the carbamate separator (C1101) of the medium within, which also drains to the urea tank.</p> <p>During this time the reducing pressure will mean the safety valves (see general remarks) on top of the HP units will need to be opened to allow the release and capture of gases in the emergency absorber.</p>
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A3.2.1 General remarks on Hazop and P&IDs

Mechanical equipment failure or valve failure listed in the Hazop could be related to erosion or corrosion, due to the very corrosive material flow through the process. Although the MOC is chosen to limit these problems, data shows that equipment subject to the harshest conditions (HP and MP sections) continues to be the cause of the greatest downtime in urea plants. From literature, the most at risk units are the CO₂ compressor, the heat exchangers, the decomposers, the stripper and the reactor⁴⁴. Whilst the entire plant must be regularly inspected to identify problems before catastrophic failure, extra care should be taken with the equipment which has proven to cause problems in the past.

The safety system (OSBL), often referred to in the Hazop descriptions, consists of an emergency absorber, an aqueous urea tank, and an aqueous ammonia tank.

The safety equipment installed to deal with the emergency situations outlined above, must be regularly checked. PSVs which cannot be checked will have backups on all critical vessels, for example on the reactor.

With regard to the P&IDs shown above, several important pieces of equipment and emergency lines mentioned in the Hazop descriptions were omitted from the drawing to avoid cluttering the document. The details are thus listed below:

- Backup valves and backup safety devices were often not indicated, but these are necessary to be able to efficiently rectify many of the situations described in the Hazop analysis above.
- Flanges are installed in all lines in order to allow for efficient removal and repair or replacement of equipment.
- All units have draining capabilities to ensure medium can be safely removed TSL (aqueous urea tank) in the event of a shutdown.
- The same units also include emergency lines to release vapors to an emergency absorber, which in turn collects the absorbed vapors in the aqueous ammonia tank. An example of this can be found in the MP P&ID on V1201.

A3.3 Chemical Exposure Index

The Chemical Exposure Index (CEI) of liquid ammonia was documented for this process. Liquid ammonia was chosen after comparing the NFPA-codes of all substances involved in the process. From the codes it was clear that ammonia is the most dangerous substance regarding both health and flammability.

From all vessels found in the plant, the unit with the highest CEI is the ammonia receiver (V1201), since this vessel contains more ammonia than any other vessel in the plant. Therefore, the most hazardous situation involving ammonia would occur in an emergency situation surrounding the receiver. The information related to the chemical exposure of this situation is given below.

Table 14: Chemical Exposure Index for ammonia

Stofgegevens deel1:			NH3
naam gekozen in "1-stof":	ammonia		ammonia
molgewicht	17	[kg/kmol]	
atmosferisch kookpunt (Tb)	-33	[°C]	
smeltpunt (Ts)	-78	[°C]	
vlampunt (Tv)	132	[°C]	
zelfontbrandingstemperatuur (Tz)	630	[°C]	
"exotherm start" temperatuur (Ta)	630	[°C]	
meldendheid (ZMS)	ZM		geur en/of directe lichaamsreactie bij ongevaarlijke concentratie
Stof is zelfmeldend	ZM		geur en/of directe lichaamsreactie bij ongevaarlijke concentratie
Stof is niet-zelfmeldend	NZM		geen specifieke geur en geen direct lichaamsreactie bij ongevaarlijke concentratie
NFPA -code Health (NFPAH)	3		Blootstelling gedurende een korte tijd aan deze stof kan ernstig (voorbijgaand of blijvend) letsel veroorzaken, zelfs indien er onmiddellijk medische hulp gegeven is.

NFPA -code Health 4	4	Blootstelling gedurende een korte tijd aan deze stof kan de dood ten gevolge hebben of een blijvend zwaar letsel, zelfs indien er onmiddellijk medische hulp gegeven is.
NFPA -code Health 3	3	Blootstelling gedurende een korte tijd aan deze stof kan ernstig (voorbijgaand of blijvend) letsel veroorzaken, zelfs indien er onmiddellijk medische hulp gegeven is.
NFPA -code Health 2	2	Langdurige, herhaalde blootstelling aan deze stof kan de getroffen tijdelijk uitschakelen of mogelijk blijvend letsel veroorzaken, tenzij onmiddellijk medische hulp gegeven.
NFPA -code Health 1	1	Blootstelling aan deze stof veroorzaakt irritatie maar slechts zeer licht blijvend letsel, zelfs indien er geen medische hulp wordt gegeven.
NFPA -code Health 0	0	Stof die bij brand niet meer hinder veroorzaakt dan "gewone" brandbare stoffen.
NFPA -code Flammability (NFPAF)	1	Stof die moet worden verhit, voordat ontsteking kan plaats hebben.
NFPA -code Flammability 4	4	Stof die snel of totaal verdampt bij kamertemperatuur en atmosferische druk; of stof die zich in de lucht snel verspreidt en heel gemakkelijk vlam vat.
NFPA -code Flammability 3	3	Vloeistof of vaste stof die onder vrijwel alle omstandigheden aan de (buiten)lucht kan ontstoken worden.
NFPA -code Flammability 2	2	Stof die wat verwarmd moet worden of aan relatief hoge (buiten)-lucht temperaturen moet worden blootgesteld voordat ze ontstoken kan worden.
NFPA -code Flammability 1	1	Stof die moet worden verhit, voordat ontsteking kan plaats hebben.

NFPA -code Flammability 0	0		Onbrandbare stof.
NFPA -code Reactiviteit (NFPAR)	0		Stabiele stof die, zelfs in een brand met water kan reageren.
NFPA -code Reactiviteit 4	4		Stof die "vanzelf" kan detoneren of explosief kan ontleden of reageren bij normale temperatuur en druk.
NFPA -code Reactiviteit 3	3		Stof die pas kan detoneren of explosief ontleed indien een sterke ontstekingsbron aanwezig is, of indien de stof onder afsluiting verhit wordt. Als de stof met water reageert, behoort ze ook tot deze categorie.
NFPA -code Reactiviteit 2	2		Stof die instabiel is en gemakkelijk een heftige chemische reactie ondergaat, maar niet detoneert. Als de stof die heftig met water reageert of er een potentieel explosieve mengsel mee vormt, behoort tot deze categorie.
NFPA -code Reactiviteit 1	1		Stof die in normale omstandigheden stabiel is, maar onstabiel kan worden bij verhoogde temperaturen en drukken. Als de stof onder warmte-ontwikkeling met water reageert, behoort ze tot deze categorie.
NFPA -code Reactiviteit 0	0		Stabiele stof die, zelfs in een brand met water kan reageren.
Stofgegevens deel2:			
warmtecapaciteit vloeistof (Cp)	0	[kJ/kg.°C]	voor organische verbindingen 1-2 kJ/kg.°C
verdampingswarmte (Hv)	0	[kJ/kg]	voor organische verbindingen 300 - 400 kJ/kg
ratio Cp/Hv (CpHv)	0.0044	[1/°C]	(default 0.0044 tenzij Cp en Hv beide ingevuld.)

verbrandingswarmte (Hc)	18.6	[MJ/kg]	
dampdruk (bij 20°C) (Po)	8.5	[bar]	
richtwaarde acute toxiciteit (TOX)	720	[mg/m ³]	(volgens 190/96 V&AH 20-03-96 copie BST 3/7/98)
L.E.L waarde in lucht (LEL)	15	[vol.%]	(indien niet brandbaar 0 invullen)
U.E.L waarde in lucht (UEL)	29	[vol.%]	(indien niet brandbaar 0 invullen)
dichtheid vloeistof bij Tp (sm)	595	[kg/m ³]	voor organische verbindingen 500 - 1000 kg/m ³
Buitenlucht omstandigheden:			
buitenlucht temperatuur (To)	10	[°C]	(default 10 tenzij anders ingevuld)
L.E.L waarde in lucht (LELm)	106	[g/m ³]	
U.E.L waarde in lucht (UELm)	205	[g/m ³]	
Procesomstandigheden:			
proces-druk (absoluut) (Pp)	18	[bar]	systeem op overdruk
proces-temperatuur (Tp)	40	[°C]	gasvorming bij 1 atm
vloeistof in proces	0	[-]	vloeistofstroomt uit
vloeistof in proces	0	[-]	vloeistofstroomt uit
gasfase in proces	1	[-]	gasfase uitstroming
Uitstroom-scenario-info:			
guillotine breuk leiding	1	[-]	guillotine breuk leiding aangenomen
guillotine breuk leiding	1		guillotine breuk leiding aangenomen
openscheuren leiding	0		geen guillotine breuk aangenomen
geen flenslekkage	0	[-]	geen flenslekkage aangenomen

grote flenslekkage	2		grote flenslekkage aangenomen $D=0,02*Do$
kleine flenslekkage	1		kleine flenslekkage aangenomen $D=0,005*Do$
geen flenslekkage	0		geen flenslekkage aangenomen
diameter leiding (Do)	50	[mm]	
diametergat berekening (D)	50	[mm]	
vloeistofhoogte t.o.v. uitstroomopening (h)	1	[m]	(gebruik beginhoogte)
volume vat (Vv)	51.8	[m ³]	(vloeistof-inhoud beschouwd systeem/vat)
diameter leidingen (DI)	0	[mm]	(t.b.v. bepalen vloeistof-inhoud beschouwd systeem)
lengte leidingen (LI)	0	[m]	(t.b.v. bepalen vloeistof-inhoud beschouwd systeem)
inhoud vloeistofhouder (V)	51.8	[m ³]	(inhoud achterliggend vloeistofvolume)
nalevering van vloeistof (Qv)	43.2	[m ³ /u]	(vloeistof welke a.g.v. de regelingen naar de uitstroomopening wordt gevoerd)
	3.98	[m]	diameter tank o.b.v. Vv en $D/H=1$
lengte opvangbak (Lbb)	6.00	[m]	
breedte opvangbak (Bbb)	7.00	[m]	tank past in opvangbak
diameter tank (Dt)	5.00	[m]	(dit oppervlak wordt in mindering gebracht)
Uitstroom scenario:			
Airborne Quantity gas (AQ)	0.00	[kg/s]	
Liquid release rate (Lo)	75	[kg/s]	(initiele release rate)

maximaal release o.b.v. buffer (La)	103	[kg/s]	(minimale duur 5 min en als beschikbaar volume in < 5 min vrijkomt dan wordt L berekend o.b.v. 5 min.)
Liquid release rate (Lb)	75	[kg/s]	(gebruikte L o.b.v. beschikbaar vrijgekomen vloeistof)
nalevering van vloeistof (Lc)	7	[kg/s]	
Liquid release rate met nalevering (Ld)	75	[kg/s]	(gebruikte L o.b.v. beschikbaar vrijgekomen vloeistof met nalevering)
Totaal vloeistof release (Wt1)	67641	[kg]	(o.b.v. 15 minuten uitstroming)
Totaal vloeistof release (Wt2)	67641	[kg]	(o.b.v. 15 minuten uitstroming en beschikbaar buffer))
Fractie vloeistof die flashed (Fv)	0.32	[-]	(o.b.v. Tb en Tp)
Airborne Quantity o.b.v. flash (AQf)	75.16	[kg/s]	(als Fv>0.2 alles airborne)
Plasgrootte (Wp)	0	[kg]	(o.b.v. 15 minuten uitstroming)
Plasgrootte (Ap)	0	[m^2]	(o.b.v. 10 mm vloeistofhoogte of gedefinieerde opvangbak)
Plastemperatuur (Tpl)	-33	[°C]	
dampdruk bij Tpl (Ppl)	1.00	[bar]	foutieve formule
Airborne Quantity verdamping plasoppervlak (AQp)	0.00	[kg/s]	
Berekende uitstroom-gegevens:			
Released Quantity Rate RQR) begin (RQRo)	75.2	[kg/s]	<-- Uitgestroomde hoeveelheden:
RQR over 5 minuten (RQR5)	75.2	[kg/s]	
(RQ5)	22547	[kg]	
RQR na 15 minuten (RQR15)	75.2	[kg/s]	
(RQ15)	37247	[kg]	
RQ na 1 uur (RQ60)	56525	[kg]	
Airborne Quantity Rate (AQRo) begin	75.2	[kg/s]	<-- Hoeveelheden Airborne:

AQR5 over 5 minuten	75.2	[kg/s]	
AQ5m	22547	[kg]	massa van de wolk na 5 minuten.
AQR15 na 15 minuten	75.2	[kg/s]	
AQ15m	37247	[kg]	massa van de wolk na 15 minuten.
plasgrootte (Ap) na 15 minuten	0	[m ²]	<-- Hoeveelheden op de grond:
"plasgrootte" (Wp) na 15 minuten	0	[kg]	
Gevolgen van "Loss of Containment":			
Scenario:	Bij uitstroming:		gaswolk bestaande uit gas en vloeistof-druppeltjes
	Na uitstroming:		gas blijft in de gasfase in de gaswolk en vloeistof druppeltjes verdampen in de gaswolk
Chemical Exposure Index (CEI) Toxiciteit	119.9533562		(o.b.v. 5 minuten release)
	5		(factor tot letale dosis o.b.v. richtwaarde acute toxiciteit)
Hazard Distance Toxiciteit (HD)	947	[m]	
Chemical Exposure Index (CEI) Explosie en brandgevaar	17.42		(o.b.v. 5 minuten release)
Hazard Distance Explosie en brandgevaar (HD) o.b.v. L.E.L.	174	[m]	
Hazard Distance Explosie en brandgevaar (HD) o.b.v. U.E.L.	125	[m]	
volume tussen L.E.L. en U.E.L.	11504	[m ²]	
"explosief volume/gebied"	5752	[m ²]	
Hazard Distance Explosie en brandgevaar (HDstof)	n.v.t.	[m]	

Hazard Distance Explosie en brandgevaar (HDLELcor)	99	[m]	
Hazard Distance Explosie en brandgevaar (HDUELcor)	71	[m]	
"volume" tussen L.E.L. en U.E.L. (Aex)	3695	[m ²]	
"explosief volume/gebied"	1848	[m ²]	
Hazard Distance Explosie en brandgevaar (HD) o.b.v. (LEL+UEL)/2	85	[m]	
	3.113325031	effect factor explosie	
Hazard Distance m.b.t. Effect van explosie en/of brand (HDex)	2947	[m]	

Findings

The Chemical Exposure Index of the ammonia receiver is **120**. The calculations tabulated above reveal that the hazard distance is thus **2947 m**. This means that a urea plant should be built at least around **3km** away from built up areas and communities, in order to avoid exposing residents to hazardous chemicals in case of an emergency. In the case that a community is closer or near to the 3km radius of exposure, emergency procedures to inform the community of any hazardous situations must be put in place.

A3.4 Fire Explosion Index

Just as with the Chemical Exposure Index, the Fire & Explosion Index (F&EI) gives an indication of the safety measures that should be in place in a chemical plant. More specifically, the F&EI gives an indication of fire or explosion hazard that a process plant can have in case of malfunction.

From the substances found in the process, the most dangerous regarding fire and/or explosion is ammonia. Though the vessel which contains the greatest volume of ammonia was found to be the ammonia receiver (see CEI study), the conditions in the reactor are much harsher regarding temperature and pressure, so the chance of flames or explosion is especially high for this piece of equipment. Below the F&EI study of the reactor R1101, with respect to ammonia can be found.

Table 15: Fire Explosion index for ammonia

	ammonia		
<u>DOW F&E Index</u>			Applies to startup, continuous operation and shutdown.
<u>Material Factor (MF)</u>	4		Liquids & Gases Flammability or Combustibility
Input data:			
<u>Proces temperatuur (FEITp)</u>	188	[°C]	Temperature adjustment MF
<u>Buiten temperatuur (FEITo)</u>	10	[°C]	Default should be 10°C.
<u>NFPAft</u>	2		Temperature corrected NFPAF
<u>NFPART</u>	0		Temperature corrected NFPAR
<u>Material Factor T corrected (MFt)</u>	10		
<u>1. General Process Hazards:</u>	Penalty Factor		Applies under the most hazardous normal operating conditions.
Base Factor:	1.00		
A. Exothermic Chemical Reactions:	0.50		Applies to process unit.
2f. Condensation	0.5		Joining together of two or more organic molecules with the splitting off of H ₂ O, HCl or other compounds.
B. Endothermic Process:	0.00		Applies only to reactors.
0. No Endothermic Process	0		
C. Material Handling and Transfer:	0.00		Applies to pertinent Proces Units.
0. No Material Handling and Transport	0		

0. No warehouse or yard storage involved	0		
D. Enclosed or Indoor Process Units:	0.00		Roofed area with 3 or more sides or roofless structure with walls on all sides.
0. No enclosed area involved.	0		
No mechanical ventilation present	0.00		Only applicable if enclosed area.
E. Access:	0.00		1. Access from at least two sides and 2. one access approaches from the roadway.
0. Adequate access present	0		
F. Dranage and Spill Control:	0.00		Only applicable if Tv < 60 °C.
0. Excellent draining is present	0		
General Process Hazards Factor (F1):	1.50		
2. Special Process Hazards:	Penalty Factor		
Base Factor:	1.00		
A. Toxic Material(s):	0.60	1.60	Based on NFPAH.
B. Sub-Atmospheric Pressure:	0.00	1.60	Applies to trippers, distillation column and some compressor.
C. Operation In or Near Flammable Range:	0.00	1.60	
2a. Due to equipment or instrument failure in or near flammable range.	0.30		Applicable for process equipment or process storage tanks.
0. Not applicable.	0.00		
D. Dust Explosion:	0.00	1.60	Applied to Any process unit involving dust handling: transferring, blending, grinding, bagging etc.
0. No dust explosion possible; NFPAF=0 or no dust.	0.00		Bij FEITo is deze sFEITof geen vaste sFEITof!
0. Not applicable.	0.00		Applicable to dust with NFPAF>0

E. Relief Pressure:	1.27	2.87	
Input data:			
Operating Pressure (Pp):	150	[bar]	pressure in bar absolute.
Pp=	2161.061444	[psig]	
Relief Pressure (Pr):	157.5	[bar]	
Pr=	2269.839704	[psig]	
1. Flammable & Combustible liquids (FEITp>Tv or Tv<FEITo).	0.98		based on Pp not corrected for Pr.
3. Liquefied flammable gases and vapors.	1.30		Only applicable if over pressure.
F. Low Temperature:	0.00	2.87	Applied for normal and abnormal operating conditions.
0. Not applicable due to material choice or absence of needed abnormal operating conditions.	0.00		
G. Quantity of Flammable/Unstable Material:	0.00	2.87	
Input data:			
Mass of material involved (Qhm):	4	[ton]	Quantity unit is 1000 kg
Mass of material involved (Qhm):	4	[ton]	Quantity unit is 1000 kg
Liquid volume involved (Qhv):	6.15	[m^3]	calculation based on density sm.
Mass of solids or dust involved (Qhd):	0	[ton]	Quantity unit is 1000 kg
Energy hold-up (Btu):	0.00	[GBtu]	
Mass solid/dust hold-up (lb):	0.01	[Mlb]	
0. Not applicable, due to Tv>60°C, FEITp,Tv or Nr<2.	0.00		
H. Corrosion and Erosion:	0.00	2.87	NHPAF>1
5a. Lining used to prevent corrosion.	0.20		
I. Leakage - Joints and Packing:	0.00	2.87	NHPAF>1
2. Regular leakage problems at pumps, compressors and joints flange.	0.30		
J Use of Fired equipment:	0.48	3.36	NHPAF>1
Input data:			

Distance to anticipated process unit (Df):	20	[m]	
Df:	66	[ft]	
2. Process unit with FEITp > Tb.	0.48		Distance to process unit with NFPAF>1 material.
K. Hot Oil Heat Exchange System:	0.00	3.36	Depending of TpHO, TvHO en TbHO.
Input data:			
Quantity of heat exchanger system (active part)		[m^3]	
Process temperature HO (TpHO):		[°C]	
Flash point HO (TvHO):		[°C]	
Boiling point HO (TbHO):		[°C]	
0. No hot oil heat exchanger system is used.	0.00		
L. Rotating Equipment:	0.50		
2. Rotating equipment: pump > 75 hp.	0.50		
Special Process Hazards Factor (F2):	3.9		
Process Unit Hazards Factor (F1*F2)=F3:	5.8		
Fire and Explosion Index (F3*MF=F&EI):	58		Degree of Hazard LIGHT.
	49	[ft]	
	15	[m]	Radius of exposure

Findings

From the calculations carried out in excel, the Fire & Exposure Index is **58**, which corresponds to a LIGHT degree of hazard. This also means that, in case of any flames or explosion, the radius of exposure would be **15 meters**, which is relatively small.

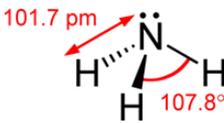
From the two indexes it could be concluded that the biggest hazard in the urea plant is not the risk of flames or explosions, but rather the risk of exposure to chemicals and the health risks concerned.

Appendix 4. Substances and Specifications

A4.1 MSDS Summary and Vademecum

A4.1.1 Ammonia

Table 16: MSDS ammonia

Substance	Ammonia		
Trivial name	Hydrogen nitride, trihydrogen nitride, nitro-sil, nitrogen trihydride		
chemical structure			
chemical formula	NH ₃		
Molar mass in kg/kmol	17.03 g/mol		
Physical data		at:	
T boiling point in °C	-33.35	1	atm
T triple point in °C	-77.7	1	atm
T critical point in °C	132.4		bar
density liquid in kg/m ³	682	-33.5	°C
density vapor in kg/m ³	0.73	15	°C
heat capacity liquid in J/(mol K)	80.80		°C
heat capacity vapor in J/(mol K)	37.00	15	°C
heat of evaporation in kJ/kg	1371	-33.5	°C
T flash point in °C	11		
T auto ignition in °C	651		
LEL in vol. %	15		
UEL in vol. %	28		
PEL in ppm	50		

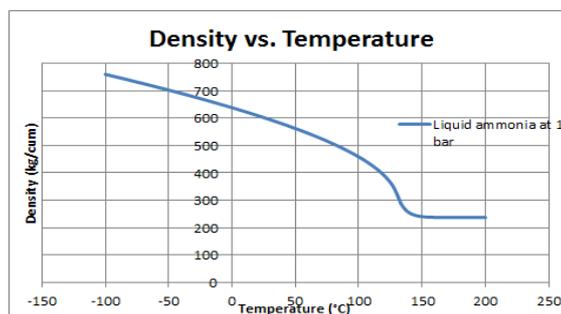
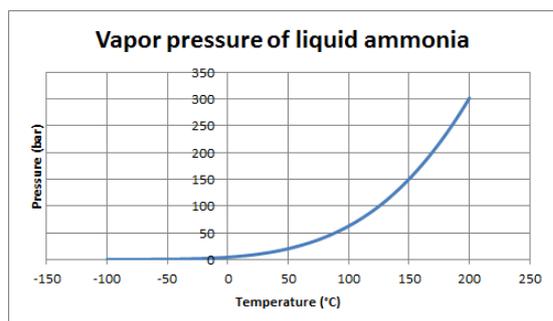
Risk data

- R10: Flammable gas
- R23: Toxic by inhalation
- R34: Causes burns
- R50: Very toxic to aquatic organisms

Safety advice

- S1/2: Keep locked out and out of the reach of children
- S9: Keep containers in well ventilated places
- S16: Keep away from sources of ignition (e.g. smoking)
- S26: In case of contact with eyes, rinse immediately with plenty of water and seek medical help
- S36/37/39: When handling, use suitable protecting clothing, gloves and eye and face protection
- S45: In case of accident or if feeling unwell, immediately seek for medical attention
- S61: Avoid release to the environment. The permissible exposure limit (according to US laws) is 50 ppm.

Relevant ammonia data in process conditions

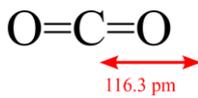


Note: The density of liquid ammonia is not affected by the pressure, hence only the relation between density and temperature for liquid ammonia at 1 bar is given.

A4.1.2 Carbon dioxide

Table 17: MSDS carbon dioxide

Substance	Carbon dioxide		
trivial name	Carbonic acid gas, carbonic anhydride, carbonic oxide, carbon oxide, carbon (IV) oxide, dry ice (when in solid phase)		
chemical formula	CO ₂		

chemical structure			
Molar mass in kg/kmol	44.01		
Physical data		at:	
T crystallization point in °C ⁴⁵	-55.6	1	atm
T boiling point in °C ⁴⁶	-78.5	sublimes	atm
T triple point in °C ⁴⁷	-56.6	5,185	atm
T critical point in °C ⁴⁷	30	73,8	bar
density liquid in kg/m ³ ⁴⁵	820		°C
relative to water	0.82		°C
density vapor in kg/m ³ ⁴⁶	1.83		°C
relative to air	1.52		°C
heat capacity solid in kJ/kg°C ⁴⁸	0.05	-83,2	°C
heat capacity liquid in J/(mol K) ⁴⁹	5.00	20	°C
heat capacity vapor in J/(mol K) ⁴⁹	0.85	300	°C
heat of crystallization in kJ/kg ⁴⁸	196.5	triple point	°C
heat of evaporation in kJ/kg ⁴⁷	379	0-31	°C
PEL in ppm ⁵⁰	5000		

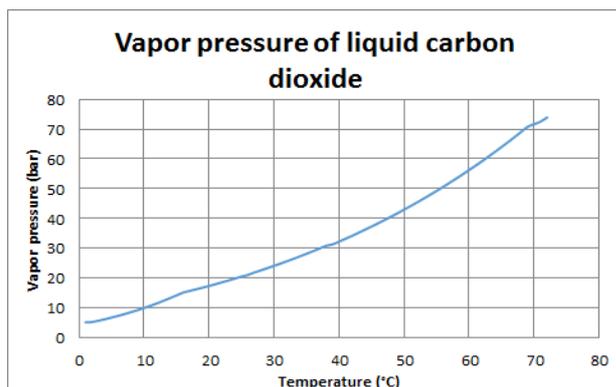
Risk data

None

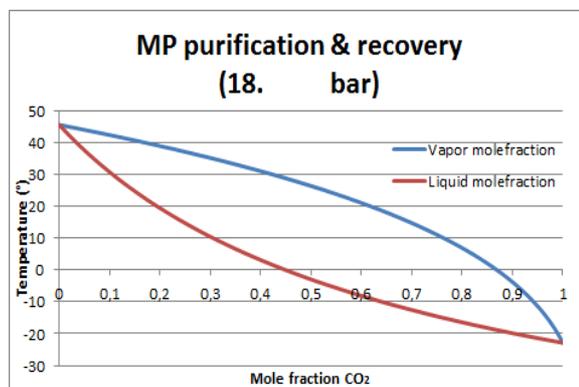
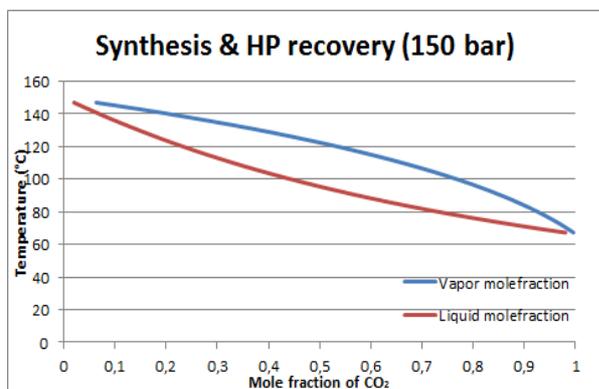
Safety advice

None

Relevant carbon dioxide data for process conditions *Ammonia group*



Note: Ammonia and carbon dioxide form an azeotrope:



A4.1.3 Ammonium carbamate ^{51 52}

Table 18: MSDS ammonium carbamate

Substance	Ammonium carbamate		
trivial name	Ammonium amoniformate, carbamic acid, ammoniate, carbamic acid ammonium salt, carbamic acid monoammonium salt		
chemical formula	CH ₆ N ₂ O ₂		
chemical structure	$\begin{array}{c} \text{O} \\ \parallel \\ \text{H}_2\text{N}-\text{C}-\text{O}^- \\ \text{NH}_4^+ \end{array}$		
Molar mass in kg/kmol	78.07		

Physical data		at:	
T crystallization point in °C	152		atm
T boiling point in °C	251		atm
density solid in kg/m ³	1380	20	°C
relative to water	1.38		°C
LEL in vol.%	16		
UEL in vol.%	25		

Risk data

- R22: Harmful if swallowed
- R23: Toxic by inhalation
- R24: Toxic in contact with skin
- R34: Causes burns
- R36: Irritating to eyes
- R38: Irritating to skin

Safety advice

- S3: Keep in a cool place
- S20: Do not eat or drink when using
- S24: Avoid contact with skin
- S25: Avoid contact with eyes
- S43: In case of fire use water
- S60: This material and its container must be disposed of as hazardous waste

Relevant ammonium carbamate data for process conditions

Crystallization of ammonium carbamate is a real hazard in the urea plant thus, the units where this is most possible due to low temperatures and high carbamate concentrations have been evaluated:

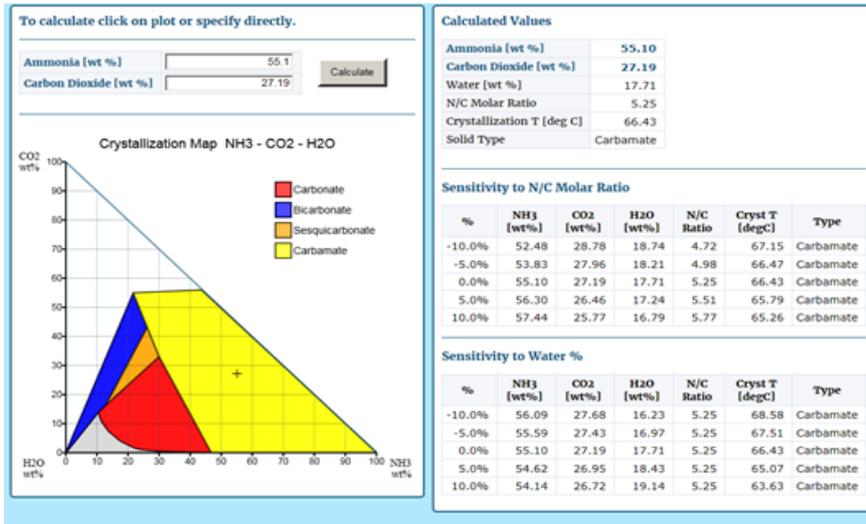


Figure 61: Carbamate solution going out the carbamate separator (V1101)¹⁸

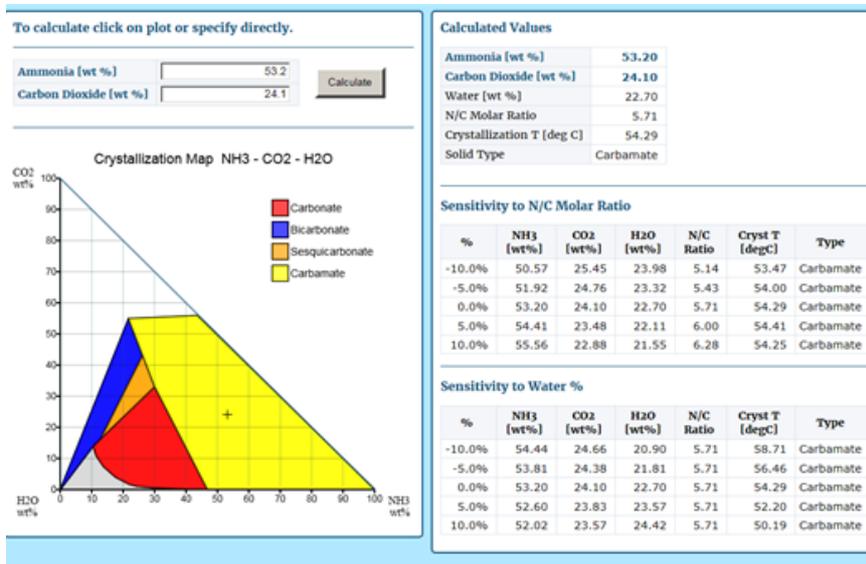
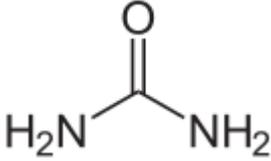


Figure 62: Carbamate solution in the bottom of the ammonia-carbamate separation column (C1202)¹⁸

A4.1.4 Urea^{53 54 55 56}

Table 19: MSDS urea

Substance	Urea		
trivial name	Carbamide, carbonyl diamide, carbonyldiamine, diaminomethanal, diaminomethanone		
chemical formula	CH ₄ N ₂ O		

chemical structure			
Molar mass in kg/kmol	60.06		
Physical data			at:
T crystallization point in °C	133-135		atm
T boiling point in °C	Decomposes		atm
T triple point in °C	102.3	6535	atm
density solid in kg/m ³	1320	20	°C
relative to water	1.32		°C
heat capacity solid in kJ/kg°C	1.92		°C

Risk data

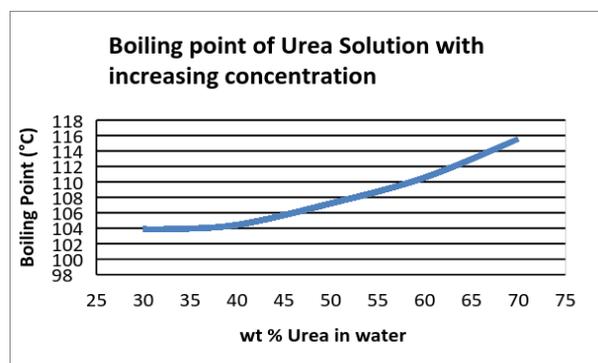
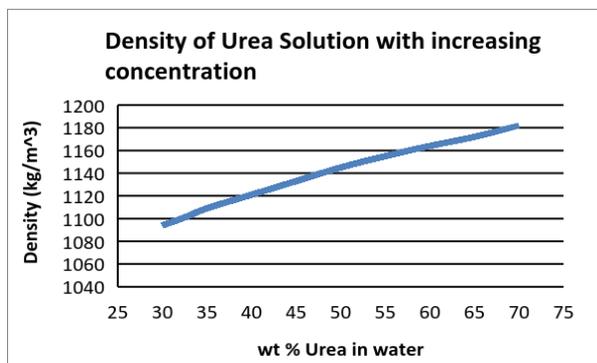
- R36/38: Irritating to eyes and skin
- R40: Possible risks of irreversible effects

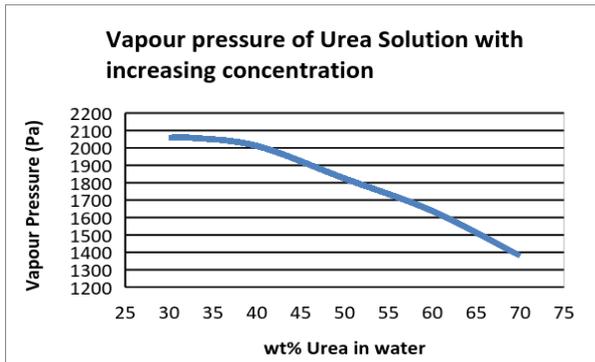
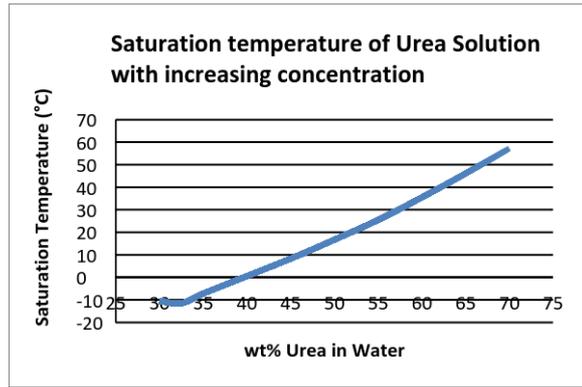
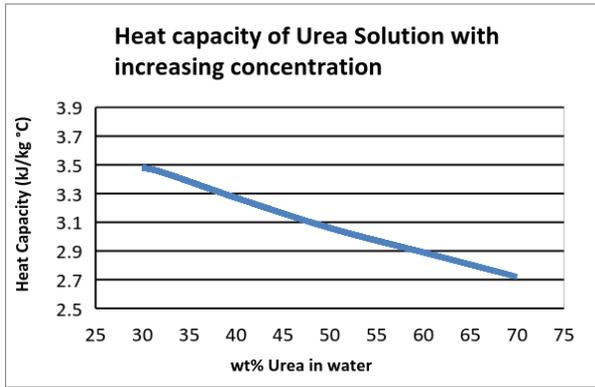
Safety advice

- S24/25: Avoid contact with skin and eyes

Relevant urea data for process conditions

As Urea in the process is mostly in aqueous solutions, the following data is relevant to the process:





Several properties of pure urea are also important:

Temperature (°C)	Solubility in water (g/L)	Critical relative humidity, CRH (%)
20	1079	
25		76.5
30		74.3
40	1670	69.2
60	2510	
80	4000	

A4.2 Material Specifications

A4.2.1 Carbon dioxide

The carbon dioxide needed in the manufacturing of urea needs to fulfill some requirements regarding its composition. The impurities present, as well as their concentration are depicted below.

Table 20: carbon dioxide specification

Component	Unit	Value
Water	ppm	<40
NO	ppm	<2.5
NO ₂	ppm	<2.5
Hydrocarbons (including methanol)	ppm	<500
Aromatic hydrocarbons	ppm	<0.1
Volatile organic residues (excluding methanol)	ppm	<1.2
Hydrogen sulfide	ppm	<0.2
Carbonyl sulfide	ppm	<0.1
Sulfur dioxide	ppm	<1
Dimethyl sulfide	ppm	<1.1
Carbon monoxide	ppm	<50
Ethene	ppm	<0.2
Hydrogen cyanide	ppm	<20

Provided feed

The carbon dioxide used in the urea plant is supplied by the adjoining Ammonia plant. The impurities are able to be removed before using the feed to produce urea, if necessary. However, if the supply is too low, or not possible at all, carbon dioxide could also be obtained from a variety of other vendors.

Boconline is one of the available carbon dioxide suppliers, and it features refrigerated liquefied gas. Boconline claims that their carbon dioxide has the following composition:³⁵

Table 21: Boconline carbon dioxide

Component	Unit	Value
Carbon dioxide	volume%	99.9
Moisture	ppm	20
Oxygen	ppm	30
Carbon monoxide	ppm	5
Nox	ppm	2.5
Ammonia	ppm	2.5
Hydrocarbons (as methane)	ppm	50
Benzene	ppm	0.02
Acetaldehyde	ppm	0.02
Sulphur (as S)	ppm	0.1
Non-volatile organic residues	ppm	5
Non-volatile residues	ppm	10

Another supplier of carbon dioxide is OCI. The composition of their product:

Table 22: OCI carbon dioxide

Component	Unit	Value
Carbon dioxide	volume%	>98
Ammonia	ppm	10-17
Methanol	ppm	43009
Methane	ppm	600-1100
Selexol	ppm	<1
Carbon monoxide	ppm	10-15
Hydrocarbons	ppm	42278
Hydrogen	ppm	1800-3000

A4.2.2 Ammonia Ammonia group

The ammonia is also preferably sourced from the nearby Ammonia plant. The composition they are able to supply is listed below. Due to this data, the urea plant was modelled in Aspen with the ammonia stream containing 2% methane.

Table 23: Ammonia composition from ammonia plant

Mass Frac	
NH3	0.9817668
CH4	0.0166938
H2	2.66E-09
AR	7.16E-07
N2	0.0015272
O2	2.26E-07
WATER	1.12E-05
ETHANE	3.33E-09
PROPANE	2.44E-13
MDEA	4.33E-12
Total Flow kmol/hr	796.6578
Total Flow kg/hr	13561.72
Total Flow cum/hr	22.6947
Temperature C	20
Pressure bar	20

A4.2.3 Urea

Urea can be produced in various shapes and sizes. In this project a urea solution of 99.6% purity was produced. In industry this purity is only demanded when the molten urea is further processed to prills or granules.

Prilled/granulated urea

Purity:	99-100%	
Particle size:	Prilled:	1-4mm (90%)
	Granulated:	2-4mm (90%)
Weight% Nitrogen:	46-46,5%	
Weight% Biuret:	1%	
Weight% Moisture:	0,5%	
Free NH3:	60-160 ppm	

Urea Solution

Purity:	30-70%
Weight% free NH3:	0,5-1%
Weight% Biuret:	0,7-1%
Weight% water:	28,8-68,8%
pH range:	7-10

Appendix 5. Derivation of Equipment Size

A5.1 HP section

Reactor (R1101)

The reactor is a bubbling column that is mostly filled with liquid so the most important feature is its volume, from this volume it is possible to calculate a height and a diameter. The reactor has a residence time of approximately 25 minutes¹ and the outflow of the reactor can be determined using aspen (49 m³/hr). This makes it possible to calculate the volume required for the reactor using Eq. (5).

This led to a volume of 20.5 m³ a small degree of overdesign is required to allow the reactor to handle changes in the process flow. To illustrate this the volume is increased with 10% leading to a volume of 22.5 m³.

Stripper (E1102)

The stripper is a falling film type heat exchanger with a basic one pass tube and shell design. The condensation of medium pressure steam (25.5 bar 225°C) provides the heat for the endothermic decomposition of ammonium carbamate.

The heat transfer coefficient U for steam to light organics is estimated to be 750 W/(m² °C) and the heat provided by the steam is shown to be 1763 kW in aspen. The mean temperature difference can be calculated using Eq. (3), giving a value of 28.91°C. This allows us to calculate the heat transfer area required with Eq. (4), which is shown to be 81.3 m².

The stripper is not supposed to have a liquid level however it does have a level control. To make this all work it was decided to add a small holding volume under the heat exchanger area to allow for the level control. The volumetric outflow of the stripper is 37 m³/hr and the desired retention time is 5 minutes this makes for a required volume of 3m³ according to Eq. (5).

Carbamate condenser (E1101)

The carbamate condenser is a 2 pass heat exchanger which resembles a kettle reboiler where the ammonia and carbon dioxide from the separation column and the stripper off-gas react to form ammonium carbamate. The exothermic reaction is used to heat condensed medium pressure steam from the medium pressure decomposer to form low pressure steam (4.5 bar 147°C). The heat transfer coefficient U for light organics to water was estimated to be 750 W/(m² °C) and the heat released was shown to be 812 kW in aspen. The mean temperature difference can be calculated using Eq. (3), giving a value of 18.93°C. This allows us to calculate the heat transfer area required with Eq. (4), which is shown to be 57.18 m².

The only function of the carbamate separator is to allow the separation of gasses and liquids coming from the carbamate condenser. So assuming a residence time of 15 minutes and using Eq. (5), a volume of 5 m³ is found, since it is undesirable to operate the vessel completely full and some headroom is wanted to allow for some fluctuations in the process stream. So a volume of 10 m³ is chosen.

A5.2 MP section

MP decomposer (C1201)

The MP decomposer consists of three parts. The top being a column with packing, the middle section is a heat exchanger where the decomposition occurs and the bottom, a holding section (for the explanation of how these sections were modelled in Aspen see appendix 2).

The top section contains pall ring packing. From literature the packing in this section is approximately 1.3m high¹³. Above the packing there is space where the solution is fed, and below the packing there is space for a distributor before the begin of the ferrules (see theory section in chapter 2 for diagram of MP decomposer).

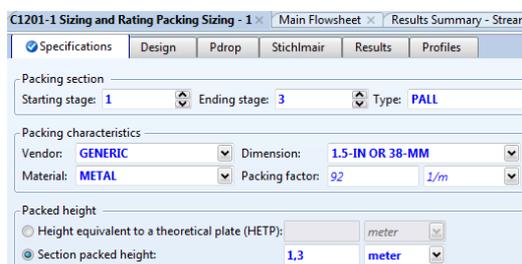


Figure 63: Defining decomposer packing in Aspen

The diameter of the column:

Parameter	Value	Unit
Section starting stage:	1	
Section ending stage:	3	
Column diameter:	0,752299	meter
Maximum fractional capacity:	0,62	
Maximum capacity factor:	0,0598799	m/sec
Section pressure drop:	0,00186597	bar
Average pressure drop / Height	1,43536	mbar/m
Maximum stage liquid holdup:	18,7467	l
Max liquid superficial velocity:	0,0151761	m/sec
Surface area:	1,3	sqcm/cc

Figure 64: Calculations for decomposer in Aspen

The diameter for this section was found in Aspen to be 0.75m (Figure 64) and the height was thus approximated as:

$$h = h(\text{above}) + h(\text{packing}) + h(\text{below})$$

The top of this section was estimated to be twice the height between trays, and the height of the bottom section was approximated as one tray spacing (as this column is in reality directly attached to the heat exchanger section, so there is no liquid holdup).

$$h = (2 \times 0.61) + 1.3 + 0.61 = 3.1m$$

The heat exchanger section of the MP decomposer requires the condensation of MP steam (225°C , 25.5 bar) to provide the heat for the decomposition of carbamate and to heat the solution from 134°C to 155°C .

This process requires:

$$Q_H = 2494 \text{ kW}$$

The MP steam required (as modelled in Aspen, see utility section):

$$4749 = \text{kg/h}$$

The temperature difference was calculated:

$$\Delta T_m = 81^\circ\text{C} \quad \text{Eq.(3).}$$

The heat exchanger section is a falling film heat exchanger. To calculate the required heat exchange area, the formula for a basic one shell and two tube-pass heat exchanger was used. The overall heat transfer coefficient between organic solvents and steam from literature is within a range of 500-1000 W/m²K. As the solution within the decomposer also contains vapours, upon the decomposition of carbamate, the U value would be higher than for pure solvents. Thus an overall heat exchange of U = 750 W/m²K, was chosen to achieve an approximate required surface area¹⁹:

$$A = 41.3 \text{ m}^2 \quad \text{Eq.(4).}$$

It should be noted that from diagrams found in literature the heat exchanger section is of smaller diameter than the top separator section¹³. However, the calculated diameter of 0.75m has been used in order to calculate the height of the bottom holder section, where the solution resides for around five minutes (long residence times should be avoided as this will cause the product stream to undergo unfavourable side reactions, forming biuret) and the outgoing solution has a volumetric flow rate of 20 m³/h.

$$\text{bottom (height)} = \frac{V}{\pi\left(\frac{D}{2}\right)^2} = \frac{(20 \times \left(\frac{5}{60}\right))}{\pi\left(\frac{0.75}{2}\right)^2} = 3.8 \text{ m}$$

Ammonia-carbamate separation column (C1202)

For modelling purposes the column was split into two units. The tray spacing was left at 0.6m (the default in aspen), to leave room for maintenance operations. The flooding factor was also left as an estimate of 0.8. From literature, the trays in C1202 are Bubble Cap type trays¹³.

The top column (C1202-2) contains four stages with tray type and spacing specified as:

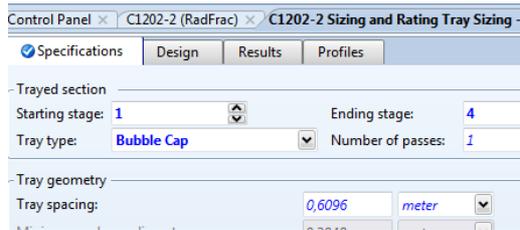


Figure 65: Defining trays in C1202-2

The bottom column (C1202-1) contains three stages, the bottom stage being a reboiler:

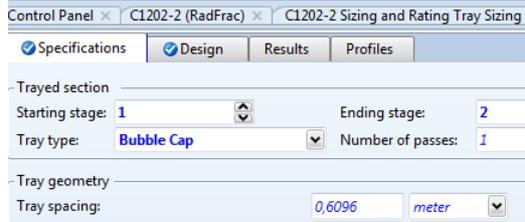


Figure 66: Defining trays in C1202-1

The diameters calculated for both columns:

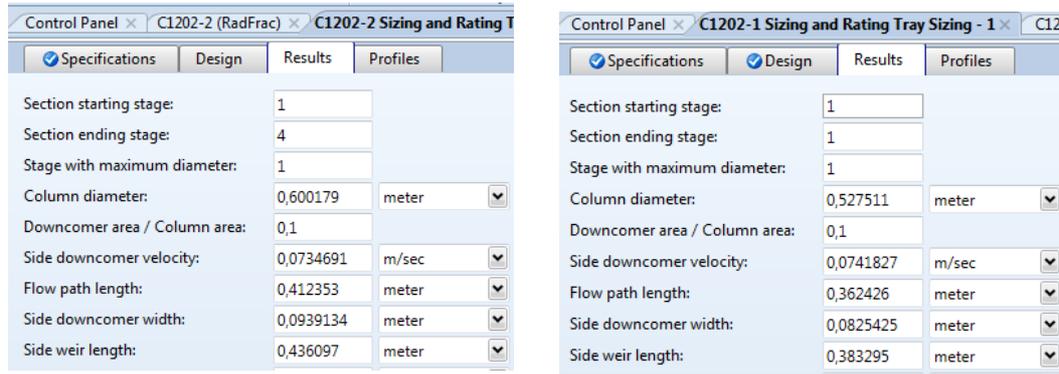


Figure 67: Diameter of C1202 calculated in Aspen

The calculations were continued with the use of the larger diameter: 0.6m. An estimated residence time of 10 minutes was chosen to allow for a longer holdup in the bottom of the column, which better simulates the situations described in several patents⁴³, and a volumetric flow rate of 13 m³/h.

The column height was calculated:

$$h = (\text{tray spacing} \times (\text{stages} - 1)) + h(\text{bottom}) + h(\text{top})$$

$$h(\text{bottom}) = \frac{V}{\pi \left(\frac{D}{2}\right)^2} = \frac{(13 \times \left(\frac{10}{60}\right))}{\pi \left(\frac{0,6}{2}\right)^2} = 7.7m$$

$$h(\text{top}) = 2 \times \text{tray spacing} = 2 \times 0.6 = 1.2m$$

$$h = (0.6 \times (7 - 1)) + 7.7 + 1.2 = 12.5m$$

The height to diameter ratio:

$$12.5/0.6 = 20.8$$

From general column design guidelines⁵⁷ the ratio should be less than 20-30 and column height should be less than 53 m thus, this estimated column size falls within these design guidelines.

Ammonia condenser (E1202)

The ammonia condenser utilises cooling water of 25°C ($\Delta=10$) to condense the ammonia vapours at 45 °C to ammonia liquid (with residual inert vapours) at 40 °C.

This process gives off:

$$Q_H = 2141 \text{ kW}$$

The cooling water required:

$$cw = 1.8 \times 10^5 \text{ kg/h} \quad \text{Eq.(1).}$$

The temperature difference was calculated:

$$\Delta T_{tm} = 12^\circ\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a one shell and two tube-pass heat exchanger, using an overall heat transfer coefficient for condensing organic vapours with water: $U = 800 \text{ W/m}^2\text{K}$. This value was chosen as an average between the range of 500-700 $\text{W/m}^2\text{K}$ for organics (some non-condensables) and water, and the range 700-1000 $\text{W/m}^2\text{K}$ for organic vapours and water¹⁹:

$$A = 223 \text{ m}^2 \quad \text{Eq.(4).}$$

This surface area is very large as a lot of heat is given off by the condensation of ammonia and because the small temperature difference between shell and tube side is very small.

MP carbamate condenser (E1201)

The MP carbamate condenser utilises cooling water of 25°C ($\Delta=10$) to partially condense a solution of carbamate, ammonia, carbon dioxide and water at 87 °C to 75 °C.

This process gives off:

$$Q_H = 955 \text{ kW}$$

The cooling water required:

$$cw = 8.2 \times 10^4 \text{ kg/h} \quad \text{Eq.(1).}$$

The temperature difference was calculated:

$$\Delta T_{lm} = 51^{\circ}\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a one shell and two tube-pass heat exchanger, using an overall heat transfer coefficient estimate in the middle of the range of 700-1000 W/m²K for condensing organic vapours with water: U = 850 W/m²K. This value was chosen as there are remaining condensable gases in the stream, which contribute to a higher overall heat transfer coefficient¹⁹:

$$A = 22.1 \text{ m}^2 \quad \text{Eq.(4).}$$

Ammonia receiver (V1201)

The size of the MP ammonia receiver vessel was calculated to be independent of NH₃ supply for one hour²⁰, this ensures urea production may continue during short problems with raw material supply.

The vessel will be operated half full of liquid, as per design guidelines for horizontal separators.¹⁹

The volumetric flow of gases out of vessel:

$$v = 36.2 \text{ m}^3/\text{h}$$

The volumetric flow of liquid out of vessel:

$$v = 25.9 \text{ m}^3/\text{h}$$

The vapour residence time must not be as long as the liquid residence time, thus the design of the vessel will be carried out with one hour residence of the liquid, as specified above.

Volume of receiver (to operate half full):

$$V = (v \times t_r) \times 2 = (25.9 \times 60) \times 2 = 51.8 \text{ m}^3$$

From a patent of the construction of an ammonia receiver, the length was estimated to be 8 m²⁰ thus, the diameter could be calculated:

$$D = 2 \times \sqrt{\frac{V}{\pi L}} = 2 \times \sqrt{\frac{51.8}{\pi \times 8}} = 2.9 \text{ m}$$

The length to diameter ratio:

$$\frac{8}{2.9} = 2.8$$

From design guidelines¹⁹, the most economical ratio for horizontal separators operating between 0 – 20 bar should be 3. Thus, these dimensions are economical for the ammonia receiver.

The ammonia receiver is built with a recovery column installed atop the horizontal vessel. From literature, this tower contains approximately 3m of pall ring packing to prevent the escape of too much gaseous ammonia to the scrubber²⁰. This was modelled in Aspen, with the average sized pall ring packing:

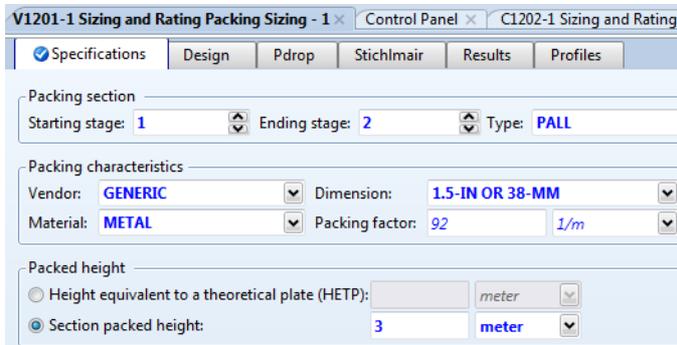


Figure 68: Defining packing for ammonia receiver tower

The diameter of the tower:

Parameter	Value	Unit
Section starting stage:	1	
Section ending stage:	2	
Column diameter:	0.355055	meter
Maximum fractional capacity:	0.62	
Maximum capacity factor:	0.0158165	m/sec
Section pressure drop:	0.00432461	bar
Average pressure drop / Height:	1.44154	mbar/m
Maximum stage liquid holdup:	23.9544	l
Max liquid superficial velocity:	0.0380853	m/sec
Surface area:	1.3	sqcm/cc

Figure 69: Diameter of tower calculated in Aspen

There is no liquid holdup at the bottom of this tower as it is mounted directly on the receiver thus, the height is calculated in the same manner as the top section of the MP decomposer above.

$$h = h(\text{above}) + h(\text{packing}) + h(\text{below})$$

$$h = (0.6 \times 2) + 3 + 0.6 = 4.8\text{m}$$

From a technical drawing of the ammonia receiver the height of the tower approximately corresponds to the 4.8m calculated above²⁰.

The height to diameter ratio:

$$\frac{4.8}{0.4} = 12$$

This again falls within the specifications for column design.

Scrubber (C1203)

The MP scrubber has four stages which were modelled with nutter float valve trays ¹⁵:

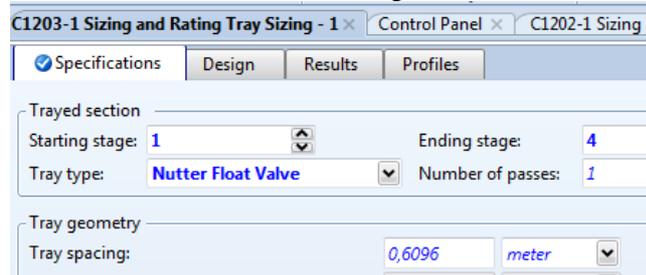


Figure 70: Defining trays for C1203

The Diameter of the washing tower:

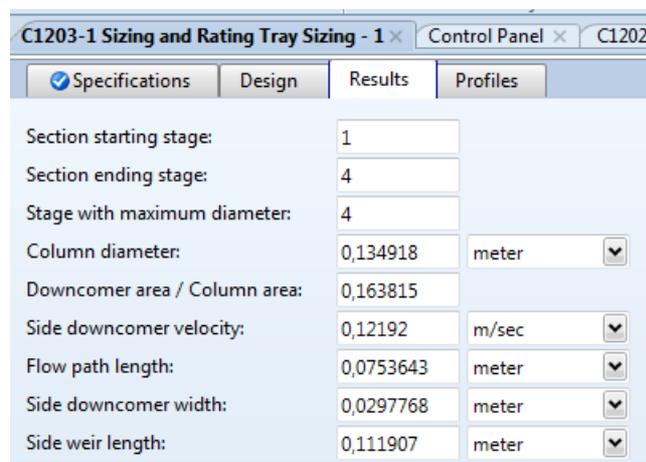


Figure 71: Diameter of C1203 calculated in Aspen

The volumetric flow rate of 1 m³/h out of the bottom of the scrubber results in an unrealistic L/D ratio when using the diameter calculated by Aspen and estimating the residence time as 5 minutes.

It should be noted that the vapour flow through the scrubber could be larger in reality than what was modelled in aspen. The purpose of the scrubber is to remove ammonia from the inert purge stream thus, the outgoing vapour flow is largely inerts. In reality there would be a larger flow of inerts than modelled due to possible leaks in the vacuum section or leaks of inerts from pump or compressor seals ⁵⁸. Thus, the diameter (0.3m) was estimated to be larger than the value calculated above by Aspen, in order to make allowances for a larger vapour flow.

The column height was calculated:

$$h = (\text{tray spacing} \times (\text{stages} - 1)) + h(\text{bottom}) + h(\text{top})$$

$$h(\text{bottom}) = \frac{V}{\pi \left(\frac{D}{2}\right)^2} = \frac{(1 \times \left(\frac{5}{60}\right))}{\pi \left(\frac{0.3}{2}\right)^2} = 1.2m$$

$$h(\text{top}) = 2 \times \text{tray spacing}$$

$$h = (0.6 \times (4 - 1)) + 1.2 + 1.2 = 4.2\text{m}$$

The height to diameter ratio:

$$4.2/0.3 = 14$$

Thus, by designing a larger column (diameter of 0.3m instead of 0.1m) higher vapour flow rates can be accommodated, whilst remaining within the general column design guidelines of a H:D ratio less than 20-30.⁵⁷

The lower half of the scrubber is also cooled during the absorption process; this was modelled by adding a heat exchanger to the bottom stream. The cooling water of 25°C ($\Delta=10$) cools the outflow from 108 °C to 65 °C.

This process gives off:

$$Q_H = 45 \text{ kW}$$

The cooling water required:

$$cw = 3.9 \times 10^3 \text{ kg/h} \quad \text{Eq.(1).}$$

The temperature difference was calculated:

$$\Delta T_{lm} = 55^\circ\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a single pass shell and tube heat exchanger, using an overall heat transfer coefficient for heat exchange between water and water: $U = 800 \text{ W/m}^2\text{K}$, due to the main component of the bottom stream being water (80 wt% water). The lowest value in the range of 800-1500 $\text{W/m}^2\text{K}$ was chosen, in order to be closest to the next most applicable range of 250-750 $\text{W/m}^2\text{K}$, for coolers with organic solvents and water¹⁹:

$$A = 1 \text{ m}^2 \quad \text{Eq.(4).}$$

This value shows that indeed only a small section of the column would require cooling.

Pre-heater shell (C1302-1)

The preheater requires 1836 kW of heat to make the endothermic decomposition of carbamate (tube side) possible. This heat is provided by the partial condensation and exothermic reaction of gases and carbamate solution (as explained in process technology section of chapter 2) in the shell of the preheater.

The combined heat produced by the reaction and condensation was required to be equal to 1836 kW. To get an idea of the heat of reaction, the shell was modelled as a zero duty reactor, followed by a condenser specified to produce the desired heat for the tube side reaction (see Aspen model description).

The temperature difference was thus calculated for a shell side solution entering at 160 °C and leaving at 87°C, heating the tube side solution of 86°C to 105°C:

$$\Delta T_{lm} = 13^{\circ}\text{C} \quad \text{Eq.(2).}$$

The way the temperature difference has been calculated above suggests that the tubes are heated by an incoming stream of 160°C. This is a very rough estimation of the temperature difference, as the exothermic reaction is in reality occurring inside the shell as a function of time (the actual stream enters at 106°C). Condensation is also occurring during this time thus, the temperature profile within the shell is much more complicated than suggested however, for the purposes of finding a rough surface area, 13°C will be used.

The heat exchange area was calculated for a single pass shell and tube heat exchanger. The heat transfer is occurring between organic solvents (100-300 W/m²K) however, as there is a large quantity of condensable vapours present the coefficient of heat transfer would be considerably higher and therefore, a value from the lower end of the organic solvents and steam range (500-1000 W/m²K) was chosen. The value of U= 500 W/m²K¹⁹.

$$A = 282 \text{ m}^2 \quad \text{Eq.(4).}$$

This area is very large due to the fact that the exiting shell side stream is too close in temperature to the exiting tube side solution to be feasible in reality. Perhaps the conversion specified in the shell side is in reality higher than modelled, or the duty required for carbamate decomposition (tube side) is less than modelled. A lower duty in the preheater would for example be achieved if the LP decomposer were more effective in lowering carbamate concentrations before the solution reached the preheater.

A5.3 LP section

The dimensions of the medium pressure decomposer and rectifier, the low pressure decomposer and rectifier and the preheater are equal. The difference lies on the heat exchanging area, which is different for each of them, and also on the top of the vessels: the medium- and low pressure decomposers have a packing on the top, while the preheater has some trays.

Low pressure decomposer

The heat exchanging area of the low pressure decomposer and rectifier was calculated from the following Eq. (4).

Since the heat was supplied by the condensation of low pressure saturated steam, the mean temperature difference was calculated with Eq. (3).

The saturation temperature of the used low pressure is 148°C. The inlet temperature of the product line is 126°C and the outlet temperature is 138°C. The calculated mean temperature difference is then 15.2°C. According to Aspen, the heat needed by the low pressure decomposer is equal to 1105kW. If an overall heat transfer coefficient of 750W/m²/°C is taken, the heat exchanging area of the low pressure decomposer is then 54.1m².

This is an approximation, since the decomposition of ammonium carbamate needs energy, so the energy transferred from the low pressure steam in the shell side to the tube side of the decomposer is not only used to heat up the product, but also to decompose some of the remaining ammonium carbamate.

To calculate the height of the packing, Aspen is used to make an estimation of the diameter. The number of stages is chosen as three, and the height of the packing is chosen to be equal to the one from the medium pressure decomposer and rectifier: $H=1.3\text{m}$. From Aspen, it is calculated that the diameter of the packing is equal to 0.39m .

Preheater

To calculate the median temperature difference of the preheater, Eq. (2). is used. Here again it is difficult to define the values of the inlet and outlet temperature of the product line, but it is also difficult to determine the inlet temperature of the heating medium. This is due to the fact that heat is supplied by the condensation reaction between ammonia and carbon dioxide in the shell side of the preheater, so there is not really an inlet temperature, but rather a temperature profile in the shell. For simplicity, the tube side of the preheater was modelled just as the low pressure decomposer and this way the necessary heat was calculated. The shell side was modelled as a reactor followed by a heat exchanger, which gave an “inlet temperature” (or actually, the outlet temperature of the reactor, which can be seen as the highest temperature possible) of 160°C and an outlet temperature of 87 for the hot fluid, while the cold fluid (in this case, the product line) has an inlet temperature of 86°C and an outlet temperature of 105°C . The heat exchanger used in modelling the preheater was tuned according to the necessary heat, which was equal to 1836kW . From these calculations, the value of the heat exchanging area in the preheater is 282 m^2 .

Low pressure carbamate condenser

The low pressure carbamate condenser was modelled just as the preheater. The inlet and outlet temperatures of the product line are 84°C and 40°C respectively. As cooling medium, cooling water was chosen with an inlet temperature of 20°C and an outlet temperature of 41°C . The duty was calculated at 617 kW , and the value of U was chosen identical to above calculations. The heat exchanging area of the condenser was then calculated to be 49 m^2 .

Pumps

The pumps were both modelled using Aspen and the same specifications found in the chapter “Equipment List”. However, pumps P1302 does not appear in this model, since in the process it is only used to provide for the friction losses. From the aspen model, it appears that pump P1301 needs 4.67 kW when running on a volumetric flow of $3.69\text{m}^3/\text{hr}$. Pump P1302 was modelled separately:

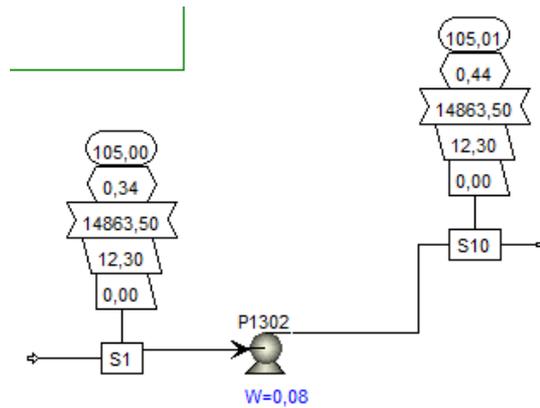


Figure 72: P1302

It appears that to raise the pressure of the product line, a variable flow pump (both pumps were chosen as variable flow) need 0.08 kW.

Carbamate receiver

In case of shutdown, the ammonium carbamate receiver should be able to hold all the carbonate solutions in the process [3]. This can be estimated as the reactor effluents in one hour, which requires a tank volume of 49.18 m³. If a ratio of D/L=0.4 is chosen, the diameter of the tank is calculated to be 2.93 m and the length of the cylindrical, horizontal vessel to be 7.31m.

A5.4 Vacuum section

The evaporators

The evaporators consist of two parts: a heat exchanging part and a cyclone part. The size of the evaporators was calculated with some constrictions on the diameter of the inlet. The size of the inlet then has influence on the diameter of the separator. Then using standard sizing of cyclones the length of each part of the cyclones could be calculated.

The empirical constrictions on the inlet diameter are:

$$d1 \geq 0.0007\{Q_G(\rho_L - \rho_G)/\eta_G\}^{0.333} \quad (7)$$

$$d1 \geq 0.144\rho_G^{0.25} Q_G^{0.5} \quad (8)$$

$$d1 \geq 1.13 Q_L^{0.5} \quad (9)$$

$$d1 \geq 0.226 Q_G^{0.5} * \quad (10)$$

*If erosive material is present in the feed

d1= diameter of the inlet (m)

Q_G=volumetric gas flow rate (m³/h)

Q_L=volumetric liquid flow rate (m³/h)

ρ_L=liquid density (kg/m³)

ρ_G=vapour density (kg/m³)

η_G= vapour viscosity (kg/m·s)

The lowest value that satisfied all these equations should be used.

The diameter of the cyclone can then be calculated with these formulas:

$$D \geq 3.5d_1 \quad (11)$$

$$D \geq 0.652 Q_G^{0.5} \quad (12)$$

D= diameter of cyclone(m)

Again the lowest value satisfying both equations shall be used. ⁵⁹

Under the assumption that gas-liquid and gas-solid cyclones have similar shapes, the height can be estimated along with the lengths of certain parts of the cyclone. ¹⁹

Heat exchangers

For the sizing of the heat exchangers Eq. (3), and Eq. (4), are used. It is assumed that no correction factor is required. This correction factor is not required due to the design accuracy of the plant. For sizing the condensers, it is assumed that both product streams are cooled to 40°C.

The overall heat exchanger coefficient was estimated using the tables in ¹⁹. For the heat exchangers E1401 and E1402 a heat transfer coefficient of 3000 W/m²°C is used. The range for condensing steam-light organic solvents is 2500-3500 W/m²°C.

For the condensers E1403 and E1404 a heat transfer coefficient of 750W/m²°C. The range of organic solvents-water is 250-750 W/m²°C. It was chosen over the steam-water range of 1500-4000 W/m²°C. However, the fact that this coefficient is higher is the reason the heat transfer coefficient was chosen to be at the high end of the organic solvents-water range.

A5.5 Wastewater section

T1501

T1501 stores wastewater. The liquid flow is 8.35 m³/hr. For a buffer of 1 day and with the tank half full at normal operation, the total storage is 2 days. So the total volume is 401 m³. Eq. (5).

R1501

The hydrolyzer consists of a horizontal cylindrical reactor with 11 vertical baffles. The baffles are cut alternating at the bottom and both the bottom and the top to create a plug-flow.

The height of the baffles are 80% of the diameter.

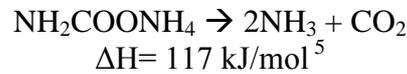
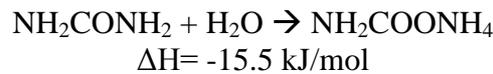
The residence time is 30 min. ³⁰

The liquid Inflow is 10,2 m³/hr

Inflow steam 219 m³/hr or 2000 kg/hr

Liquid volume reactor: 5.08 m³. Eq. (5).

With the assumption there is 10% vapor above the liquid, the total volume would be 5.59 m³.
 Reactions occurring in hydrolyser:



C1501

C1501 consist of a top and bottom section.

The tray spacing is 0.6 m, the flooding factor is 0.8 and the trays are Sieve type.
 The top section of the column contains 8 stages and the bottom section contains 17 stages.
 The column has no reboiler as live steam is supplied for heat.

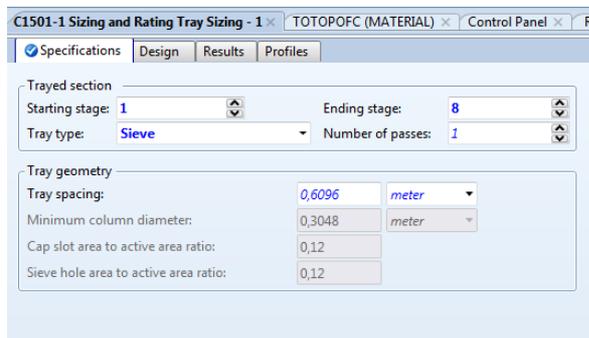


Figure 73: top section of C1501

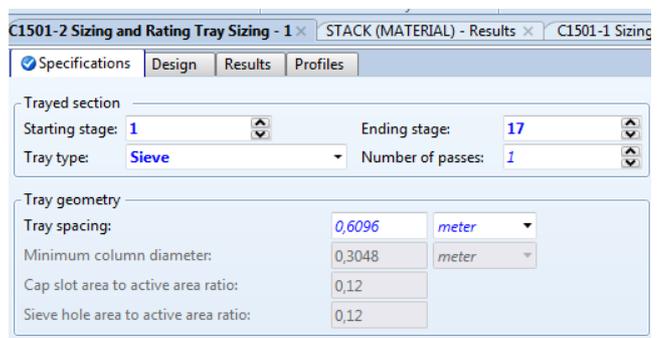


Figure 74: bottom section of C1501

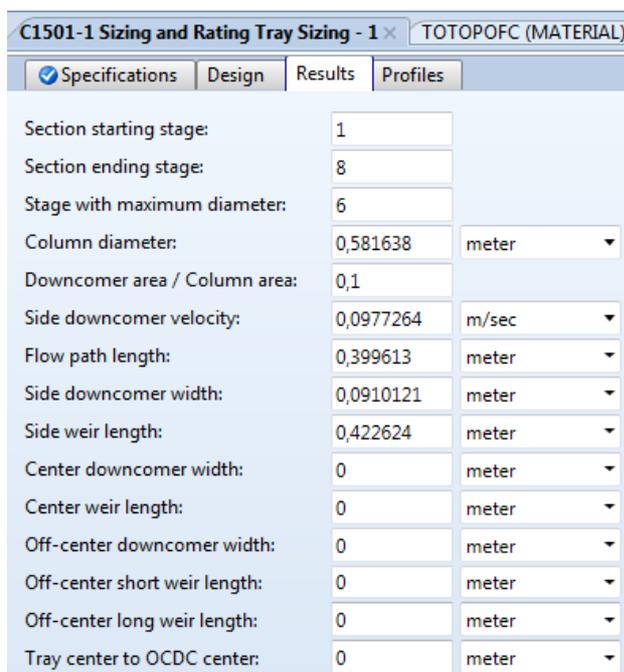


Figure 75: aspen calculation of top

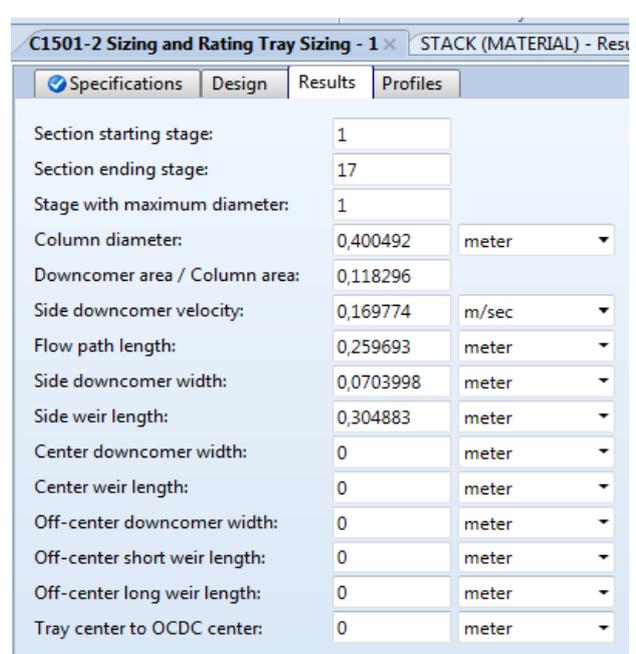


Figure 76: aspen calculation of bottom

The diameter is chosen to be 0.58 m for both the top as the bottom.

For both the top as the bottom, an estimated residence time of 5 minutes was chosen to allow buffer in the bottom of the column to control the level.

For the top: Volume flow of effluent is $9.23 \text{ m}^3/\text{hr}$, residence time of 5 min would require 0.77 m^3 of effluent buffer at the bottom. Eq. (5). With a diameter of 0.58 m, the height would be 2.91 m. Eq.(6). With a vapor buffer of 2 times the tray spacing, the total height would be 8.71 m.

For the bottom: Volume flow of effluent is $9.14 \text{ m}^3/\text{hr}$, residence time of 5 min would require 0.76 m^3 of effluent buffer at the bottom. With a diameter of 0.58 m, the height would be 2.88 m. With a vapor buffer of 2 times the tray spacing, the total height would be 14.47 m.

The total height of C1501 is 23.18 m.

P1501

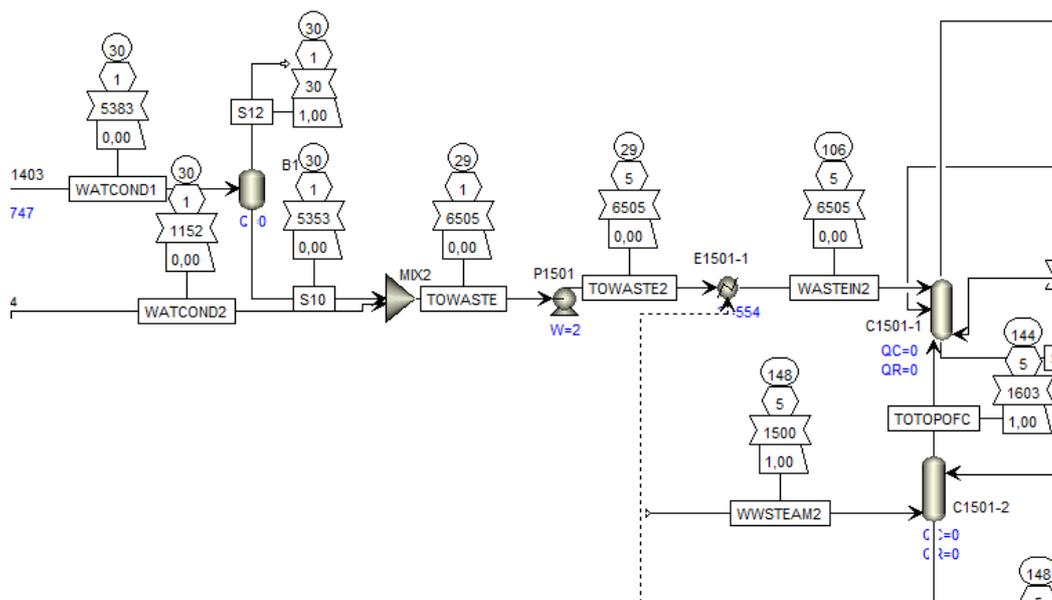


Figure 77: P1501

Because in the aspen model, there is a vapor fraction in the wastewater stream, p1501 isn't in it. To calculate the size of the pump, a flash is put after E1403, which results in no vapor fraction. The vapor you lose is 0.46 wt%, which is added to the volume flow and power.

Heat exchangers

E1501

The purpose of E1501 is to preheat the wastewater entering C1501 and cool down the purified process condensate out of C1501. The heat transfer is 544 kW.

The temperature difference was calculated:

$$\Delta T_{lm} = 51^{\circ}\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a shell and tube heat exchanger, using an overall heat transfer coefficient estimate of 800 W/m²/K.¹⁹

$$A = 13.6 \text{ m}^2 \quad \text{Eq.(4).}$$

E1502

The purpose of E1502 is to preheat the aqueous flow entering R1501 and cool down the effluent out of R1501. The heat transfer is 539 kW.

The temperature difference was calculated:

$$\Delta T_{lm} = 6^{\circ}\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a shell and tube heat exchanger, using an overall heat transfer coefficient estimate of 800 W/m²/K.¹⁹

$$A = 114 \text{ m}^2 \quad \text{Eq.(4).}$$

E1503

The purpose of E1503 is to condense the top vapor of C1501 with cooling water of 25°C ($\Delta=10$). The heat transfer is 1899 kW.

The cooling water required:

$$cw = 1.63 * 105 \text{ kg/h} \quad \text{Eq.(1).}$$

The temperature difference was calculated:

$$\Delta T_{lm} = 30^{\circ}\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a shell and tube heat exchanger, using an overall heat transfer coefficient estimate of 1000 W/m²/K.¹⁹

$$A = 63 \text{ m}^2 \quad \text{Eq.(4).}$$

E1504

The purpose of E1504 is to cool down the process condensate to acceptable temperatures to release in the environment, which is 40°C. The utility is cooling water of 25°C ($\Delta=10$). E1504 is not shown in the aspen model. For calculating the heat transfer it is later added.

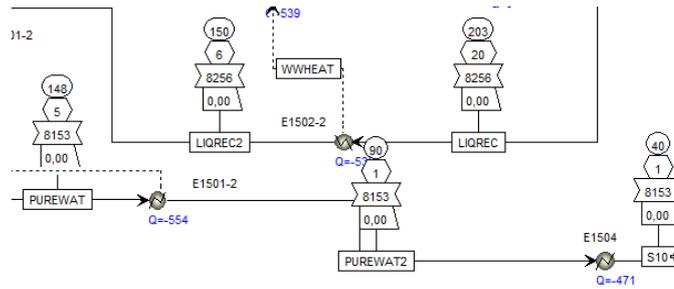


Figure 78: Heat exchangers of the wastewater section

The heat transfer is 417 kW.

The cooling water required:

$$cw = 4.05 * 10^4 \text{ kg/h} \quad \text{Eq.(1).}$$

The temperature difference was calculated:

$$\Delta T_{lm} = 31^\circ\text{C} \quad \text{Eq.(2).}$$

The required heat exchange area was calculated for a shell and tube heat exchanger, using an overall heat transfer coefficient estimate of 1000 W/m²/K.¹⁹

$$A = 19\text{m}^2 \quad \text{Eq.(4).}$$

Appendix 6. Stream Results for Model Improvements

Table 24: scrubbing system

	Units	EXTRAW AT	EXTRWA T2	LIVESTM	LPSTEA M	PREHV AP	PRODU CT	PUREWA T2	S12
From							V1402	E1501-2	EJECT OR
To		V1401	V1402	C1501NE W	EJECTO R	C1401			C1403
Phase:		Vapor	Vapor	Vapor	Vapor	Mixed	Liquid	Liquid	Mixed
Component Mass Flow									
UREA	KG/HR	0	0	0	0	5	12922	0	409
CARB	KG/HR	0	0	0	0	0	3	0	0
CO2	KG/HR	0	0	0	0	32	0	0	0
NH3	KG/HR	0	0	0	0	320	0	0	0
H2O	KG/HR	140	110	1500	600	2908	49	7009	1375
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		0,0E+00	0,0E+00	0,0E+00	0,0E+00	1,7E-03	1,0E+00	2,2E-08	2,3E-01
CARB		0,0E+00	0,0E+00	0,0E+00	0,0E+00	9,5E-08	2,1E-04	0,0E+00	2,8E-06
CO2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	9,9E-03	9,7E-15	9,1E-51	1,6E-09
NH3		0,0E+00	0,0E+00	0,0E+00	0,0E+00	9,8E-02	1,8E-09	5,0E-07	7,1E-06
H2O		1,0E+00	1,0E+00	1,0E+00	1,0E+00	8,9E-01	3,8E-03	1,0E+00	7,7E-01
N2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
O2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
Mass Flow	KG/HR	140	110	1500	600	3266	12974	7009	1784
Volume Flow	CUM/ HR	58	46	630	252	15938	10	7	9984
Temperatur e	C	150	150	148	148	88	134	90	170
Pressure	BAR	4,6	4,6	4,5	4,5	0,3	0,0	4,5	0,3
Vapor Fraction		1,0	1,0	1,0	1,0	1,0	0,0	0,0	1,0
Liquid		0,0	0,0	0,0	0,0	0,0	1,0	1,0	0,0

Fraction									
Mass Enthalpy	KJ/KG	-13212	-13212	-13215	-13215	-12203	-5078	-15609	-11099
Enthalpy Flow	KW	-514	-404	-5506	-2203	-11070	-18301	-30393	-5499
Mass Density	KG/CU M	2	2	2	2	0	1244	967	0

	Units	S2	S20	S21	SCRBL Q	SCRBL Q1	SCRBL Q2	SCRUB VP	SCRUBV P1
From		MIX1	C1501NE W	C1501NE W	C1401	C1402	C1403	C1401	C1402
To		E1403	E1503	E1501-2	C1402	C1403	E1401- 1	MIX1	MIX1
Phase:		Mixed	Vapor	Liquid	Liquid	Liquid	Liquid	Vapor	Vapor
Component Mass Flow									
UREA	KG/HR	0	0	0	5	56	464	0	0
CARB	KG/HR	0	0	0	0	0	0	0	0
CO2	KG/HR	32	32	0	0	0	0	32	0
NH3	KG/HR	321	321	0	1	0	0	319	2
H2O	KG/HR	4565	682	7009	156	277	226	2952	1613
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		3,3E-09	1,2E-11	2,2E-08	3,3E-02	1,7E-01	6,7E-01	1,5E-10	9,9E-09
CARB		2,0E-19	0,0E+00	0,0E+00	1,9E-06	2,5E-06	8,4E-06	8,7E-24	6,0E-19
CO2		6,6E-03	3,1E-02	9,1E-51	5,0E-07	3,0E-10	8,9E-14	9,8E-03	5,7E-06
NH3		6,5E-02	3,1E-01	5,0E-07	6,3E-03	2,6E-05	8,8E-08	9,6E-02	1,2E-03
H2O		9,3E-01	6,6E-01	1,0E+00	9,6E-01	8,3E-01	3,3E-01	8,9E-01	1,0E+00
N2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
O2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
Mass Flow	KG/HR	4918	1035	7009	162	332	690	3303	1615
Volume Flow	CUM/H R	25689	421	8	0	0	1	17212	8476
Temperature	C	67	134	148	67	70	82	67	69

Pressure	BAR	0,3	4,5	4,5	0,3	0,3	0,3	0,3	0,3
Vapor Fraction		1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0
Liquid Fraction		0,0	0,0	1,0	1,0	1,0	1,0	0,0	0,0
Mass Enthalpy	KJ/KG	-	-13212	-13215	-	-12203	-5078	-15609	-11099
Enthalpy Flow	KW	-514	-404	-5506	-2203	-11070	-18301	-30393	-5499
Mass Density	KG/CU M	2	2	2	2	0	1244	967	0

	Units	SCRUBV P2	TOWAS TE	UREASL U2	UREASL U3	UREASL U4	UREAS OL	WASTEI N2	WATCON D1
From		C1403	MIX2	E1401-1	V1401	E1402-1		E1501-1	E1403
To		E1404	E1501-1	V1401	E1402-1	V1402	E1401-1	C1501N EW	MIX2
Phase:		Vapor	Mixed	Mixed	Liquid	Mixed	Liquid	Mixed	Mixed
Component Mass Flow									
UREA	KG/HR	0	0	13381	13331	13331	12917	0	0
CARB	KG/HR	0	0	3	3	3	3	0	0
CO2	KG/HR	0	32	0	0	0	0	32	32
NH3	KG/HR	0	321	1	0	0	1	321	321
H2O	KG/HR	1626	6191	2108	714	714	1882	6191	4565
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		8,3E-08	2,3E-08	8,6E-01	9,5E-01	9,5E-01	8,7E-01	2,3E-08	3,3E-09
CARB		1,6E-18	5,5E-19	1,7E-04	1,9E-04	1,9E-04	1,8E-04	5,5E-19	2,0E-19
CO2		1,8E-09	5,0E-03	5,9E-07	2,0E-10	2,0E-10	6,2E-07	5,0E-03	6,6E-03
NH3		1,3E-05	4,9E-02	5,9E-05	9,1E-07	9,1E-07	6,1E-05	4,9E-02	6,5E-02
H2O		1,0E+00	9,5E-01	1,4E-01	5,1E-02	5,1E-02	1,3E-01	9,5E-01	9,3E-01
N2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
O2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
Mass Flow	KG/HR	1626	6544	15493	14048	14048	14803	6544	4918
Volume	CUM/	8533	148	8614	11	47598	12	14	118

Flow	HR								
Temperature	C	69	39	130	130	134	105	103	30
Pressure	BAR	0,3	0,3	0,3	0,3	0,0	0,3	4,5	0,3
Vapor Fraction		1,0	0,0	0,2	0,0	0,2	0,0	0,0	0,0
Liquid Fraction		0,0	1,0	0,8	1,0	0,8	1,0	1,0	1,0
Mass Enthalpy	KJ/KG	-13351	-15234	-6250	-5565	-5436	-6400	-14972	-15081
Enthalpy Flow	KW	-6030	-27694	-26899	-21716	-21211	-26314	-27217	-20605
Mass Density	KG/CU M	0	44	2	1224	0	1208	482	42

	Units	WATCOND 2	WATER 1	WATER 2	WATERI N	WATEVAP 3	WATVA P	WWRCY C
From		E1404				V1402	V1401	E1503
To		MIX2	C1402	C1403	C1401	EJECTOR	C1402	
Phase:		Liquid	Liquid	Liquid	Liquid	Vapor	Vapor	Mixed
Component Mass Flow								
UREA	KG/HR	0	0	0	0	409	50	0
CARB	KG/HR	0	0	0	0	0	0	0
CO2	KG/HR	0	0	0	0	0	0	32
NH3	KG/HR	0	0	0	0	0	1	321
H2O	KG/HR	1626	200	200	200	775	1534	682
N2	KG/HR	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0
Component Mass Fraction								
UREA		8,3E-08	0,0E+00	0,0E+00	0,0E+00	3,5E-01	3,2E-02	1,2E-11
CARB		1,6E-18	0,0E+00	0,0E+00	0,0E+00	4,2E-06	3,2E-07	0,0E+00
CO2		1,8E-09	0,0E+00	0,0E+00	0,0E+00	2,3E-09	5,8E-06	3,1E-02
NH3		1,3E-05	0,0E+00	0,0E+00	0,0E+00	1,1E-05	5,6E-04	3,1E-01
H2O		1,0E+00	1,0E+00	1,0E+00	1,0E+00	6,5E-01	9,7E-01	6,6E-01
N2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
O2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
Mass Flow	KG/HR	1626	200	200	200	1184	1585	1035
Volume Flow	CUM/H R	2	0	0	0	55476	9467	7
Temperature	C	69	25	25	25	134	130	30
Pressure	BAR	0,3	1,0	1,0	1,0	0,0	0,3	4,5
Vapor Fraction		0,0	0,0	0,0	0,0	1,0	1,0	0,0

Liquid Fraction		1,0	1,0	1,0	1,0	0,0	0,0	1,0
Mass Enthalpy	KJ/KG	-15697	-15881	-15881	-15881	-10026	-12936	-12097
Enthalpy Flow	KW	-7089	-882	-882	-882	-3297	-5696	-3477
Mass Density	KG/CU M	991	1038	1038	1038	0	0	151

Table 25: condensing system

	Units	EXTRAW AT	EXTRWA T2	LIQRE C	LIQRE C2	LPSTEA M	PREHV AP	PRODU CT	PUREW AT
From				R1501-1	E1502-2			V1402	C1501-2
To		V1401	V1402	E1502-2	C1501-2	EJECTOR	E1405-1		E1501-2
Phase:		Vapor	Vapor	Mixed	Mixed	Vapor	Mixed	Liquid	Liquid
Component Mass Flow									
UREA	KG/HR	0	0	0	0	0	5	12920	0
CARB	KG/HR	0	0	0	0	0	0	3	0
CO2	KG/HR	0	0	2	2	0	32	0	0
NH3	KG/HR	0	0	3	3	0	320	0	0
H2O	KG/HR	140	110	6586	6586	600	2908	49	6368
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		0,0E+00	0,0E+00	3,6E-08	3,6E-08	0,0E+00	1,7E-03	1,0E+00	3,8E-08
CARB		0,0E+00	0,0E+00	4,7E-08	4,7E-08	0,0E+00	9,5E-08	2,1E-04	4,9E-08
CO2		0,0E+00	0,0E+00	2,7E-04	2,7E-04	0,0E+00	9,9E-03	9,7E-15	7,8E-46
NH3		0,0E+00	0,0E+00	5,1E-04	5,1E-04	0,0E+00	9,8E-02	2,0E-09	2,6E-09
H2O		1,0E+00	1,0E+00	1,0E+00	1,0E+00	1,0E+00	8,9E-01	3,8E-03	1,0E+00
N2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
O2		0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00	0,0E+00
Mass Flow	KG/HR	140	110	6591	6591	600	3266	12972	6368

Volume Flow	CUM/HR	58	46	8	34	252	15938	10	7
Temperature	C	150	150	211	158	148	88	134	148
Pressure	BAR	4,6	4,6	20,0	6,0	4,5	0,3	0,0	4,5
Vapor Fraction		1,0	1,0	0,0	0,0	1,0	1,0	0,0	0,0
Liquid Fraction		0,0	0,0	1,0	1,0	0,0	0,0	1,0	1,0
Mass Enthalpy	KJ/KG	-13212	-13212	-15073	-15285	-13215	-12203	-5078	-15365
Enthalpy Flow	KW	-514	-404	-27595	-27984	-2203	-11070	-18298	-27177
Mass Density	KG/CU M	2	2	789	193	2	0	1244	892

	Units	PUREWAT 2	S1	S12	S2	S4	S6	SCRUBL Q	SCRUBLQ 1
From		E1501-2	E1405-1	EJECTOR	MIX1	E1406-1	E1407-1	E1405-2	E1406-2
To			E1405-2	E1407-1	E1403	E1406-2	E1407-2	B7	B7
Phase:		Liquid	Mixed	Mixed	Vapor	Mixed	Mixed	Liquid	Liquid
Component Mass Flow									
UREA	KG/HR	0	5	408	1	50	408	5	50
CARB	KG/HR	0	0	0	0	0	0	0	0
CO2	KG/HR	0	32	0	32	0	0	0	0
NH3	KG/HR	0	320	0	321	1	0	0	0
H2O	KG/HR	6368	2908	1375	4377	1534	1375	18	47
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		3,8E-08	1,7E-03	2,3E-01	1,8E-04	3,2E-02	2,3E-01	2,2E-01	5,1E-01
CARB		4,9E-08	9,5E-08	2,8E-06	1,3E-11	3,2E-07	2,8E-06	1,3E-05	5,3E-06
CO2		7,8E-46	9,9E-03	1,6E-09	6,9E-03	5,8E-06	1,6E-09	6,1E-07	3,4E-10
NH3		2,6E-09	9,8E-02	8,0E-06	6,8E-02	6,3E-04	8,0E-06	4,5E-03	1,3E-05
H2O		1,0E+00	8,9E-01	7,7E-01	9,3E-01	9,7E-01	7,7E-01	7,7E-01	4,9E-01
N2		0,0E+00	0,0E+0	0,0E+0	0,0E+0	0,0E+0	0,0E+0	0,0E+00	0,0E+00

			0	0	0	0	0		
O2		0,0E+00							
Mass Flow	KG/HR	6368	3266	1783	4731	1586	1783	23	97
Volume Flow	CUM/H R	7	15109	9982	24773	7872	6658	0	0
Temperature	C	90	71	170	73	76	84	71	76
Pressure	BAR	1,0	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Vapor Fraction		0,0	1,0	1,0	1,0	1,0	0,8	0,0	0,0
Liquid Fraction		1,0	0,0	0,0	0,0	0,0	0,2	1,0	1,0
Mass Enthalpy	KJ/KG	-15610	-12249	-11099	-12584	-13137	-11639	-13265	-10211
Enthalpy Flow	KW	-27610	-11111	-5498	-16538	-5786	-5766	-85	-274
Mass Density	KG/CU M	967	0	0	0	0	0	1035	1108

	Units	SCRUBL Q2	SCRUBL QT	SCRUB VP	SCRUBV P1	SCRUBV P2	STACK STACK	STACK 2	TOHYDR O
From		E1407-2	B7	E1405-2	E1406-2	E1407-2	C1501-1	P1502	E1502-1
To		B7	E1401-1	MIX1	MIX1	E1404	P1502	E1502-1	R1501-1
Phase:		Liquid	Liquid	Vapor	Vapor	Vapor	Liquid	Liquid	Liquid
Component Mass Flow									
UREA	KG/HR	407	462	0	1	2	2	2	2
CARB	KG/HR	0	0	0	0	0	0	0	0
CO2	KG/HR	0	0	32	0	0	0	0	0
NH3	KG/HR	0	0	320	1	0	2	2	2
H2O	KG/HR	161	226	2890	1487	1214	6386	6386	6386
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		7,2E-01	6,7E-01	8,2E-05	4,0E-04	1,3E-03	3,7E-04	3,7E-04	3,7E-04
CARB		8,7E-06	8,4E-06	9,8E-12	2,0E-11	1,7E-10	4,2E-11	4,2E-11	4,2E-11
CO2		1,2E-13	2,1E-08	1,0E-02	6,2E-06	2,3E-09	8,7E-07	8,7E-07	8,7E-07
NH3		1,1E-07	1,5E-04	9,9E-02	6,7E-04	1,2E-05	3,2E-04	3,2E-04	3,2E-04

H2O		2,8E-01	3,3E-01	8,9E-01	1,0E+00	1,0E+00	1,0E+00	1,0E+00	1,0E+00
N2		0,0E+00							
O2		0,0E+00							
Mass Flow	KG/HR	568	688	3242	1489	1216	6391	6391	6391
Volume Flow	CUM/HR	0	1	15109	7872	6657	7	7	8
Temperature	C	84	81	71	76	84	148	149	198
Pressure	BAR	0,3	0,3	0,3	0,3	0,3	4,5	20,0	20,0
Vapor Fraction		0,0	0,0	1,0	1,0	1,0	0,0	0,0	0,0
Liquid Fraction		1,0	1,0	0,0	0,0	0,0	1,0	1,0	1,0
Mass Enthalpy	KJ/KG	-8061	-8539	-12242	-13327	-13311	-15358	-15353	-15134
Enthalpy Flow	KW	-1271	-1631	-11026	-5511	-4494	-27263	-27255	-26866
Mass Density	KG/CU M	1166	1153	0	0	0	892	891	815

	Units	TOTOPO FC	TOWAS TE	UREASL U2	UREASL U3	UREASL U4	UREAS OL	WASTEI N2	WATCON D1
From		C1501-2	MIX2	E1401-1	V1401	E1402-1		E1501-1	E1403
To		C1501-1	E1501-1	V1401	E1402-1	V1402	E1401-1	C1501-1	MIX2
Phase:		Vapor	Mixed	Mixed	Liquid	Mixed	Liquid	Mixed	Mixed
Component Mass Flow									
UREA	KG/HR	0	2	13379	13329	13329	12917	2	1
CARB	KG/HR	0	0	3	3	3	3	0	0
CO2	KG/HR	2	32	0	0	0	0	32	32
NH3	KG/HR	3	321	1	0	0	1	321	321
H2O	KG/HR	1718	5591	2108	714	714	1882	5591	4377
N2	KG/HR	0	0	0	0	0	0	0	0
O2	KG/HR	0	0	0	0	0	0	0	0
Component Mass Fraction									
UREA		2,9E-11	4,0E-04	8,6E-01	9,5E-01	9,5E-01	8,7E-01	4,0E-04	1,8E-04
CARB		6,4E-13	4,4E-11	1,7E-04	1,9E-04	1,9E-04	1,8E-04	4,4E-11	1,3E-11
CO2		1,0E-03	5,5E-03	5,9E-07	2,0E-10	2,0E-10	6,2E-	5,5E-03	6,9E-03

							07		
NH3		2,0E-03	5,4E-02	6,5E-05	1,0E-06	1,0E-06	6,1E-05	5,4E-02	6,8E-02
H2O		1,0E+00	9,4E-01	1,4E-01	5,1E-02	5,1E-02	1,3E-01	9,4E-01	9,3E-01
N2		0,0E+00							
O2		0,0E+00							
Mass Flow	KG/HR	1723	5947	15491	14045	14045	14803	5947	4731
Volume Flow	CUM/HR	723	146	8617	11	47585	12	13	118
Temperature	C	148	38	130	130	134	105	101	30
Pressure	BAR	4,5	0,3	0,3	0,3	0,0	0,3	4,5	0,3
Vapor Fraction		1,0	0,0	0,2	0,0	0,2	0,0	0,0	0,0
Liquid Fraction		0,0	1,0	0,8	1,0	0,8	1,0	1,0	1,0
Mass Enthalpy	KJ/KG	-13190	-15178	-6251	-5565	-5436	-6399	-14916	-15048
Enthalpy Flow	KW	-6314	-25072	-26896	-21712	-21207	-26314	-24639	-19776
Mass Density	KG/CUM	2	41	2	1224	0	1208	455	40

	Units	WATCO ND2	WATEV AP3	WAT VAP	WWR CYC	WWR EC	WWREF LUX	WWSTE AM1	WWSTE AM2	WWV AP
From		E1404	V1402	V1401	WWS PLIT	E1503	WWSPLIT			C1501-1
To		MIX2	EJECTOR	E1406-1		WWS PLIT	C1501-1	R1501-1	C1501-2	E1503
Phase:		Liquid	Vapor	Vapor	Mixed	Mixed	Mixed	Vapor	Vapor	Vapor
Component Mass Flow										
UREA	KG/HR	2	408	50	0	0	0	0	0	0
CARB	KG/HR	0	0	0	0	0	0	0	0	0
CO2	KG/HR	0	0	0	34	35	0	0	0	35
NH3	KG/HR	0	0	1	322	325	3	0	0	325
H2O	KG/HR	1214	775	1534	923	932	9	200	1500	932

	R									
N2	KG/H R	0	0	0	0	0	0	0	0	0
O2	KG/H R	0	0	0	0	0	0	0	0	0
Component Mass Fraction										
UREA		1,3E-03	3,5E-01	3,2E-02	2,2E-07	2,2E-07	2,2E-07	0,0E+00	0,0E+00	2,2E-07
CARB		1,7E-10	4,2E-06	3,2E-07	3,7E-16	3,7E-16	3,7E-16	0,0E+00	0,0E+00	3,7E-16
CO2		2,3E-09	2,3E-09	5,8E-06	2,7E-02	2,7E-02	2,7E-02	0,0E+00	0,0E+00	2,7E-02
NH3		1,2E-05	1,2E-05	6,3E-04	2,5E-01	2,5E-01	2,5E-01	0,0E+00	0,0E+00	2,5E-01
H2O		1,0E+00	6,5E-01	9,7E-01	7,2E-01	7,2E-01	7,2E-01	1,0E+00	1,0E+00	7,2E-01
N2		0,0E+00								
O2		0,0E+00								
Mass Flow	KG/H R	1216	1183	1586	1279	1292	13	200	1500	1292
Volume Flow	CUM/ HR	1	55463	9470	6	6	0	16	630	528
Temperature	C	69	134	130	30	30	30	225	148	137
Pressure	BAR	0,3	0,0	0,3	4,5	4,5	4,5	25,5	4,5	4,5
Vapor Fraction		0,0	1,0	1,0	0,0	0,0	0,0	1,0	1,0	1,0
Liquid Fraction		1,0	0,0	0,0	1,0	1,0	1,0	0,0	0,0	0,0
Mass Enthalpy	KJ/KG	-15683	-10026	-	-	-	-12810	-13123	-13215	-10407
Enthalpy Flow	KW	-5295	-3296	-5697	-4552	-4598	-46	-729	-5506	-3735
Mass Density	KG/C UM	991	0	0	200	200	200	12	2	2

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