Report on the Development of the Wally-AHT Pilot AWG

Joint Project between REHOS Product Designs and Cirrus Water Management Rentals executed in the time-period October 2019 - December 2020

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Pilot plant constructed and tested on the Manufacturing Premises of Cirrus Water Management Rentals (Pty) Ltd, at 67 Carlisle Street, Paarden Eiland, Cape Town, South Africa.

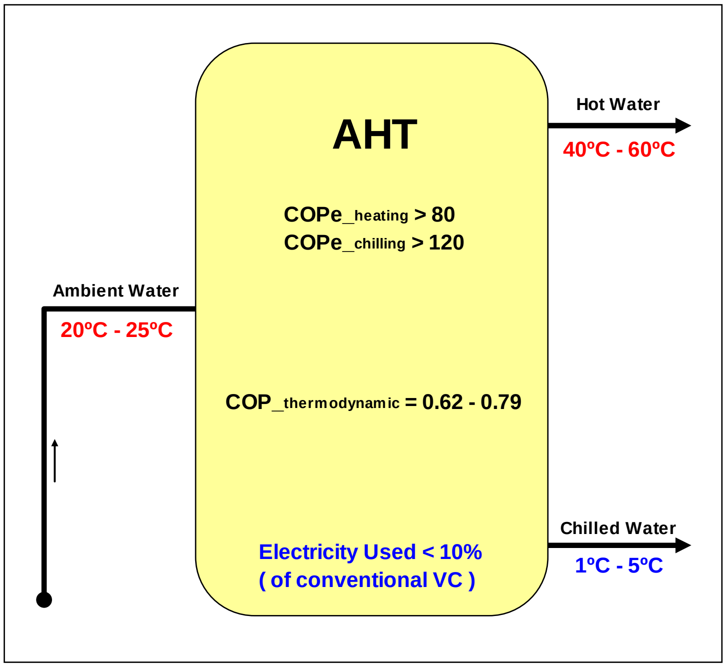
Abstract:

This report is compiled by combining the theory of atmospheric water generation (AWG) and a novel simplified absorption heat transformer (AHT) with a practical designed and constructed developed Wally-AHT pilot model. It also describe some of the testing done on the pilot and highlight the lessons learned about the use of ammonia-water (NH_3-H_2O) binary mixtures.

Special emphasis is placed on the more challenging process concepts and how it was resolved. In this regard the vapor bubble upflow velocity in the distillation process had to be reduced and flow restricted by a filter to enhance heat exchange between the vapor and liquid in the bubble reactor to efficiently concentrate NH_3 as explained in the theory section. Also, additional high turbulence liquid recirculation had to be employed to enhance the vapor absorption sufficiently for establishing the required temperature (and NH_3 concentration) gradient in the distillation column of the bubble reactor. These are only two of numerous operational pitfalls the testing team had to overcome to demonstrate the concepts described in the theory section of this report.

The section on lessons learned covers not only construction difficulties and material limitations due to the high corrosivity of the medium used, but also process challenges tied to the use of such a volatile component as NH_3, as part of the binary mixture. It also highlight some practical experiences of the team regarding operational safety.

In the discussion and future models section, the report highlight that the pilot model was constructed to resolve all the practical pitfalls in the development of the technology of a real commercially viable AWG machine, making use of the (ambient) heat powered AHT as chiller unit as per adjacent sketch. Real electricity use of the developed AHT amount to less than 10% of the electricity used by a conventional VC chiller unit. The hot water output of the AHT is not used in the AWG and is discarded as a re-heat of the chilled air (for energy balance) in the AWG hot coil. This "temperature upgraded" hot water would be best utilized to power a simple organic rankine cycle (ORC) power expander that may deliver just enough electrical energy to serve all the AHT liquid pumping requirements as well as the AWG fan, to make the resulting **Wally-REHOS AWG** unit totally heat powered. This then create an AWG that does not require any external electricity! Energy is literally sucked out of the air to produce AWG water.....



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1.) Introduction

The standard atmospheric water generator (AWG) machines utilized by Cirrus until now consist of a de-humidifying concept where atmospheric air is chilled to below the dew point, condensing water from the air in a cold evaporation coil, after which the chilled, dry air is used as coolant for the heat rejection (hot condensing) coil. A standard conventional vapor compression (VC) refrigeration unit coupled between the two coils complete the classical AWG machine. The main operating cost of such an AWG unit is the cost of electricity, required to power the refrigeration unit compressor.

The Wally version of AWG that Cirrus have recently been experimenting with, seek to replace the VC cooling unit with an alternative means of air chilling, increasing the competitive edge in AWG by utilizing an air chilling concept that use less electricity than the conventional standard VC Chiller, making the produced water cheaper.

The patented REHOS technology subsection currently of interest to Cirrus and the AWG industry, involve the novel simplified absorption heat transformer (AHT), doing the same function as a conventional VC heatpump, but utilizing ambient heat to power the process, instead of the much more expensive electricity utilized by a conventional chiller unit. This novel AHT make use of a pseudo-isobaric temperature glide concept, in a zeotropic ammonia-water (NH_3-H_2O) binary mixture, filling a direct contact heat exchanger (H/E) distillation column, we call a bubble reactor. The machine is heat powered, and the only electricity used by this AHT is for liquid pumping, generally a few orders of magnitude smaller than vapor compression.

Combining the water chilling capability of the AHT (REHOS Technology) with the De-Humidification Technology of the Wally AWG (Cirrus Technology) therefore avoid the high cost electrical vapor compression and optimize the water production from AWG operation with a seriously decreased electricity consumption, as well as a lower chilling temperature to guarantee AWG operation even at very low humidity with dew points as low as 3 - 4°C. Even though both the AWG technology and the conventional AHT technology are proven, commercialized technologies, the Wally-AHT AWG combination is a novel concept, and have never before been constructed. The IP developed is therefore also protected by Cirrus with the aim of patent rights in many countries globally. The promise of a radical reduction in operational cost (and therefore AWG water cost) was the motivator to have Cirrus Water Management Rentals (Pty) Ltd join forces with REHOS Product Designs cc and embarked on a Wally-AHT development project, starting with a pilot model to:

- Demonstrate experimentally the Wally-AHT AWG process on a pilot scale large enough to properly formulate future component sizing calculations with the minimum error, to minimize costly over-design of heat exchanging equipment, specifically of the Bubble Reactor utilized, and confirming the theory.
- Establish locally available suppliers of materials and services for future design and construction of Wally-AHT machine models.
- Establish safe and practical construction and commissioning procedures for handling NH_3-H_2O media when working with future zeotropic binary media

machines. Gain experience in the selection and construction of various materials/methods.

- Document performance results of power usage, operating range and water production of the AWG pilot machine to predict future prototyping and production machine performance with reasonable accuracy.
- Document and adapt to "teething" problems by multiple re-design and error correction where necessary as it is the first machine of its kind ever built. Although the process and scientific facts are 100% proven with heat-, mass-, and species balance, the heat exchange rate achieved in the various direct contact H/E components had to be verified experimentally, as information in the literature was not found for this specific first-of-its-kind configuration and application.
- Develop the most economical methods and formulations to design and construct practical commercial Wally-AHT prototypes and other AWG applications that may be manufactured for commercial gain.

The heart of the novel AHT designed as part of this pilot plant is the NH3-H2O bubble reactor, largely simplifying a conventional AHT to make it a really practical heat pump, able to extract heat even from waste heat sources at, or below ambient temperatures, with an evaporator working at a design temperature between 2°C and 15°C. Heat rejection of the high temperature side is at a design temperature of 60°C for our pilot, so the AHT may easily be utilized as chiller for AWG operation, or water heater generating hot water, or both. Heat energy for powering the AHT is extracted from the low temperature side and in AWG operation it literally suck heat out of the air to power the machine. The energy comes from the latent heat of condensation at the dew-point temperature of water vapor, present as humidity in the atmospheric air. Energy required to chill the air down to the dew point is recovered when the chilled, dried air is used as coolant to drop the atmospheric ambient humid air temperature down to dew point.

As the AHT is heat powered, the amount of electricity used is extremely low, making this type of heatpump extremely economical on operational cost for refrigeration as well as hot water systems. In our pilot design the heatpump coefficient of performance relating to electricity use (COPe) calculates to ~ 200, as can be seen in the results of table 2, in sharp contrast to the COPe of ~ 10, typical of conventional VC type heat pumps utilized in AWG configurations. This have the consequence that using an AHT to pump heat in refrigeration plant may produce 20 times more output, for the same electricity used. Put differently, the AHT utilization may reduce electricity cost of cooling, air conditioning and refrigeration systems to less than 10% of what it conventionally was......

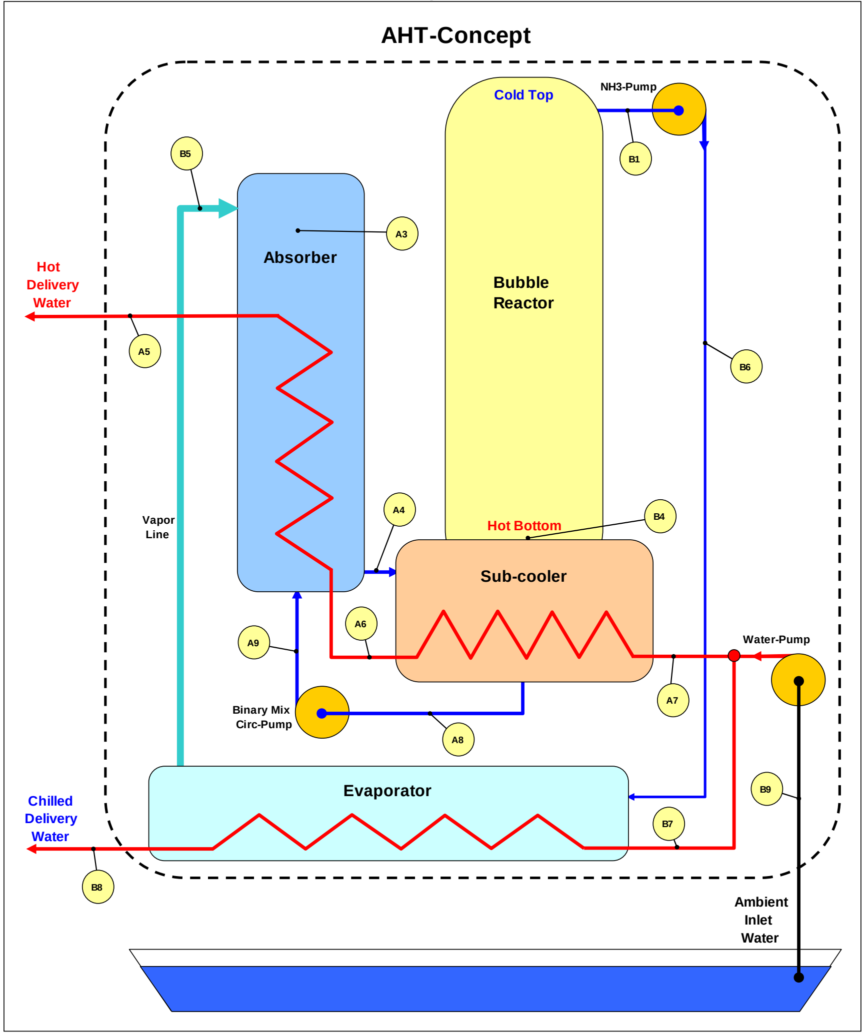
Realizing that about 17% of all global electricity generated is used for refrigeration and air conditioning, the size of the commercial impact of this novel, patented development piloted in the Wally-AHT AWG is difficult to fully realize...

Can we really afford not to put absolute maximum support for this development team in place for moving as fast as possible to follow-up projects, so everybody can start benefiting from the revolutionary proven concepts earlier rather than later?

2.) The Theory

The process variables labeled in the sketches of process layout diagrams for the complete Wally-AHT model are listed as part of table 1, and the operational results summarized in table 2.

Figure 1



A typical AHT machine configured as a heat pump to recover heat from an ambient water source would simplify to the concept sketched in figure 1. It would consist of an evaporator, absorber and distillation column we call a bubble reactor. Liquid movement is generated by three liquid pumps, two operating with binary NH3-H2O mixture as medium, namely the main process pump we named the NH3-Pump and the binary mixture absorber circulation pump we refer to as the Absorber Circ-Pump, or simply Circ-Pump. The third pump is the water distribution pump we named the Water-Pump, or CW-Pump. This CW pump is actually not part of the closed thermodynamic cycle, but we decided to group it with the two process pumps for simplicity in enclosing the AHT for inclusion in practical applications. The two pumps in direct contact with the highly corrosive NH3-H2O binary medium should both be seal-less or mag-driven to guarantee no rotating shaft is required to be sealed to keep the NH3 medium out of the environment.

The bubble reactor work on the well-known isobaric temperature gliding principle. Any binary zeotropic mixture column completely sealed into a gravitational field, and heat added to the bottom, would boil off the more volatile component, in this case NH3, and the higher density, lower NH3 concentration would heat up and migrate to the column bottom due to the higher density acting on gravity. The released volatile component, in our case NH3, boiled off in vapor form, will be re-absorbed higher up in the column, increasing the %NH3, and, due to the higher NH3 concentration as well as vapor bubbles present, have a much lower two-phase mixture density, forming a stream flowing to the column top due to the lower density in the gravitational field. This distillation (NH3 concentrating) process, where the mixture up-flow is powered by the vapor-lift reaction, is an endothermic process, absorbing heat from the mixture as it flows upwards in the gravitational force field. (When NH3 dissolves in H2O, the dilution process is exothermic, heating the mixture, opposite to the distillation process). In this upwards flowing NH3 concentration process, vapor bubbles are gradually absorbed, generating heat to release more NH3 vapor bubbles going upwards, and the higher temperature, lower %NH3 liquid with higher density is forced downwards by gravity. This low concentration NH3, heated liquid stream increase in mass and temperature as it flows downwards, also forming a hot stream in direct contact with the colder, two-phase, low density upward flowing stream, and therefore heat is exchanged in this direct contact counter flow dual stream "heat exchanger" along the length of the distillation column. The endothermic NH3 flow process in the upwards direction therefore concentrates the NH3, and cool down the mixture, creating a cold, high %NH3 column top.

This temperature gradient (hot area in the bottom and cold area at the top) in the column, at constant pressure (nearly isobaric) and staying saturated everywhere, accompanied by a NH3 concentration gradient (high %NH3 at the top and low %NH3 at the bottom) is named an "isobaric temperature glide", and is a well known concept in the literature. Even when no more heat is added, with the flows stagnating, the gradients set up in the column will dissipate extremely slowly, by radiant and conduction heat loss only, as convection (that we are used to in pure liquids like water) is inhibited while the column stays in the gravitational force field. Density differences between the bottom and the top will tend to maintain the gradients that have been set up.....

Even in columns not completely sealed, but mass flow forced into the column bottom and removed from the column top, the process stays identical to what was already described, as long as the column diameter is large enough (eg. maintaining an average void of some 20%) to guarantee sufficient vertical flow space not to hamper the two counter flow liquid streams.

In evaluating mass, heat and species balance of the distillation column, the formulations of Ganesh and Srinivas [1] proved very useful. This paper was used to generate look-up tables for NH3-H2O binary mixtures with varying concentration levels. Both constant pressure tables at various different values of pressure, as well as constant %NH3 tables at various different values of %NH3 was generated for the calculation of the required process variables in all sections of the models to be tested.

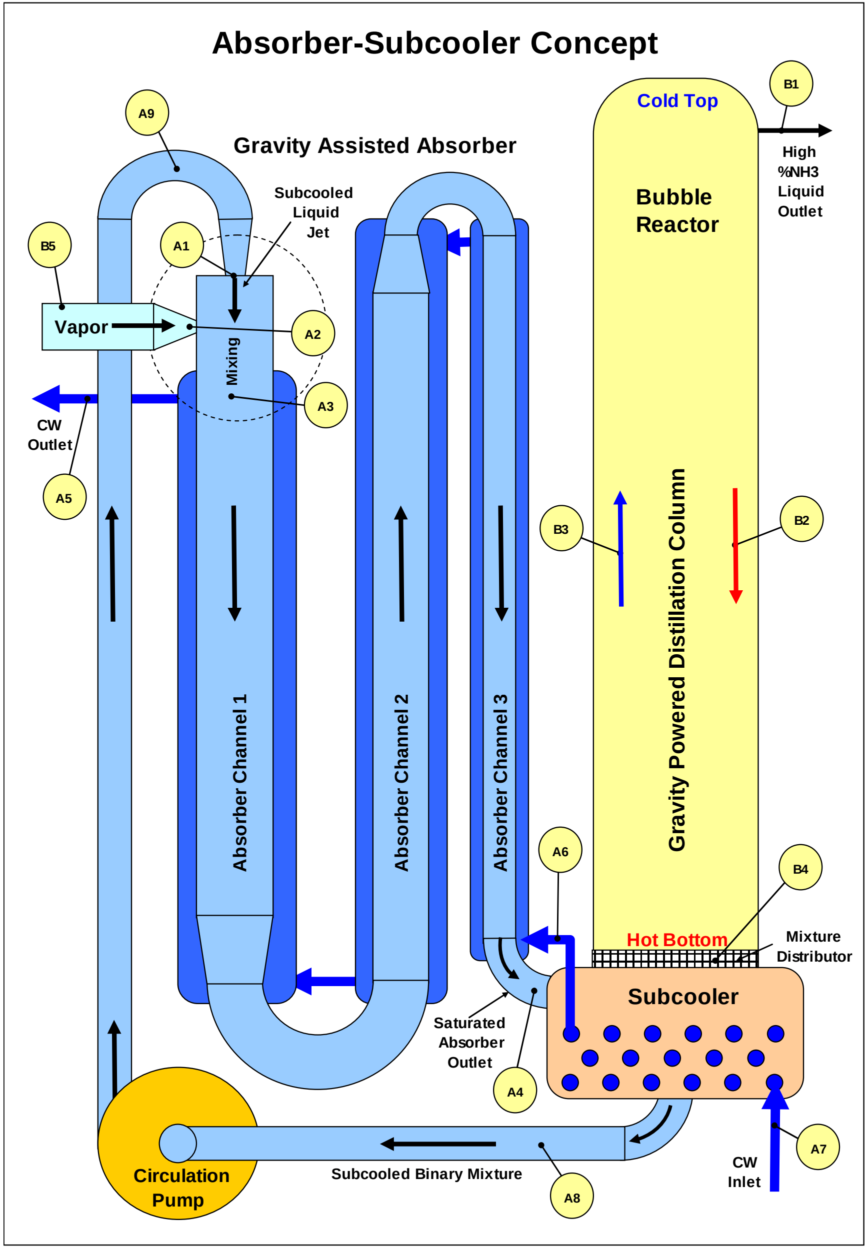
For calculation purposes the distillation column was divided into numerous small horizontal virtual discs with the upflow two-phase stream inflow into the disc bottom, as well as the two-phase stream outflow from the disc top considered, together with the heated, higher density lower %NH3 downflow into the disc top and the increased mass and temperature downflow from the disc bottom was taken into consideration in the balancing equations. This way of utilizing balance calculations in a continuum was done by Govindaraju in 2005 [4] analyzing a bubble flow absorber. Assuming a fixed, linear distribution of %NH3 with column height, the required mass-, heat-, and species balance calculations was done for each disc in the column. The result of these calculations at the column top, point (B1), midpoint (B2) downflow and (B3) upflow, and column bottom (B4) form part of the process variables listing in table 1. Even though the two counter flow streams at the column bottom and top have very close to the same temperature, the large temperature differential in the column mid-section, with (B2) = 48.2°C and (B3) = 22.9°C suggest a large heat exchange in the column mid-section. Calculation results correspond remarkably well to the work of Govindaraju as part of her master's thesis [4]. This also make the large H/E taking place in the total distillation column (see table 2) of 41.6 kW even though the heat input (B4) delivered by (A4) from the absorber is only 8.09 kW at 60°C.

In the distillation column, the saturated liquid density is highest at the bottom (B4) and decrease nearly linearly with height to the lowest density at the top. In all areas of the distillation column, the binary mixture is at the saturation temperature corresponding to the isobaric column pressure. The mixture in the sub-cooler below the distillation column is in contact with a cooling coil, where heat is removed from the mixture. This cooling, with the NH3 concentration constant, lead to subcooling, where the cooled mixture temperature drop below the saturation level for the pressure in the reactor. The top of the sub-cooler, where the mixture is still saturated at (A4) the temperature is 60.1°C but due to the cooling, the sub-cooler outlet temperature at (A8) drops to 45°C, subcooled by some 15°C. The liquid density at the sub-cooler top at 60°C is 985 kg/m3, while the subcooled mixture exit at (A8) liquid density is 995 kg/m3 at 45°C, highlighting that subcooled liquid density increase with subcooling. The colder liquid would therefore drop to the sub-cooler bottom where the circ-pump suction inlet would draw liquid from.

The circ-pump inlet at (A8) is at the reactor pressure of 2.8 Bar Abs and the pump increase the pressure to 3.09 Bar Abs at position (A9) from where the subcooled liquid is forced through a nozzle to drop the dynamic pressure in a subcooled liquid jet entering the mixing section of the absorber. Vapor from the evaporator also enter the mixing section via a vapor nozzle and mix with the highly turbulent, subcooled liquid jet to form a thoroughly mixed two-phased vapor-liquid flow column exchanging heat and mass as the vapor is absorbed in the subcooled liquid. Later in the absorption channels gravity becomes important, as it help forcing the liquid flow downwards. Although the vapor density difference to the liquid, acting on gravity, try to force the vapor bubbles upwards in counter flow to the liquid, the overall effect is to keep the vapor in H/E contact with the liquid for a longer time, absorbing vapor as the flow proceed, so the vapor bubble diameters become smaller and smaller in the flow direction. This enhance the rate of heat and mass transfer further, until saturated liquid with a very small vapor component reaching the absorber outlet at (A4). As the absorber outlet is still a two-phase mixture, the density of the mixture as noted in table 1 calculates to 210 kg/m3, carrying just the correct amount of energy in latent vapor form to furnish the distillation column with the additional distillation heat of 8.09 kW required.

The complete absorber-bubble reactor is in pressure balance, so any additional heat present in the absorber outflow at (A4) will generate too much vapor, forcing more than the required 8.09 kW into the distillation column and just increasing the reactor pressure! To remove this additional heat in order to drop the pressure back to the design point, additional cooling is required, so the CW mass flow rate becomes an easy and logical way to control the reactor pressure to design point.

Figure 2



The absorption process in the absorber, where vapor is in contact with the subcooled liquid and being absorbed, not only generate heat, but also pressure, as the mass NH3 vapor being absorbed increase the liquid NH3 concentration. The higher NH3 concentration have a higher saturation pressure, so local pressure is easily increased at the absorption point. It is therefore very important that the liquid should be subcooled, so absorption heat may be used to increase the liquid temperature from the subcooled to the saturation temperature, instead of building pressure. Also, absorption heat should be removed from the vapor-liquid contact face as soon as possible, hence the use of high liquid velocity to generate turbulence. The rate of heat absorption in the absorber is very strongly related to:

- H/E area, calculated as surface area of the vapor bubbles (and number of bubbles) and the bubble diameters in the mixture;
- the rate of heat removal from the vapor-liquid interface brought by turbulence and high velocity of the liquid flow;

- the relative frictional movement (shear force) of the lower density vapor bubble stream to the higher density liquid stream creating turbulence, also responsible for breaking up vapor bubbles into smaller bubbles, generated by the force field eg. gravity or centrifugal force;
- the degree of subcooling in the liquid flow. Higher subcooling generate higher rates of heat transfer without raising the local pressure.

These effects where identified in the literature by several authors in the past, like Golden [6] in 2012, Al-Hemiri et al [8] in 2008 as well as [10] by the same authors in the same year and Hernandez-Alvaro et al in 2017. The rate of absorption heat transfer and the contributing effects also form part of several technical reviews, like Ibarra-Bahena et al [5] in 2014, Shu et al [7] in April 2019 and Kantarci et al [9] in 2005. It is therefore clear that absorber design may enhance the rate of H/E substantially by using the known chemical process intensifiers developed in recent years. The vortex centrifugal bubbling reactor tested by Kuzmin et al [3] demonstrated this for water with air bubbles already in 2005.

It is therefore not surprising to find that keeping all other parameters equal, a change in vapor bubble diameter in a vapor-liquid contact device (like both the distillation column and the absorber columns) have the following effect on the volumetric rate of heat exchange:

- bubbles 10mm diameter => 1 MW/m3;
- bubbles 5mm diameter => 3 MW/m3;
- bubbles 2mm diameter => 12 MW/m3.

Also, looking at the effect of increasing the force field (from standard gravity = 1G to a force of 10G) with all other parameters kept equal:

- Force = 2G => rate of H/E increase by 9%;
- Force = 3G => rate of H/E increase by 14%;
- Force = 4G => rate of H/E increase by 18%;
- Force = 5G => rate of H/E increase by 22%;
- Force = 10G => rate of H/E increase by 32%;

These examples indicate the large potential for process enhancement in both the bubble reactor and the absorber designs.

Mass-, heat-, and species balance calculations across the complete absorber, balance the pressure-, kinetic-, and enthalpy components of both liquid and vapor phases, as well as external heat removal by the CW jacket in the two-phase flow, from the inlet (mixing) area at (A3) to the final output at (A4). Balance result in the subcooling requirement of 15°C (Saturated 60°C - subcooled 45°C) to achieve the correct output pressure at (A4) corresponding to the saturation pressure of the mixture at (B4).

Liquid from the cold, high concentration NH3 at the reactor top is withdrawn at (B1) and pumped into the evaporator. Evaporator pressure is controlled at 1.5 Bar above the reactor pressure by a liquid pressure regulator set at 4.3 Bar Abs. Design point temperature at the evaporator inlet is -10.3°C at the pressure regulator output, but due to the NH3-pump action, the liquid is subcooled entering the evaporator at (B6). Being heated inside the evaporator, it reach the saturation temperature of close to 1°C (chosen in design so water being chilled inside the evaporator never reach freezing conditions) and start evaporating. As more and more NH3 in vapor form is boiled off inside the evaporator, the remaining NH3 concentration in the liquid is decreasing, with the corresponding increase in saturation temperature, up to the final vapor output (B5) where 90% (or more) of the liquid is vaporized and the output two-phase vapor stream is at a temperature of 15°C. Controlling the evaporator pressure therefore guarantee that heat of evaporation is extracted in the evaporator in the range 15°C to 1°C, with ambient water flowing through the evaporator from (B7) at 25°C to the chilled output of 2°C at (B8).

Table 1

	Temp	Pressure	Density	Enthalpy	Mass Flow	Quality	Liquid	Vapor	
Label	**Celsius**	**Bar Abs**	**kg/m3**	**KJ/kg**	**kg/s**	**X**	**%NH3**	**%NH3**	**Description**
A1	45.0	3.094	995	15.53	0.553	0.0%	28.0%	95.9%	Subcooled Binary Mixture Jet
A2	-10.3	2.800	24.63	1118.50	0.038	9.0%	91.0%	100.0%	Vapor Inflow Jet
A3	45.0	2.800	27.6	107.24	0.591	6.5%	28.0%	95.9%	2PH Binary Mixture after Vapor Injection
A4	60.1	2.800	210	88.96	0.591	0.7%	28.2%	94.7%	Absorber Outlet Binary Mixture
A5	55.0	1.000	986	230.19	0.327	0.0%	N/A	N/A	Heated CW Outlet
A6	51.1	1.000	988	213.47	0.327	0.0%	N/A	N/A	Heated Subcooler CW Outlet
A7	25.0	1.483	997	104.85	0.327	0.0%	N/A	N/A	Ambient CW Inlet to Subcooler
A8	45.0	2.800	995	15.53	0.553	0.0%	28.0%	95.9%	Subcooled Binary Mixture Pump Inlet
A9	45.0	3.094	995	15.53	0.553	0.0%	28.0%	95.9%	Subcooled Circ Pump Outlet
B1	-10.3	2.800	655	-122.84	0.038	0.0%	91.0%	100.0%	High Concentration NH3 Liquid Outlet
B2	48.2	2.800	944	4.48	0.095	0.0%	34.3%	97.42%	Heated Low %NH3 Liquid Downflow
B3	22.9	2.800	29.6	-21.36	0.133	7.9%	49.1%	99.61%	Vaporlift High %NH3 2PH Upflow
B4	60.1	2.800	210	88.96	0.038	0.7%	28.2%	94.74%	Distillation Column 2PH Mixture Inlet
B5	15.0	4.300	3.59	1157.93	0.038	90.0%	65.9%	99.94%	Vapor from Evaporator to be Absorbed
B6	-10.3	4.300	655	-122.84	0.038	0.0%	91.0%	100.0%	Pumped High %NH3 Liquid Mixture
B7	25.0	1.483	997	104.85	0.507	0.0%	N/A	N/A	Ambient CW Inlet to Evaporator
B8	2.0	1.348	1000	8.42	0.507	0.0%	N/A	N/A	Chilled CW Leaving Evaporator
B9	25.0	1.000	997	104.85	0.834	0.0%	N/A	N/A	Ambient CW Inlet to AHT
C1	20.5	1.000	998	86.03	0.004	0.0%	N/A	N/A	Water Condensed from Humid Air
C2	20.5	1.000	998	86.03	0.507	0.0%	N/A	N/A	Remaining Chilled Water after H/E
C3	25.0	1.000	997	104.85	0.004	0.0%	N/A	N/A	AWG Product Produced
C4	4.0	1.000	1.26		1.976	0.0%	N/A	N/A	Chilled Dried Air Outlet
C5	25.0	1.000	1.17		1.979	0.0%	N/A	N/A	Ambient Humid Air Inlet

Cape Town Humidity	**76%**	**Annual Average**	**AWG Water Delivered**	**308.4**	**Liters per 24 Hour period**
Fan Power Required	**2.30**	**kW**	**Wally-AHT Electricity Used**	**60.9**	**kWh per 24 Hour period**
AHT Pumps (3 off) Power	**0.24**	**kW**	**Electricity Used (Ignoring Fan)**	**5.7**	**kWh per 24 Hour period**

Economy Wally-AHT	**197.6**	**kWh/m3**
Economy Ignoring the fan Power	**18.6**	**kWh/m3 (No Fan Used)**

Chilled Dried Air Heat Recovered **41.7** **kW by using it for Cooling Ambient Humid Air to Dewpoint.**

Table 2

Q_in_ambient =	48.9	kW	@	25	Celsius
Q_chilled_out =	48.9	kW	@	2	Celsius
Q_hot_output =	41.0	kW	@	55	Celsius
Q_subcooler =	35.5	kW			
Q_absorber =	5.5	kW			
COPe_chiller =	204	Used as Cooler			
COPe_heater =	171	Used as Heater			
NH3-Pump Eff =	15%	Isentropic			
CW-Pump Eff =	25%	Isentropic			
Circ-Pump Eff =	18%	Isentropic			
Bubble Reactor average Void	20%				
Reactor Diameter (to get Void)	0.246	m			
Distillation Heat Added	8.09	kW	@	60	Celsius
Total Reactor Countercurrent H/E	41.6	kW			
Absorber H/E Rate =	6.48	MW / m3			
Subcooler H/E Rate =	1.74	MW / m3			
Distillation Column H/E Rate =	1.00	MW / m3			
Evaporator H/E Rate =	2.00	MW / m3			

The mass flow of ambient water flowing through the evaporator is high enough so 48.9 kW of heat is extracted from the water. Of this heat, some 41 kW is delivered as hot water at position (A5) at a temperature of 55°C, while the balance of 8.09 kW is used for the distillation process. This give a real thermodynamic coefficient of performance as heat pump of COP = 0.83, but with the three liquid pumps together only consuming 240 Watt, the performance calculation parameters, COPe for cooling service = 204 and the COPe for heating service = 171 as listed in table 2. This is fairly conservative, using the average pump efficiency of only 20%, but should different types of pumps be used (eg. The pitot type pump) the efficiency would increase to ~50%, making the total electricity consumption only 96 Watt. The performance figures (COPe) would then look quite different, namely COPe for cooling service = 509 and the COPe for heating service = 427!

The AHT, as described above, is described in its active, operational state, but consideration should be given to start-up scenarios. Remember the binary mixture sealed into the machine consist of NH3-H2O mixture, which will distribute throughout the piping and tanks and would eventually be of uniform concentration everywhere at ambient temperature. To get it into the "active" state, energy must be added to the absorber-reactor combination, so that the temperature gradient is present in the reactor column. This AHT is said to be "active" when the bubble reactor top is at the design temperature (-10°C) while the sub-cooler, where it joins the bubble reactor is at the design high temperature value (60°C), while all three pumps are in operation. Should the system be designed for extracting heat from a source at higher temperature than ambient, just starting the pumps would gradually increase the gradients in the reactor as the higher temperature waste heat circulating through the evaporator would already generate vapor, starting the process. If the design was for heat to be extracted from a heat source at, or even below ambient temperature, just starting the pumps would not start the system, as no vapor is produced in the evaporator. Some means should be used to start the process and produce vapor for heating the reactor bottom. Several different means may be utilized as starting devices, namely, eg:

1. Use an external electrically powered vacuum pump / compressor to remove vapor from the reactor top and compress it into the absorber inlet. Vapor removal from the reactor top would drop the pressure and flash off some NH3 vapor, removing a lot of latent heat of liquid vaporizing from the reactor top and cool it down. Simultaneously, the compressed vapor injected into the absorber would be absorbed, generating heat into the sub-cooler....Once design point temperatures at the correct reactor pressure have been reached, the vacuum pump is simply switched off, as heat extracted in the evaporator in normal operation would maintain the design gradient conditions further.

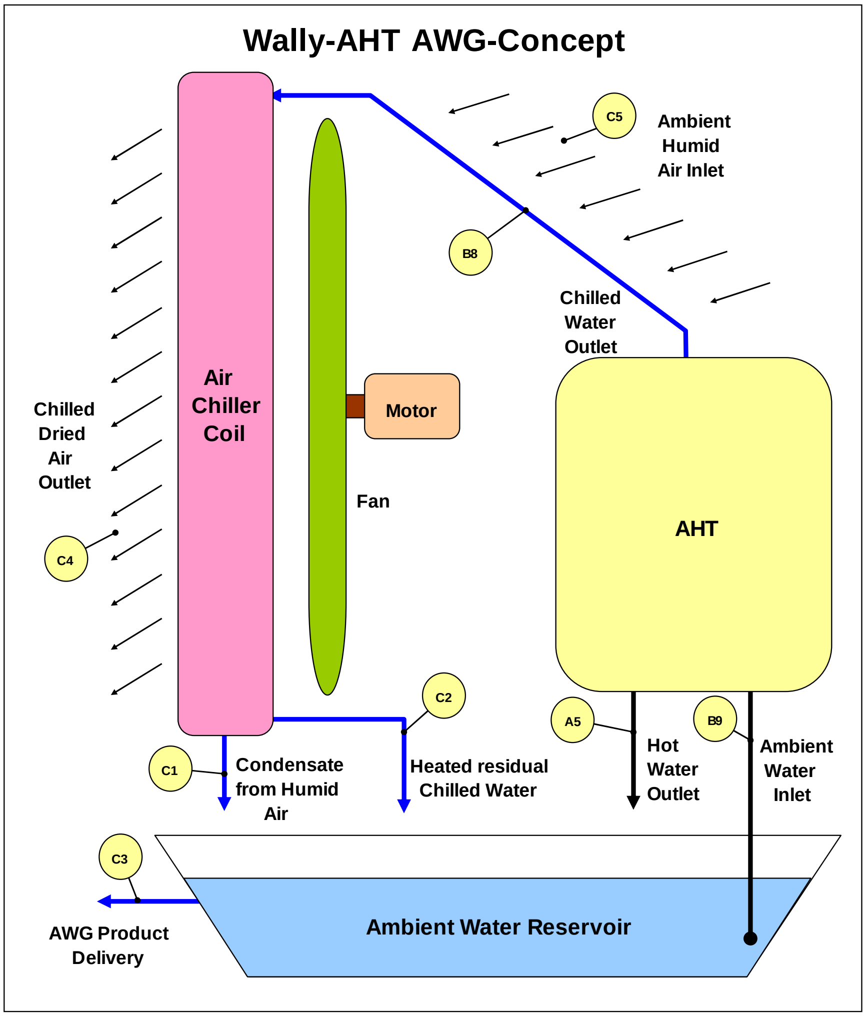
2. Provide a heating element into the evaporator, to generate vapor electrically (or by some external heat source), for starting purposes. This would probably be the best starting device, as the external heat source for starting may even be a low temperature waste heat source, as long as it is a higher temperature by some 10°C minimum above the saturation temperature of the binary mixture at the evaporator controlled pressure of 3.3 Bar (G). Starting higher pressure in the reactor may limit the speed of starting, though, as during the initial starting stage with the sub-cooler and CW both at the same temperature, no heat will be removed from the sub-cooler, with the resultant lack of reactor pressure control....Using a reasonable reactor pressure overshoot capability in the design should make this starting device, being an adjustable electrical heating element, the cheapest practical starting device. Limiting the heat input by choosing a small enough heating element would also resolve pressure overshoot issues.

3. To avoid the mentioned overpressure reaction on the reactor vessel during start-up, the heating element in the evaporator may generate vapor, but instead of injecting it direct into the absorber, for starting it may be routed to and used to power an ejector that would do the same function as the first mentioned vacuum pump, just a lot cheaper.....

4. Provide a heating element into the sub-cooler that can be switched on for starting. Initial starting of all three pumps would not start the AHT, as no vapor is generated anywhere. Heating the sub-cooler drive NH3 to the reactor top, creating the higher concentration NH3 required in the pumped liquid for the evaporator to generate vapor from, as the pressure is kept constant. This would take a lot longer for achieving "active" conditions in the reactor though, and there is a risk of too much heat added, with the result that the reactor pressure rise dangerously high.

As they say, there are more ways to kill a cat than to drown it in butter.....

Figure 3



Activation of the bubble reactor (Start-up), using method 2, would typically proceed as follows:

- Initially binary mixture, at (design value) 50%NH3 concentration throughout the complete system, and therefore also in the evaporator, at the constant pressure controlled at 3.3 Bar (G), have a saturation temperature of 34.32°C. The start-up heater is switched on, generating vapor at this saturation temperature. This vapor, being absorbed in the absorber, increase the mixture temperature, concentrating NH3 in the bubble reactor with the highest concentration at the reactor top. This higher concentration NH3 liquid at the pump suction point, is pumped into the evaporator...
- Assuming the mixture, now at eg. 55%NH3, saturation temperature drop to 27.21°C for vapor generation at saturation temperature. The absorption heating process and NH3 distillation at the reactor top now deliver eg. 60%NH3 to the pump....
- As the evaporator mixture gradually increase in %NH3 to 60%, with saturation temperature dropping to 21.05°C, generating vapor at this lower temperature...
- With time, the mixture concentration in the evaporator increase gradually, dropping the saturation temperature gradually. When the concentration reach 75%NH3, the saturation temperature have dropped to 8.13°C, still at the controlled pressure of 3.3 Bar (G), lower than ambient temperature by a large margin, allowing the ambient CW at the higher temperature constantly being pumped through the evaporator, to take over the vapor generation function done by the starting heater. At this stage the starting heater may be switched off, as

normal AHT operation would take over. Design point conditions will be reached in the reactor in time......

Figure 3 sketch the process layout of the complete Wally-AHT AWG concept, where the chilled water output (B8) is used in an Air-Water heat exchanger to condense water vapor from humid air. The humidity assumed for calculations was chosen as 76%, which is the annual average humidity for Cape Town. This give a dew point temperature of 20.5°C. Both the H/E coil outside at (C1) representing the condensate from the air, and the coil inside at (C2) carrying the heated residual chilled water back to the reservoir would therefore be at this dew point temperature. As the design of the AHT evaporator is such that the chilled water produced may be as low temperature as 2°C, the AWG will keep operating and produce water at (C3) even with very low humidity, eg. less than 30% humidity, having dew point temperatures below 6°C at the chosen ambient temperature of 25°C. Obviously the AWG machine output would just decrease in mass flow at such low humidity.

For the design of a very compact AWG machine, an electric fan was included in the design, however, the electric power consumption of the fan is quite high. To design a compact industrial AWG machine, it is absolutely essential, though. Comparing with various commercial AWG units, however, the fan power consumption vary tremendously. Low power fans used on some AWG units are in fact a lot less power-hungry than our test-rig, so it would not be fair to include the high fan power drawn into the equations when evaluating the performance of the pilot model installation.

Because the AHT is a very low-cost heatpump device generating both heat (at 60°C in our design) and cold (at 2°C in our design) from the ambient (25°C) heat energy available, that it is only logical that alternative uses are also possible. In the current pilot design, we concentrated on the utilization of the refrigeration effects, driving the AWG concept, but also usable for air conditioning and other chilled water applications.
It is interesting to know that current state-of-the-art AWG machines like the CWM1000 manufactured by Cirrus use ~ 336 kWh electrical energy to produce one cubic meter of water, working on the conventional vapor-compression type chiller. In contrast, the heat powered Wally-AHT of similar size, use only 198 kWh, some 40% lower, even though the liquid pump efficiencies are low (see table 2). This design also include a powerful fan for a compact machine design. Should the fan be totally omitted (or reduced to a very low-powered fan), the power consumption of the AWG would go down to only 18.6 kWh / m3 of AWG water produced. This configuration would be able to produce water from the air with a saving of ~ 94% off the conventional CWM1000 AWG machine, and, depending on the local cost of electricity, represent a real water cost lower than most municipal domestic water from conventional purification plants. Clearly this would undercut conventional desalination plant water cost with a huge margin....

Overall performance results for the mass-, heat-, and species balanced AHT of figure 1 are listed in table 2.

Replacing the gravitational force field needed by both the absorber and the distillation column (bubble reactor) described above, with a centrifugal force field, would have the following advantages and consequences:

- Physical dimensions of the H/E equipment depends directly on the rate of heat exchange achievable in the flow fields, and although this rate is high as a result of the direct contact nature of the vapor-liquid mixtures as shown in the volumetric H/E rates in table 2. Heat transfer rates in Helical Tubes, presented and published by Zhao et al, [13] in an International Journal - July 2020, read together with the published correlations of Shevchuk & Khalatov in 1996 in rotational channels suggest H/E rates of 2 - 3 times as high, due to both centrifugal (buoyancy) and Coriolis forces in rotational systems. This enhancement would need physical H/E channels, pressure vessels and containers, to be half the size of the gravitational equivalent machines, with obviously the corresponding large reduction in capital cost of the equipment.

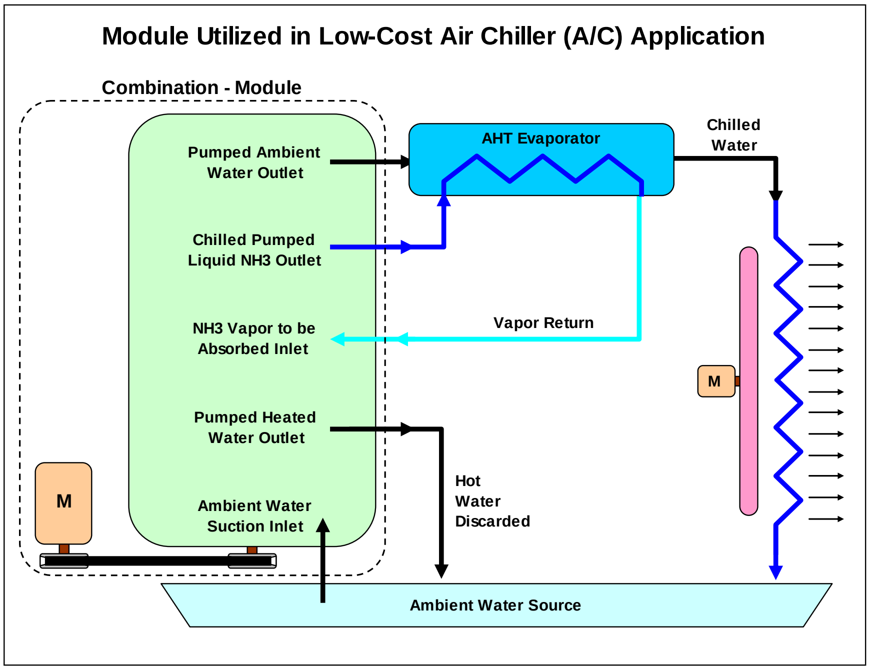
- Pumps required by the standard gravitational system generally have very low thermodynamic efficiencies, as shown in table 2. The NH3-Pump utilized in the pilot model is a sliding vane, magnetic coupled seal-less pump, but the isentropic efficiency is only 15%. Similarly, the Absorber Circ-Pump, of centrifugal design, but seal-less rotor construction render an efficiency of only 18%. These discreet separate pumps may easily be integrated into the rotational system by using the well-known pitot-pump principles, described in detail by Neilson, [12] in a symposium paper, presented in March 2018. Pitot Pumps are very simple to design and render isentropic efficiencies ~ 50% - 65%, ideally suited to low flow, high pressure applications. Operation curve of these type of pumps are generally very flat, with very little change in pump efficiency when flow is increased from 0% to 100%. Integrating these pumps (together with a CW-Pump and internal oil pump) also do away with the need for an expensive magnetic coupling, making the integrated combination smaller, much cheaper and driven by a single external electrical motor.

The fixed rotational speed would be designed to suit the physical installation and may be as high as 1000-1500 RPM on very small machines, while larger machines would see much lower rotational speeds eg. 100 - 300 RPM.

An integrated module sealing in a rotational (rolled up) absorber and distillation column with an integrated NH3-Pump, absorber Circ-Pump as well as a CW pump, combined with its own, internal oil pump feeding the bearings and seals would scale very easy from a few kW operation to as much as a few MW. The simplicity of a system utilizing this combination module can be seen in figure 4, and it is not difficult to see the huge advantages of sealing in all the complicated NH3-H2O process equipment.

Even system starting (activating the pseudo-isobaric temperature glide), becomes strait-forward, as it would be done by adding a start-up heating element in the external evaporator. Reactor pressure control would be done by removing NH3 from the reactor to an external NH3 Controller Tank to decrease the concentration, dropping the pressure in the reactor. Mass balance in the reactor would be achieved by pumping some liquid mixture from the absorber circ pump to or from an external mixture reservoir. In the evaporator, a temperature controller will regulate the mass flow of chilled water to keep a specific chilling water temperature (eg. 2°C) and evaporator pressure will be controlled by a vapor service backpressure regulator.

Figure 4



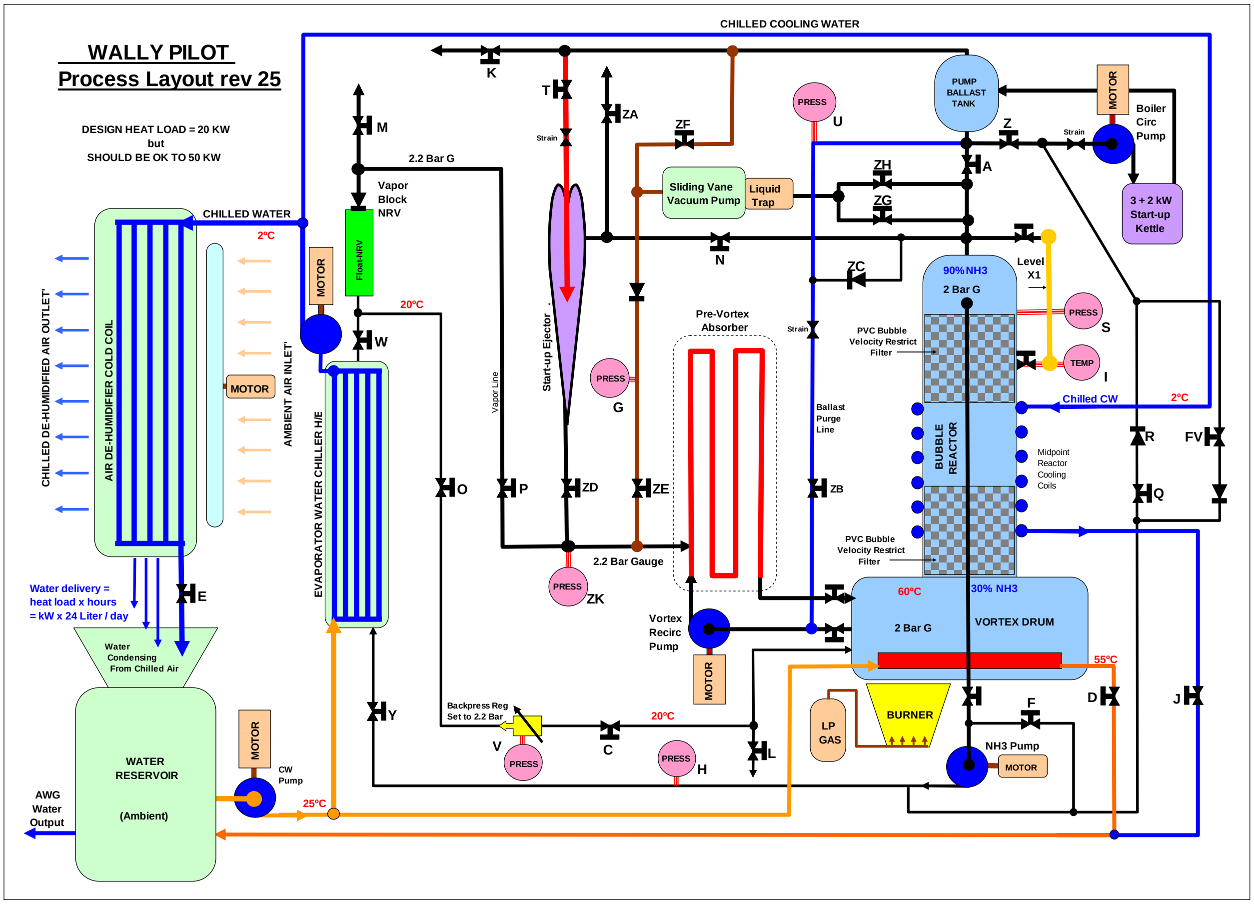
The complete AHT therefore is made up of one of these centrifugal reactor units, coupled with an external evaporator and two binary mixture tanks.

Modularizing the AHT design like this, have the added advantage of construction, NH3 filling and commissioning of the module in a factory environment, where a test bench with numerous testing gauges may be coupled to the normally sealed off test lines via flexible bundle of small-diameter PTFE tubing for commissioning purposes. Using the module on a client's site involve no NH3 work (if the evaporator is also coupled in the factory) and the final user or client does not even need to know what happens inside the module......

3.) Pilot plant Construction

The actual process layout of the pilot is sketched in figure 5 below, but went through several revisions as the development progressed. This revision 25 was the layout after a LP Gas Burner and a sliding vane vacuum pump have been added in to test the possible function of start-up gradient generator in the reactor, in parallel with the start-up ejector. Inside the bubble reactor two PVC granule filled bubble velocity restricting filters have also been added to slow down vapor bubble up flow to avoid re-mixing of the high concentration distillate accumulating at the reactor top. Also, a path through the flash valve FV have been provided to use liquid from the ballast tank to flash into the evaporator at the start of evaporator operation.

Figure 5



The bubble reactor was manufactured from a 8" Sched 10 SS pipe of ~ 2 meter length, fitted with an end cap welded on the top side. The open bottom was welded to a 12" Sched 10 SS End cap, where a 8" hole was cut into. A SS flange was welded to the end cap, so it can be bolted to another 12" SS end cap with a flange welded onto it. This bolted drum-like double end cap container we called the Vortex Drum and it has an internal volume of ~ 36.23 Liters. The vertical column bubble reactor has an internal volume of ~ 59.38 Liters. Inside the vortex drum, a cooling coil was inserted, consisting of 3m of 14mm OD SS tubing coiled in the centre and coupled to SS fittings welded into the vortex drum bottom through which cooling water is circulating. All the piping and tanks have a pressure rating of 10 Bar (G), with safety valve settings of 9.5 Bar (G).

Inside the vortex drum, a device we called a rotating bubble trap was positioned centrally to rotate around the central NH3 pump suction tube. The design of this rotating component was such that it used the kinetic energy in the recirculated liquid mixture to cause mixture rotation, forming a liquid vortex inside the drum to enhance turbulence for better vapor bubble absorption. The device also had a set of sieves with 1 mm^2 perforations to break up vapor bubbles into smaller ones.

The ballast tank, situated on top of the vertical bubble reactor, was manufactured from a 370mm piece of 8" SS Sched 10 Pipe, with an end cap welded on each end. It has an internal volume of ~ 20 Liters, although it is never completely filled with binary mixture. The main function of the ballast tank is to provide expansion volume when vapor bubbles displace the liquid in piping, the bubble reactor, evaporator and vortex drum.

The pre-vortex absorber was manufactured from two lengths of 780mm 1" SS pipe and a 3/4" length of 780mm SS pipe, combined in up-, and down flowing conduits, fitted with a SS Tee, where the circ pump outlet flow into the 1" tube via a 9mm diameter nozzle. The total internal volume of this pre-vortex absorber is ~ 1.138 Liters.

An evaporator was manufactured, using 60m of 16.05mm ID aluminum tube, coiled into a water drum of 300 Liters. This was welded to a second coil of 28m of 9.5mm ID aluminum tube. Around the final 10 meters of aluminum tube (at the binary mixture inlet side), a polyurethane pipe of 1" was pulled as a sleeve to contain water flow in close approximation of the aluminum tube to reflect a counter flow heat exchanger with binary mixture flowing inwards and water (being cooled) flowing outwards. The volume of binary mixture contained in the aluminum coil calculate to ~ 14.12 Liters.

The start-up ejector nozzle has a 1.5mm hole to create the vapor drive jet, drawing low pressure vapor from the bubble reactor top into the 6mm diameter and 60mm long ejector mixing tube, from where the vapor mass flows via a diffuser into the 1/2" SS pipeline connecting the pre-vortex absorber.

The kettle was manufactured by coiling ~ 10m of 19mm OD aluminum tubing inside a plastic bucket filled with water. Conventional kettle electrical heating elements (3 kW and a second element of 2 kW) are fitted inside the kettle to heat the water. Normal kettle thermostats prevent the water in the kettle from reaching 70°C.

With all the additional pipe work mostly 1/2" SS piping combined with high pressure plastic piping having a combined calculated volume of ~ 14.95 Liters, the overall internal binary mixture available spacing allow a volume of 100 Liters to be charged into the reactor, leaving some 10 Liters vapor expansion space in the reactor top, as well as 10 liters in the ballast tank. This require 50/50% mixture by mass of NH_3 and H_2O to deliver 82.7 kg of 50%NH_3 in aqua mixture. At 20°C ambient temperature, this mixture is 100 Liters.

Pumping requirements was met by the magnetically coupled liquid service vane pump as NH3-pump fitted to a 370 Watt electrical motor. It delivers ~ 230 L/hour liquid at 3 Bar, running 1450 RPM. The two circ pumps (boiler circ pump as well as the vortex recirc pump) of centrifugal type, both use Calpeda circulation pumps with 3 speed settings, delivering (setting 3) ~ 2000 L/hour liquid at 30 kPa differential pressure, while the CW-pump is of centrifugal design pumping ~ 1200 L/hour at 40 kPa fitted with a 370 Watt electrical motor.

All valves shown in figure 6 are 1/2" SS Ball valves, PTFE sealed, except the needle valves used for (manual) control purposes namely valve ZG and valve C. Pressure indicators are SS, liquid damped Wika indicators with 100mm face, calibrated to 0 - 10 Bar (G). Temperatures were measured using a handheld Fluke TiS40 Infrared imaging camera, focusing on the outer metal surface of the various piping, tank, and column material. A single liquid level indicator of the reactor top, X1, was made from fiber re-enforced high pressure see-through flexible tubing.

For easy charging/discharging the mixture, a special external NH3 mixing tank was constructed of 250mm OD SS pipe of 2.65m long with internal volume of ~ 130 Liters. 1/2" fittings, as well as a pressure gauge and an overpressure safety valve was fitted to this pre-mixing reservoir. For mixing the binary mixture, a specific mass of water was first introduced into the empty mixing tank, and then charged with anhydrous NH3, bubbling through the water via the bottom entry fitting. Filling rates was paced to accommodate the dissipation of the mixing heat, and also assisted by water washing the mixing tank outer shell to avoid pressure excursion too high for the tank pressure rating. After this mixture have cooled down, it was safe to charge the reactor with the prepared 50%NH3 in aqua solution mixture.

For quicker gradient generation, a LP gas burner have been added to heat the bottom of the vortex drum. A simple circular metal plate screen around the gas flame was added to focus the flame heat onto the bottom of the vortex drum. This gas flame delivered a few kilowatt of heat when initial start-up was active, allowing the more volatile NH3 to be "boiled off" to create the concentration gradient with the high %NH3 at the reactor top and the low concentration at the reactor bottom in the vortex drum.

The dual PVC bubble velocity restrictor filters installed in the reactor consisted of two circular PTFE discs of 12mm thickness, perforated with thousands of 2mm holes, with the 400mm spacing between them filled with PVC grains (small 2mm diam and ~ 2mm long PVC pellets). These filters proved very effective in restricting the high velocity of rising vapor bubbles against gravity, providing a longer vapor-liquid contact (and heat exchange) time in the distillation section of the bubble reactor.

Because ammonia is corrosive to copper, brass and many other metals, most of our pipe work was stainless steel. PTFE (thread tape) was used on threaded joints to seal the threading. We did use rubber hoses and aluminum tubing, however, the aluminum piping began to gradually corrode as it was submerged for almost the full 12 months of testing.

4.) Lessons learned via Experimentation

- Liquid pumping of saturated binary mixtures are very sensitive to suction vacuum, as it does not draw in liquid, but rather flash the volatile liquid into vapor, creating vapor lock in pumps. No suction head can therefore be tolerated when it is required to pump saturated liquid flows.

- Volume increase of binary mixtures related to bubble formation with heat exchange (H/E) processes may be very high, as much as 30% to 70% and process equipment need to be able to accommodate the drastic change in volume during operation, eg. an external ballast for mixture overflow, or large vapor space allowed with float level detection, or similar.

- Localized contained (encapsulated by liquid borders) binary mixture flows unable to quickly increase in volume due to containment restrictions cause pressure spikes, able to damage pipes and tanks. Heat exchange equipment design need to take this into consideration to be robust enough.

- The nature of Vapor-Liquid heat exchange in saturated systems was experienced as follows: Absorption cannot take place in a saturated mixture, however, even small turbulence create localized subcooling, allowing absorption.

- Even very little vapor absorption create a little heat and a lot of pressure, increasing the mixture subcooling and therefore facilitating massive further vapor absorption with a corresponding high pressure boost.

- These absorption-generated pressure pulses may be contained and converted to heat by cooling. Localized cooling by high turbulence liquid circulation (eg. brought about by external circulation pump) or external conductive heat removal by forced circulation cooling water.

- Large volume containers with vapor injection tend to increase mixture volume without creating pressure (and subcooling) and therefore the vapor is not readily absorbed, but vapor bubbles rise very quickly to accumulate at the column top. Very little heat exchange take place, and accumulated vapor at the column top may build up pressure slowly, if it is not removed. Some kind of vapor flow restrictor, or velocity breaker need to form part of distillation columns to maximize distillation and minimize pressure generation.

- Absorption and heat exchange taking place in counterflow reactors in a force field increase the shear of the vapor-liquid contact surfaces, breaking vapor bubbles into smaller bubbles, and increasing the heat exchange surface area. The higher counter flow streams also increase turbulence, again enhancing H/E. A high force field like centrifugal is therefore much more economical in enhanced vapor-liquid direct contact H/E. This will decrease the required volume of absorber for a specific heat load.

- Large affinity of NH3 vapor for water which is subcooled absorb the NH3 vapor extremely quickly, so energy balance dictate that vapor bubbles that contained NH3 vapor would be replaced with water vapor filling the bubbles first, then further H/E and heat removal by turbulent circulation of the liquid, may cause the water vapor filled bubbles to collapse so fast that pressure spikes result (cavitation), that may cause damage to tubing, piping and tanks.

- Saturated binary mixture column will undergo isobaric temperature gliding where hot mixture with low %NH3 concentration migrate downwards in a force field (gravity or centrifugal) and colder, high %NH3 concentration mixtures migrate upwards in the force field due to density differences. Isobaric temperature gliding result in mixture cooling effect with increased NH3 concentration (distillation) because of the process of endothermic concentration of NH3. This slow migrational counter flow process may be speeded up substantially by replacing the gravity force field with a centrifugal force field.

- When a binary mixture is subcooled, density variations are opposite to those of a saturated mixture, implying colder liquid density is greater than hot subcooled liquid, therefore cold subcooled liquid migrate downwards in a force field and when heated up, hot liquid migrate upwards, allowing convection currents similar to pure water. This is exactly opposite to the saturated binary mixture reaction.

- A starting device, used for the initial creation of the required temperature and NH3 concentration gradients may be: a vacuum pump or ejector, removing vapor from the reactor column top and adding this vapor into the hot absorber, must be sized for the correct H/E rate allowed by the absorber pressure limitations.

- Corrosivity of a NH3-H2O binary mixture need to be controlled and minimized by utilizing a suitable lubricant, soluble in NH3, to protect bearings and movable parts. Correct materials and even plastics need to be used in construction. PTFE is a very good, but expensive plastic to use, but vesconite is dissolved by this binary mixture and cannot be used at all. PVC is also quite useful, but limited to low temperatures only. PVC becomes soft and unusable at around 70 - 80°C.

- Materials and specifications for components should consider the rate of H/E to accommodate the pressure spikes. Care should also be taken in the design, as cavitation may occur in certain processes.

- Rotating shafts protruding through stationary casings, tanks or pipes need to be either totally avoided (using Mag-drive technology) or especially tight-sealed to avoid NH3 contamination of the environment.

5.) Operation and Performance

The major disadvantage of ammonia as medium to work with, is its toxicity. Even if mixed with water, health hazards depend on the type of exposure. This can range from temporary discomfort to irreversible serious damage. Working with and handling of ammonia is to be done by trained and knowledgeable personnel only. We used all the relevant personal protective equipment, ranging from safety goggles, long rubber gloves, canister respirator masks and flame retardant acid resistant overalls. We also prioritized proper working space ventilation to ensure our safety while experimenting with the pilot installation.

To guide the technical staff working frequently with the pilot model, procedures were provided defining safe working with NH3 and NH3-H2O mixtures. These procedures indicated step by step how the correct binary mixture should be prepared in the pre-mixing tank and, after cooling down, charged into the reactor. Other procedures detailed how a smaller amount of binary mixture should be prepared and added to the reactor to fill it to the correct level, as well as addition of NH3 for changing the concentration of the charge contained in the reactor.

Procedures for operating the pilot for mixing (purging) the binary contents through all the piping, evaporator, ballast tank and kettle as well as the bubble reactor were drawn up as checklists, step by step instructions of which valve to open, which pump to start and when to take a pressure or temperature reading etc. Also for the start-up tests the procedure was defined in a checklist, making it easy to evaluate performance and make small changes to the procedure (and process layout) for testing a different process area etc. Every new procedure used a checklist of different revision to distinguish between different procedures. An example checklist is included in this report as Appendix A.

The Appendix A is only one example test done in the factory in Cape Town, but over the past year, a great number of tests were conducted on the pilot plant, some of which lead to changes and enhancements in the process and process layout of the pilot plant. A few of these may be listed as follows:

- Initial frequent NH3-pump vapor lock conditions led us to introduce the ballast tank and reactor level control, pumping excess liquid mixture into the ballast tank when vapor in the reactor changed the mixture density and hence, volume.

- During the first phase of the testing program, some components with moving parts were not lubricated, and as a result it jammed and not only did it affect the flow of the mixture, but the establishment of the temperature concentration gradient as well.

- In the AHT system, cooling is achieved by establishing a temperature concentration gradient in the bubble reactor. This is done by separating the two fluids, migrating the highly concentrated low temperature ammonia to the top and weak, low concentration high temperature solution to the reactor bottom. Although this was the most crucial part of the test, this proved to be the most difficult due to a number of factors, i.e.: the NH3-H2O concentration, reactor layout design difficulties and failure of components.

- The original turbulence enhancement by the internal rotational bubble trap to force vapor absorption in the vortex drum proved in our tests to be insufficient, as increasing heat load kept on increasing the reactor pressure and not enough temperature rising in the vortex drum for gradient formation. As one of our technicians commented "I believe heat reduced the ammonia absorption capacity of water. If the mixture was not saturated, the ammonia vapor from the evaporator should have been readily absorbed by the weaker solution in the vortex and during that process heat would have been liberated and cooling, instead, was required to take the heat away. In our absorber, we circulate mixture from the vortex where heat is added.", emphasizing the difficulty of vapor absorption into a saturated binary mixture. As 90% of the required heat load of absorption need to happen in the absorber, we had to add a circulation pump, driving a pre-vortex absorber external to the drum, to guarantee that 90% of vapor entering will be absorbed in the absorber and generate heat in the vortex drum instead of bubbling through, creating pressure in the reactor. Test results subsequently proved this is now the case.

- On various occasions, we tested with the NH3 concentration below or above design point because of different reasons, for example, loss of ammonia during charging, removing or adding, servicing of parts and adjusting mixture levels. After the level adjustment and running a number of tests, we discovered that the mixture NH3 concentration had deviated from design point. This created a real problem.

- Some of our tests pointed it out that vapor absorption heating would drastically increase system pressure, as a higher concentration saturated liquid (due to absorption) is subjected to the higher temperature, the higher saturation pressure would be the result. This can be countered in two ways, namely firstly, sub-cooling the saturated mixture prior to absorption heating. This allow absorption heating to increase the temperature back to saturation level, without affecting the pressure. Secondly, using cooling water to remove excess heat from the binary mixture while it absorb vapor, will also limit the pressure increases. Tests after our installation of cooling water coils inside the vortex drum to affect subcooling on the mixture proved this method of pressure control to be very effective.

- With the process requirements for 90% absorption heating to take place in the absorber, our tests proved that the remaining 10% heat load supposed to be used as distillation energy source for the reactor top, was insufficient, as the vapor bubbles opposing the gravity pull, accelerated the upwards flowing stream to a velocity where too much vapor reached the reactor top, creating system pressure instead of powering the distillation process. As one of our technicians commented "I think heat could not separate the two liquids in the mixture (NH3-H2O) or migrate ammonia to the top and still remain in liquid form. The ammonia instead vaporized and rose to the top of the reactor which I believe is the reason why we were getting high temperatures and pressure at the top of the reactor." This was remedied by adding the PVC Granules Vapor bubble Velocity Restrictor filters into the reactor top, effectively decreasing the vapor bubble upwards migration velocity. Tests after this addition proved the distillation process now works very well and large gradients are possible to set up in the reactor with little effort. The isobaric temperature glide effect is now easy to replicate.

- Several starting mechanisms were tested and proved useful for the initial gradient creation required before the AHT actually create a chilled and heated output from the energy input. Initial tests using an ejector highlighted the bad binary mixture circulation as vapor generator of the ballast, forcing us to include a boiler circ pump to circulate mixture through the kettle-ballast combination. This proved better vapor generation for powering the ejector, which in turn, proved the effect of heat generated by vapor absorption, gradually increasing the vortex drum bottom temperature.

- Another starting device tested was the sliding vane vacuum pump, also proving the vortex drum bottom heating by vapor absorption. The vacuum pump tested had the added advantage of not requiring external (kettle) heat for operation. Both the vacuum pump and the ejector had the drawback, however, of introducing heat into the absorber, but do not allow subcooling, as the time when these starting devices are needed, the absorber and cooling water are nearly the same temperature. Both starting devices therefore tested reasonable, but the reactor pressure could not be controlled, due to a lack of cooling. This was addressed by the LP gas heater.

- The LP gas heater was introduced to add heat to the vortex drum so as to generate a NH3 gradient with the vortex drum at an elevated temperature to enable the use of cooling water to create subcooling for pressure control. Further tests have proven that after a gradient have been established with the absorber at elevated temperature, cooling water can control the reactor pressure, while any of the other two starting devices, ejector or vacuum pump, is effective in growing the gradients to design point values.

- Start-up tests done for evaluating the operation of the evaporator, proved that in principle, the evaporator works, but not so well for starting conditions. During normal operation at design point, high concentration NH3 liquid binary mix at a temperature below 0°C enter the evaporator, where it absorb heat from the water circuit, causing the cold liquid binary mix to flash to vapor. Every gram of liquid flashed to vapor, however, is about 100% NH3 meaning that when NH3 flash off, the remaining liquid have a lower concentration NH3, with a corresponding higher saturation temperature. This higher flash temperature make the difference between the water circuit and the binary mixture smaller, with less drive for heat transfer. This temperature gliding at constant evaporator pressure start at the binary liquid inlet temperature below 0°C and glide up to close to the ambient at about 20°C, giving a fair span for driving heat exchange. During start-up conditions, however, the binary liquid entering the evaporator is only 2 or 3 degrees below ambient, and with the temperature glide taking it to ambient having so small a span, would produce a very small amount of vapor, totally insufficient to reach the vapor mass flow threshold to grow the gradients in the reactor. To overcome this obstacle, the evaporator need to be re-designed with precision, also introducing the starting device in the evaporator so a large mass of vapor may be produced by the starting device inside the evaporator well above the mentioned threshold to grow the gradients in the reactor to reach design point prior to putting the evaporator in use for extracting heat from the ambient water circuit.

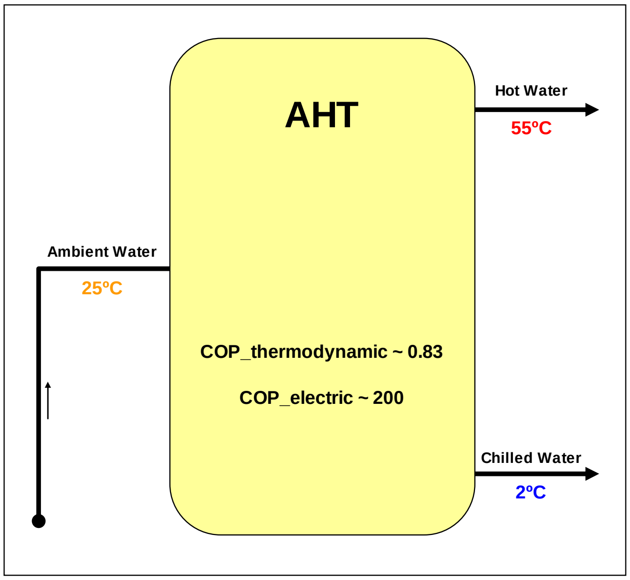
As our testing procedures spread over the past 12 months have sufficiently enhanced and proven all process aspects mentioned in the theory section of this document, even to the extend of dropping the evaporator temperature below dew point and so producing AWG water, we decided it would be more cost-effective for Cirrus, to leave the required evaporator re-design for implementation in the development of the prototype for demo purposes and production template, utilizing all our joint experience and proven solutions tested on the pilot over the past 12 months. Elongating the current pilot development project further just seem as a waste of money. Evaporator technology is, after all, a well known and fully commercialized technology and do not pose any risk on future Wally-AHT machines.

Our development project for demonstrating the generation of water from the air (AWG) was concluded early December 2020 with the first water produced.

6.) Discussion and Future Models / Pilots / Prototypes

What have we actually really achieved? We demonstrated an absorption heat transformer (AHT), using NH3-H2O as zeotropic binary operating media, able to be used as heat pump, to extract heat energy at ambient temperature from a water source exposed to the environment, to produce both chilled water at 2°C, and hot water at 55°C, utilizing the minimum electrical energy. This AHT as chiller, when compared to the conventional vapor compression (VC) heat pump, only need ~ 6% of the electricity used by the VC chiller to deliver the same output. The balance of energy needed by the AHT to power the process is extracted from the ambient water. It is really (waste-) heat powered.

Figure 6

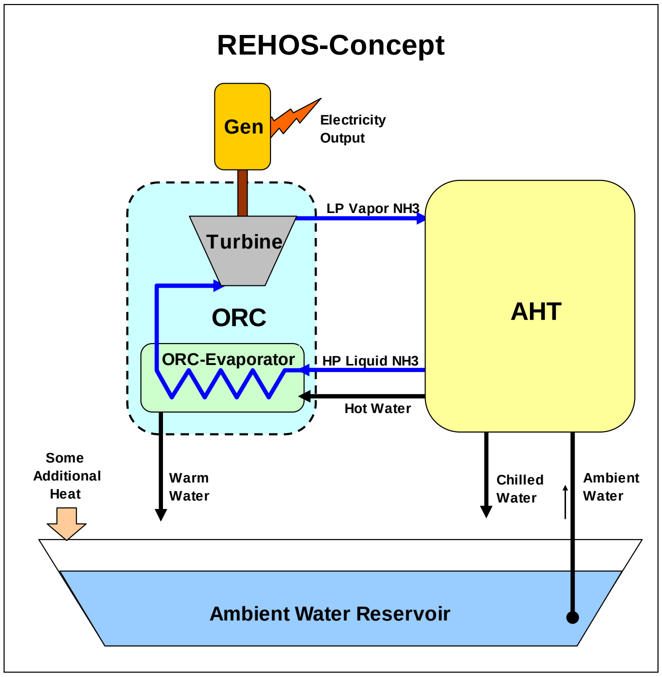


The products available from the AHT may include the use of the chilled water to drive an AWG, producing water from humid air. It may also form the base of a refrigerator, chiller for air conditioning unit. This, however, is only making use of half the AHT potential, as the hot water is discarded! It would just make sense to find a use for the hot water, in addition to the utilization of the chilling water we used for AWG service to produce water from the air.

Obviously the hot water may be utilized economically if we store it in a reservoir and use it for household hot water, or building space heating, or heating our indoor swimming pool. The hot water produced may of course also be used for generating power, however, with the temperature so low, (only 55°C - 25°C => temperature differential of only 30°C), the efficiency of a standard state-of-the-art organic rankine cycle (ORC), operating between these two temperatures would barely reach 5%.

The AHT we tested, however, make use of a bubble reactor internally. This may be seen as a sink for low pressure, low temperature vapor, as the latent heat as well as the heat of solution of NH3 vapor is utilized in an absorption process in the AHT, used for hot water generation. The bubble reactor top also make high concentration, cold NH3 in aqua available in liquid form, creating an ideal environment for an ORC. Unlike the conventional ORC that discard all the latent heat in the turbine exhaust (95% of the ORC input heat), coupling an ORC to the bubble reactor involve the regenerative recovery of all that 95% rejection heat. It is therefore not surprising that the thermodynamic cycle formed by this ORC regenerative coupling to the AHT we call the REHOS cycle, render extremely high heat to power conversion efficiencies, in very sharp contrast to the conventional 5% mentioned above! The patented REHOS thermodynamic cycle, use the tested AHT as input heat pump to suck heat energy from the environment. The cycle also use an organic rankine cycle (ORC) to utilize the recovered heat and convert it into electricity. A simple diagram like figure 7 demonstrate the simplicity of the REHOS cycle, once you understand the tested AHT principles.

Figure 7

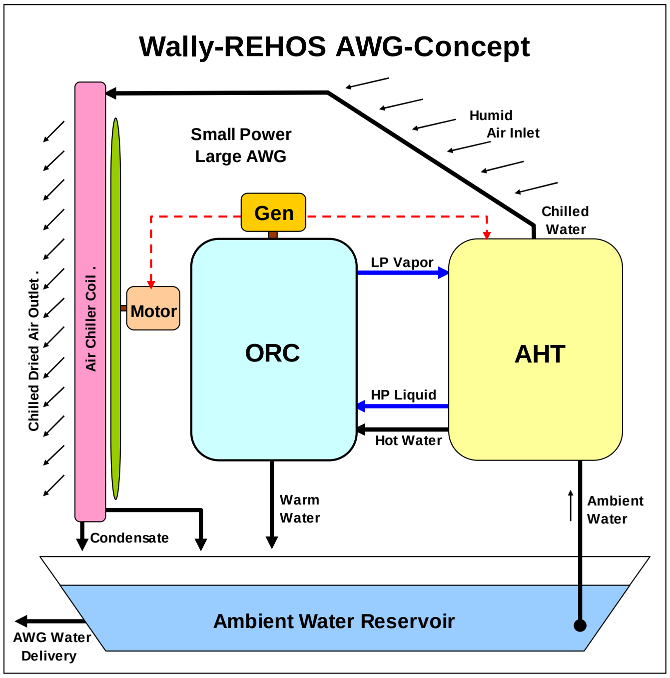


The AHT use NH3 internally, and use the NH3-pump to add pressure to the high concentration NH3 liquid at the bubble reactor top. In the REHOS cycle, that same high concentration NH3 liquid is routed through an ORC evaporator, heated by the hot water outlet of the AHT. The high pressure vapor so formed, is expanded in a power expander, or turbine, to develop electrical power. The turbine exhaust, consisting of saturated, low pressure NH3 vapor, is routed back to the AHT, where it is added to the vapor generated in the AHT by the evaporator. The latent energy in the exhaust vapor is therefore regeneratively recovered, and used in parallel to the AHT evaporator vapor.

Much more information regarding the REHOS cycle was disclosed by J. Enslin [11] in a paper compiled in 2018, as well as many other publications by the same author.
The **Wally-AHT AWG** development has shown that even though it may cause a saving of 40% on the conventional AWG machines, it still use some (very little) costly electricity. By utilizing a very simple REHOS cycle, however, this power needed for liquid pumping inside the AHT, as well as for driving the fan, and operating some controls, may be provided by the cycle itself. In this case we would call it a **Wally-REHOS AWG** machine as sketched in figure 8. Note that the purpose of this machine is to generate water from the air (AWG), without the need for external electricity. The power requirement is very small, and therefore a very simple liquid ring-, scroll-, or other positive displacement expander coupled to a small (eg. automotive) generator, would work perfectly to generate the few watts of electricity required. The standard AHT internal NH3 pump is sufficient to also provide a little pressure for ORC operation. The

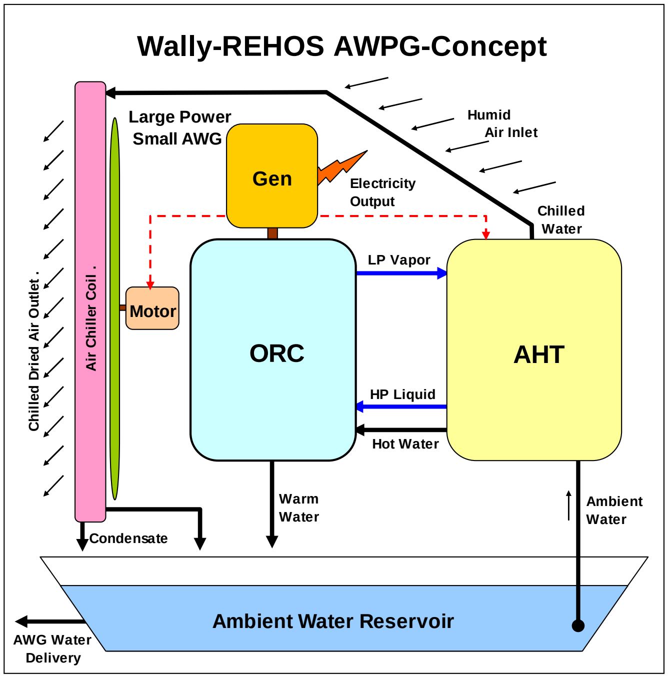
power generation efficiency is not important, as the **sole purpose of the Wally-REHOS AWG machine would remain to generate AWG water without the use of any electricity**....The real economy of this AWG machine therefore would depend on the capital repayment only. In this configuration at least some of the hot water generated by the AHT is utilized and not wasted.

Figure 8



Should power generation become the main output of the machine, the focus change a little. If you need a Wally-REHOS power generator of 50 kWe, the AHT would be designed with a much higher output temperature (eg. 80°C to 120°C) to suit the available turbine. Also, an additional NH3 pump (ORC-Pump) would be implemented, as the turbine would be better suited to a higher pressure like 15 - 25 Bar, and as the most expensive part in the machine would be the turbine, the complete design would be adapted to better suit the turbine, with it's electrical breakers, control etc.

Figure 9



We would call this machine a **Wally-REHOS Free-Power AWPG machine**, as sketched in figure 9. It would deliver 50 kWe electrical power, while a large volume of AWG water would be delivered in a 24 hour period. The water is then only a by-product, as the main revenue earning output would be electricity, literally sucked out of the air! In this type of REHOS technology, the extremely high efficiency of heat to power conversion really play a major part in defining the economy of the resulting machine.....

In the Wally-REHOS Free-Power AWPG configuration, maximum use of all the resources made available by the AHT is utilized, as losses of both chilled water (cold loss) as well as hot water (hot losses) are limited to the absolute minimum.

Now that the **Wally-AHT pilot model** was tested, It is strongly recommended to initiate a follow-up development project with the goal to design, construct and test a **Wally-REHOS AWG model as prototype**, utilizing the smaller, more compact centrifugal principles, by the same development team.

7.) Conclusions

Experimentation and testing using the pilot plant have effectively proven all the process parameters and AWG operation as detailed in the theory section 2 of this document.

The AHT developed and tested in the pilot is unique in that it utilize isobaric temperature gliding principles in the bubble reactor, forming the distillation column for generating high concentration NH3 liquid for use in the evaporator. The combined absorber-distillation column, also form the ideal latent heat recovery device, able to absorb energy in the form of low pressure and temperature vapor, and pumping this recovered heat to higher temperature, "upgrading" it in the process.

The proven Wally-AHT combination as sketched in figure 3, need very little electricity, and then only to power the liquid pumps. Compared to the classical AWG units making use of the conventional vapor compression (VC) type chiller, the Wally-AHT is clearly in a different class altogether. It literally sucks heat out of the ambient air and use this energy to power the chiller.

Should the chilled air, after water condensation, be used in an air-air heat exchanger to pre-cool the incoming ambient air to a temperature close to the dew point temperature, energy utilization would be maximized towards AWG water production, allowing water production also in near-desert environments with high ambient temperatures but very low humidity (as low as 25% - 35%).

It would make practical sense to construct a Wally-AHT prototype using a centrifugal reactor as sketched in figure 4. It combines all the solutions proven in the pilot into a single rotational configuration driven by a single external electrical motor. It combines the absorber, distillation reactor, NH3-pump, absorber circ pump as well as a water pump and hot water pump into one. This also allow very simple add-on devices to make use of the energy in the discarded warm water.

As the proven AHT not only deliver chilled water from ambient input, but also warm water, currently discarded in the pilot Wally-AHT configuration as tested, it would be only logical to recover some of the warm water energy in a simple ORC for the simultaneous production of a small amount of electricity, just enough to power the liquid pumps and fan used. This will change the Wally-AHT system into the totally **external electricity-free Wally-REHOS AWG unit** as sketched in figure 8.

8.) References

1. Development of Thermo-physical Properties of Aqua-Ammonia for Kalina Cycle systems, by N. Shankar Ganesh and T. Srinivas published in the Int Journal Material and Product Technology Vol 55, Nos. 1/2/3, 2017.

2. Void fraction, bubble size and interfacial area measurements in co-current downflow bubble column reactor with micro bubble dispersion, by Freddy Hernandez-Alvaro, Dinesh V. Kalaga, Damon Turney, Sanjoy Banerjee, Jyeshtharasj B. Joshi, Masahiro Kawaji published in Chemical Engineering Science 168, (2017) 403-413 made available by Elsevier.

3. Vortex Centrifugal Bubbling Reactor, by A.O. Kuzmin, M.Kh. Pravdina, A.I. Yavorsky, N.I. Yavorsky, V.N. Parmon published in Chemical Engineering Journal, 107 (2005) 55-62 made available by Elsevier.

4. Analysis of Absorber Operations for the 5 kW Ammonia-Water Combined Cycle, by Serisha Devi Govindaraju as Master of Science Thesis at the University of Florida, 2005.

5. Performance of Different Experimental Absorber Designs in Absorption Heat Pump Cycle Technologies:- Review by Jonathan Ibarra-Bahena and Rosenberg J. Romero published in the Open Access Journal, Energies 2014, 7, 751-766 in February 2014.

6. Ammonia-Water desorption in flooded columns, by James Hollis Golden for his Master's Thesis at the Georgia Institute of Technology in August 2012.

7. Multiscale multiphase phenomena in bubble column reactors: A review by Shuli Shu, David Vidal, Francois Bertrand and Jamal Chaouki, published in the journal Renewable Energy of 5 April 2019.

8. Development of a Heat Transfer Coefficient Model via Experimental Validation, by Adel A. Al-Hemiri and Nada Sadoon Ahmedzeki in the journal Chemical Product and Process Modeling, article 35 in Volume 3, Issue 1, 2008.

9. Review: Bubble column reactors, by Nigar Kantarci, Fahir Borak and Kutlu O. Ulgen published in the journal Process Biochemistry 40 (2005) 2263-2283.

10. Prediction of the Heat Transfer Coefficient in a Bubble Column Using an Artificial Neural Network, by Adel A. Al-Hemiri and Nada S. Ahmedzeki published in the International Journal of Chemical Reactor Engineering, article A72, Volume 6, 2008.

11. The document "Key Principles of the REHOS Cycle" was written by Johan Enslin in November 2018 and published in the Open Access Bioenergetics Journal at https://www.omicsonline.org/open-access/key-principles-of-the-rehos-cycle-

2167-7662-19-154.pdf in January 2019, as well as on my own website http://www.heatrecovery.co.za/.cm4all/iproc.php/Key Principles of the REHOS Cycle.pdf

12. A Study on the Operation of Pitot Tube Pumps, by Bryce Neilson, P.E. Presented at Asia Turbomachinery & Pump Symposium, March 2018.

13. Friction Factor and Nusselt number correlations for Forced Convection in Helical Tubes, by H. Zhao, X. Li, Y. Wu, X. Wu, published in International Journal of Heat and Mass Transfer, - July 2020.

14. A Review of Heat Transfer and Hydrodynamics in Straight Channels Rotating about a Parallel or Inclined Axis, by I.V. Shevchuk and A.A. Khalatov, published in the Russian Journal, High Temperature, Vol 34 No. 3, 1996 pp. 455-467 and translated from the original Russian.

Appendix A

As a typical example start-up procedure, the checklist rev 54 used on Friday 4 December 2020, returned as results log is attached hereto. It demonstrate the detail of logged process variables, instructions and time so evaluation is made possible. It also log the technicians involved in taking the measurements and operating the valves and pumps.

In this short example evaluation that follows, reference is made frequently to the specific line number, listed on the left-hand side in a square box in the checklist and refered to as eg. (Ref 24), pointing to the command to switch on the vacuum pump and mark the corresponding block when the action has been performed.

Analysis:

In this example report, we notice the LP gas burner being switched on at 09:13 (Ref 10) and the vortex drum bottom temperature gradually increasing in temperature from 20.2°C @ 09:17 to 48.5°C @ 10:22, representing a temperature rising rate of 21.8°C/hour. With the gas burner still on, the vacuum pump is switched on (Ref 24) and the heating phase continued until the vortex drum bottom temperature reached 55.5°C @ 10:51. After this gas burner heating phase, the reactor top pressure (pressure S) has increased from the original 1.8 Bar (G) @ 09:09 to 4.0 Bar (G) and the heating phase is therefore followed by a pressure reduction phase when the gas burner is switched off.

Pressure reduction commence at (Ref 31) with the opening of cooling valve D some fraction (3 notches ~ 15% opening) to cool the vortex drum bottom, dropping the reactor pressure S from 4 Bar @ 11:00 down to 2.7 Bar @ 12:04 (1.22 Bar/hour).

The gas heating and pressure reduction phases, utilizing the vacuum pump for short periods is seen to create a NH3 concentration of 60.06% in the reactor top, while the vortex drum bottom concentration went down to 40.8%, a concentration gradient of about 20% achieved @ 12:04, just prior to the transition to AWG (Ref 40).

During AWG operation (Ref 40 - Ref 66) what becomes glaringly clear, is that each time the ballast purge valve is not opened, but liquid level in the reactor adjustments is necessary by opening valve Q, high concentration mixture is pumped into the ballast tank. This signifies that vapor is produced by flashing in the evaporator, displacing liquid, (visible in the rising reactor level indicated by the level indicator X1) that end up being pumped into the ballast tank. This happen at (Ref 46, 48, 51, 54, 57, 60, 63, and 66), basically every 5 minutes from 12:06 - 14:26 (140 minutes). The vapor generated by the evaporator did only partially reach the absorber, though, as the heating effect of vapor being absorbed was minimal and failed to materially increase the vortex bottom temperature as expected. Several subsequent tests run after this example has proven that although the evaporator do generate vapor, the heat load is extremely low, mainly due to the primitive evaporator construction. As one of our technicians commented "I think we pumped a saturated mixture into the evaporator. This therefore reduced the rate at which it vaporized, as a result the bubbles were not sufficient to establish a temperature-concentration gradient in the reactor." We therefore determined the correct design point heat load in the evaporator would only be attainable if the evaporator is re-designed with higher precision implementation of eg. a shell and tube type heat exchanger with higher velocity countercurrent streams. This new evaporator design is likely to be implemented on a prototype Wally-AHT unit to be constructed shortly.

Start-Up with Vac Pump & Gas Burner Checklist _rev 54 (for Process Layout rev 24)

1 Set Starting Position by ticking the boxes

NH3 Pump Off ✓
Boiler Circ Pump Off ✓
CW Pump Off ✓
Vortex Recirc Pump Off ✓
Kettle both elements Off ✓
Vacuum Pump Off ✓
Gas Burner Off ✓

Responsible Person(s) JIMMY/TROY/MPALA

Should you want to add comments, please use Reference number so I can easily see where the comment refer to.

Vacuum Pump Oil Level Checked & topped up ✓ If required...

Valves Position

A Closed ✓
C Closed ✓
D Closed ✓
E Closed ✓
F Closed ✓
J Closed ✓
K Closed ✓
L Closed ✓

M Closed ✓
N Closed ✓
O Closed ✓
P Closed ✓
Q Closed ✓
T Closed ✓
W Closed ✓
Y Closed ✓

Z Closed ✓
ZA Closed ✓
ZB Closed ✓
ZD Closed ✓
ZE Closed ✓
ZF Closed ✓
ZG Closed ✓

Wally Pilot Start-Up & Transition to AWG Test

04/12/2020 Date

2 Start Reactor Water Cooling and Dump Ballast Mix into reactor

Valve D Open	✓	Vortex Drum Cooling Start	
Valve J Open	✓	Bubble Reactor top Cooling on.	
Both CW Pumps On		Initiate CW circulation	CW Pumps On Time 09:04

3 If Level X1 < Operational => Open Valve A Untill X1 = 60mm above zero **Adjust Reactor Level**

Should the level stay too low, Abort and charge with more binary mixture using the charging procedure.

If Level X1 = Operational (60mm above zero) carry on at ref 5

	Valve ZB Closed	✓	Purge blocked	
	Valve Z Open	✓	Boiler recirculation enabled	
	Valve A Closed	✓	Ballast liquid level preserved	
	Valve Q Open	✓	to fill Ballast to 15% (3liter) while pump is on.	
	Valve W Open	✓	Preparing for Evap liquid circulation	
	Valve O Open	✓	Preparing for Evap liquid circulation	
4	NH3 Pump On	✓	Ready for filling Ballast	NH3 Pump On Time 09.07
	Valve F Adjusted	✓	Adjust F to 5 Bar @ indicator H	Guarantee high enough pump press

5 Watch Level X1 drop to Operational (60mm above zero) as liquid pumped into ballast **Adjust Reactor Level**

NH3 Pump Off	✓	Reactor Level correct and Ballast filled with ~ 3 Litres binary mix, ready to start.
Valve Q Closed	✓	
Valve ZB Closed	✓	Purge blocked

6 Reactor Starting Sequence with Correct Reactor Level X1

	Pressure S Value	1,8	Bar Gauge	Measuring Time 09:09
	Pressure ZK Value	1,5	Bar Gauge	
	Pressure V Value	1,3	Bar Gauge	
	Pressure U Value	2,3	Bar Gauge	
7	Ballast Temperature	20,9	Celsius	
	Reactor Top Temperature	17,2	Celsius	
	Vortex Drum Flange Temperature	19,2	Celsius	
	Vortex Drum Bottom Temperature	18,3	Celsius	Correct Mixture Press for Vortex Drum Bottom Temp 1,46 Bar Gauge (from Table)
	Evaporator Outlet Water Temperature	20,9	Celsius	
	Water Reservoir (CW Pump Inlet) Temp	21,5	Celsius	
8	Valve ZE Open	✓	Prepare for using Vacuum Pump	
	Vortex Circ Pump On	✓	Speed Setting on 3 (Nozzle use pump power to drop dynamic Input Pressure of pre-vortex absorber)	
	Valve Z Open	✓	Allow circulation through kettle	
	Boiler Circ Pump On	✓	Speed Setting on 1 (Allow slow recirculation through kettle)	
9	NH3 Pump On	✓	Adjust F to 5 Bar @ indicator H	On Time 09:12 Autopurge start
	Valve ZB 15% Open	✓	(6 Notches) Allow purge to enable reactor Level Control	
	CW Valve D Closed	✓	Vortex Drum prepared for Gas Burner Heating	

(Estimated Burner Run Time ~ 90 min)

10	Gas Burner On	✓	Vortex Drum Heating Start	Gas Flame On Time 09:13

Adjust Q if Level X1 <> 60mm

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

11

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☑

Log measurements <u>every 5 minutes</u> Press S > 6 Bar => Burner Off for 5 minutes

12			13				
Pressure S Value	1,8	Bar Gauge	Pressure S Value	1,9	Bar Gauge	Ambient Temp	23
Pressure ZK Value	1,5	Bar Gauge	Pressure ZK Value	1,5	Bar Gauge	Ambient Humidity	57
Pressure U Value	2,5	Bar Gauge	Pressure U Value	2,5	Bar Gauge		
Ballast Drum Temperature	22	Celsius	Ballast Drum Temperature	22,8	Celsius		
Reactor Top Temperature	17,3	Celsius	Reactor Top Temperature	17,5	Celsius		
Vortex Drum Flange Temperature	19,3	Celsius	Vortex Drum Flange Temperature	22,7			
Vortex Drum Bottom Temperature	20,2	Celsius	Vortex Drum Bottom Temperature	27,3	Celsius	Abs Ch1 Temp	28,1
Evaporator Outlet Temperature	20,9	Celsius	Evaporator Outlet Temperature	21,2	Celsius	Abs Ch2 Temp	22,6
Water Reservoir (CW Pump Inlet) Temp	21,4	Celsius	Water Reservoir (CW Pump Inlet) Temp	21,7	Celsius	Abs Ch3 Temp	20,3
Measurements Time	09:17		Measurements Time	09:22			

<u>Adjust Q if Level X1 <> 60mm</u>

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☑

<u>If Vortex Drum Bottom Temperature > 45C Jump to Reference 24</u>

Log measurements <u>every 5 minutes</u> Press S > 6 Bar => Burner Off for 5 minutes

14			15				
Pressure S Value	2	Bar Gauge	Pressure S Value	2,1	Bar Gauge		
Pressure ZK Value	1,6	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge		
Pressure U Value	2,5	Bar Gauge	Pressure U Value	2,5	Bar Gauge		
Ballast Drum Temperature	22,4	Celsius	Ballast Drum Temperature	22,8	Celsius		
Reactor Top Temperature	17,8	Celsius	Reactor Top Temperature	17,9	Celsius		
Vortex Drum Flange Temperature	29	Celsius	Vortex Drum Flange Temperature	32,6			
Vortex Drum Bottom Temperature	31,9	Celsius	Vortex Drum Bottom Temperature	33,6	Celsius	Abs Ch1 Temp	25,1
Evaporator Outlet Temperature	20,3	Celsius	Evaporator Outlet Temperature	20,8	Celsius	Abs Ch2 Temp	25,7
Water Reservoir (CW Pump Inlet) Temp	22	Celsius	Water Reservoir (CW Pump Inlet) Temp	20	Celsius	Abs Ch3 Temp	21,4
Measurements Time	09:27		Measurements Time	09:37			

<u>Adjust Q if Level X1 <> 60mm</u>

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☑

<u>If Vortex Drum Bottom Temperature > 45C Jump to Reference 24</u>

Log measurements <u>every 5 minutes</u> Press S > 6 Bar => Burner Off for 5 minutes

16			17				
Pressure S Value	2,3	Bar Gauge	Pressure S Value	2,4	Bar Gauge	Ambient Temp	24,1
Pressure ZK Value	2	Bar Gauge	Pressure ZK Value	2	Bar Gauge	Ambient Humidity	55
Pressure U Value	2,6	Bar Gauge	Pressure U Value	2,6	Bar Gauge		
Ballast Drum Temperature	24,9	Celsius	Ballast Drum Temperature	23,8	Celsius		
Reactor Top Temperature	18	Celsius	Reactor Top Temperature	22,2	Celsius		
Vortex Drum Flange Temperature	359	Celsius	Vortex Drum Flange Temperature	35,9			
Vortex Drum Bottom Temperature	36,4	Celsius	Vortex Drum Bottom Temperature	39,8	Celsius	Abs Ch1 Temp	24,5
Evaporator Outlet Temperature	20,9	Celsius	Evaporator Outlet Temperature	21,8	Celsius	Abs Ch2 Temp	25,5
Water Reservoir (CW Pump Inlet) Temp	20,9	Celsius	Water Reservoir (CW Pump Inlet) Temp	21,8	Celsius	Abs Ch3 Temp	25,9
Measurements Time	09:45		Measurements Time	09:53			

<u>Adjust Q if Level X1 <> 60mm</u>

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☑

<u>If Vortex Drum Bottom Temperature > 45C Jump to Reference 24</u>

Log measurements <u>every 5 minutes</u> Press S > 6 Bar => Burner Off for 5 minutes

18			19				
Pressure S Value	2,5	Bar Gauge	Pressure S Value	2,7	Bar Gauge		
Pressure ZK Value	2,1	Bar Gauge	Pressure ZK Value	2,4	Bar Gauge		
Pressure G Value	2	Bar Gauge	Pressure G Value	2	Bar Gauge		
Pressure U Value	2,8	Bar Gauge	Pressure U Value	3	Bar Gauge		
Ballast Drum Temperature	24,2	Celsius	Ballast Drum Temperature	24,9	Celsius		
Reactor Top Temperature	26	Celsius	Reactor Top Temperature	27	Celsius		
Vortex Drum Flange Temperature	40	Celsius	Vortex Drum Flange Temperature	43,2			
Vortex Drum Bottom Temperature	42,6	Celsius	Vortex Drum Bottom Temperature	44,6	Celsius	Abs Ch1 Temp	26
Evaporator Outlet Temperature	21,9	Celsius	Evaporator Outlet Temperature	21,6	Celsius	Abs Ch2 Temp	26,5
Water Reservoir (CW Pump Inlet) Temp	22,8	Celsius	Water Reservoir (CW Pump Inlet) Temp	23	Celsius	Abs Ch3 Temp	23,3
Measurements Time	10:03		Measurements Time	10:11			

<u>Adjust Q if Level X1 <> 60mm</u>

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ✓

If Vortex Drum Bottom Temperature > 45C Jump to Reference 24

Log measurements every 5 minutes

Press S > 6 Bar => Burner Off for 5 minutes

20			21				
Pressure S Value	3	Bar Gauge	Pressure S Value	~~3,3~~	Bar Gauge	Ambient Temp	
Pressure ZK Value	2,5	Bar Gauge	Pressure ZK Value	~~2,6~~	Bar Gauge	Ambient Humidity	
Pressure G Value	2	Bar Gauge	Pressure G Value	~~2,3~~	Bar Gauge		
Pressure U Value	3,1	Bar Gauge	Pressure U Value		Bar Gauge		
Ballast Drum Temperature	26,1	Celsius	Ballast Drum Temperature		Celsius		
Reactor Top Temperature	28,9	Celsius	Reactor Top Temperature		Celsius		
Vortex Drum Flange Temperature	45,3	Celsius	Vortex Drum Flange Temperature				
Vortex Drum Bottom Temperature	48,5	Celsius	Vortex Drum Bottom Temperature		Celsius	Abs Ch1 Temp	
Evaporator Outlet Temperature	22,6	Celsius	Evaporator Outlet Temperature		Celsius	Abs Ch2 Temp	
Water Reservoir (CW Pump Inlet) Temp	23,2	Celsius	Water Reservoir (CW Pump Inlet) Temp		Celsius	Abs Ch3 Temp	
Measurements Time	10:22		Measurements Time				

Adjust Q if Level X1 <> 60mm

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☐

If Vortex Drum Bottom Temperature > 45C Jump to Reference 24

Log measurements every 5 minutes

Press S > 6 Bar => Burner Off for 5 minutes

22			23				
Pressure S Value		Bar Gauge	Pressure S Value		Bar Gauge		
Pressure ZK Value		Bar Gauge	Pressure ZK Value		Bar Gauge		
Pressure G Value		Bar Gauge	Pressure G Value		Bar Gauge		
Pressure U Value		Bar Gauge	Pressure U Value		Bar Gauge		
Ballast Drum Temperature		Celsius	Ballast Drum Temperature		Celsius		
Reactor Top Temperature		Celsius	Reactor Top Temperature		Celsius		
Vortex Drum Flange Temperature		Celsius	Vortex Drum Flange Temperature				
Vortex Drum Bottom Temperature		Celsius	Vortex Drum Bottom Temperature		Celsius	Abs Ch1 Temp	
Evaporator Outlet Temperature		Celsius	Evaporator Outlet Temperature		Celsius	Abs Ch2 Temp	
Water Reservoir (CW Pump Inlet) Temp		Celsius	Water Reservoir (CW Pump Inlet) Temp		Celsius	Abs Ch3 Temp	
Measurements Time			Measurements Time				

Adjust Q if Level X1 <> 60mm

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ✓

(Estimated Burner & Vac Pump Overlap ~ 30 min)

24		
Vacuum Pump On	✓	Prepare for Reactor Top Heat removal (Dropping Pressure)
Needle Valve ZG Open Fully	✓	Load Vacuum Pump with vapor flow
Gas Burner Still On	✓	Run Gas Burner together with Vacuum Pump for largest Gradient Developments
Purge Valve ZB Closed	✓	It will be opened only when needed

Log measurements every 5 minutes

Press S > 6 Bar => Burner Off for 5 minutes

25			26				
Pressure S Value	3,5	Bar Gauge	Pressure S Value	3,7	Bar Gauge	Ambient Temp	25,9
Pressure ZK Value	2,9	Bar Gauge	Pressure ZK Value	3	Bar Gauge	Ambient Humidity	52
Pressure G Value	3	Bar Gauge	Pressure G Value	4	Bar Gauge		
Pressure U Value	7	Bar Gauge	Pressure U Value	6	Bar Gauge		
Ballast Drum Temperature	27	Celsius	Ballast Drum Temperature	24,4	Celsius		
Reactor Top Temperature	30,1	Celsius	Reactor Top Temperature	31	Celsius		
Vortex Drum Flange Temperature	47,2	Celsius	Vortex Drum Flange Temperature	48,3			
Vortex Drum Bottom Temperature	50,7	Celsius	Vortex Drum Bottom Temperature	52,2	Celsius	Abs Ch1 Temp	30,3
Evaporator Outlet Temperature	22,7	Celsius	Evaporator Outlet Temperature	22	Celsius	Abs Ch2 Temp	30,9
Water Reservoir (CW Pump Inlet) Temp	22,9	Celsius	Water Reservoir (CW Pump Inlet) Temp	34,1	Celsius	Abs Ch3 Temp	23,5
Measurements Time	10:35		Measurements Time	10:42			
			Purge Valve ZB Open 6 Notches	~~Yes~~ 0	Only open when needed		

Adjust Q/ZB if Level X1 <> 60mm

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

If Vortex Drum Bottom Temperature > 55C Jump to Reference 31

Log measurements every 5 minutes

Press S > 6 Bar => Burner Off for 5 minutes

27			28		
Pressure S Value	4	Bar Gauge	Pressure S Value		Bar Gauge
Pressure ZK Value	3,5	Bar Gauge	Pressure ZK Value		Bar Gauge

Pressure G Value	4	Bar Gauge
Pressure U Value	6	Bar Gauge
Ballast Drum Temperature	27,5	Celsius
Reactor Top Temperature	32	Celsius
Vortex Drum Flange Temperature	52,5	Celsius
Vortex Drum Bottom Temperature	555	Celsius
Evaporator Outlet Temperature	22,6	Celsius
Water Reservoir (CW Pump Inlet) Temp	24,2	Celsius
Measurements Time	10:51	

Adjust Q/ZB if Level X1 <> 60mm

Pressure G Value		Bar Gauge
Pressure U Value		Bar Gauge
Ballast Drum Temperature		Celsius
Reactor Top Temperature		Celsius
Vortex Drum Flange Temperature		
Vortex Drum Bottom Temperature		Celsius
Evaporator Outlet Temperature		Celsius
Water Reservoir (CW Pump Inlet) Temp		Celsius
Measurements Time		
Purge Valve ZB Open 6 Notches		Only open when needed

Abs Ch1 Temp	
Abs Ch2 Temp	
Abs Ch3 Temp	

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ☐ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☐

If Vortex Drum Bottom Temperature > 55C Jump to Reference 31

Log measurements every 5 minutes

Press S > 6 Bar => Burner Off for 5 minutes

29

Pressure S Value		Bar Gauge
Pressure ZK Value		Bar Gauge
Pressure G Value		Bar Gauge
Pressure U Value		Bar Gauge
Ballast Drum Temperature		Celsius
Reactor Top Temperature		Celsius
Vortex Drum Flange Temperature		Celsius
Vortex Drum Bottom Temperature		Celsius
Evaporator Outlet Temperature		Celsius
Water Reservoir (CW Pump Inlet) Temp		Celsius
Measurements Time		

Adjust Q/ZB if Level X1 <> 60mm

30

Pressure S Value		Bar Gauge
Pressure ZK Value		Bar Gauge
Pressure G Value		Bar Gauge
Pressure U Value		Bar Gauge
Ballast Drum Temperature		Celsius
Reactor Top Temperature		Celsius
Vortex Drum Flange Temperature		
Vortex Drum Bottom Temperature		Celsius
Evaporator Outlet Temperature		Celsius
Water Reservoir (CW Pump Inlet) Temp		Celsius
Measurements Time		
Purge Valve ZB Open 6 Notches		Only open when needed

Abs Ch1 Temp	
Abs Ch2 Temp	
Abs Ch3 Temp	

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ☐ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ☐ No ☐

Entry Point in the sequence when Gas Heating was successfully Completed…

31

(Estimated Press Drop Time ~ 30 min)

Gas Burner Off	✓	Prepare for pressure dropping
Vacuum Pump Still On	✓	Prepare for Reactor Top Heat removal (Dropping Pressure)
Valve D Open 3 Notches	✓	Limited CW will drop Pressure S

Log measurements every 5 minutes

32

Pressure S Value	4	Bar Gauge
Pressure ZK Value	3,2	Bar Gauge
Pressure G Value	4	Bar Gauge
Pressure U Value	5,5	Bar Gauge
Ballast Drum Temperature	28,6	Celsius
Reactor Top Temperature	32	Celsius
Vortex Drum Flange Temperature	49,5	Celsius
Vortex Drum Bottom Temperature	48,9	Celsius
Evaporator Outlet Temperature	22,4	Celsius
Water Reservoir (CW Pump Inlet) Temp	24,4	Celsius
Measurements Time	11.00	

Adjust Q/ZB if Level X1 <> 60mm

33

Pressure S Value	3,8	Bar Gauge
Pressure ZK Value	3	Bar Gauge
Pressure G Value	4	Bar Gauge
Pressure U Value	5,5	Bar Gauge
Ballast Drum Temperature	28,5	Celsius
Reactor Top Temperature	31,8	Celsius
Vortex Drum Flange Temperature	48,2	
Vortex Drum Bottom Temperature	48,4	Celsius
Evaporator Outlet Temperature	23,6	Celsius
Water Reservoir (CW Pump Inlet) Temp	24,6	Celsius
Measurements Time	11:09	
Purge Valve ZB Open 6 Notches	NO	Only open when needed

Ambient Temp	26,9
Ambient Humidity	47

Abs Ch1 Temp	37,5
Abs Ch2 Temp	35,1
Abs Ch3 Temp	28,2

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

If Pressure S < 2.7 Bar(G) Jump to Transition Reference 38

Log measurements every 5 minutes

34

Pressure S Value	3,5	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pressure G Value	4	Bar Gauge
Pressure U Value	5,3	Bar Gauge

35

Pressure S Value	3,4	Bar Gauge
Pressure ZK Value	2,8	Bar Gauge
Pressure G Value	3	Bar Gauge
Pressure U Value	5	Bar Gauge

Ambient Temp	27,5
Ambient Humidity	45

Ballast Drum Temperature	28,4	Celsius
Reactor Top Temperature	31,1	Celsius
Vortex Drum Flange Temperature	48,4	Celsius
Vortex Drum Bottom Temperature	47,7	Celsius
Evaporator Outlet Temperature	24,1	Celsius
Water Reservoir (CW Pump Inlet) Temp	24,9	Celsius
Measurements Time	11:17	

Adjust Q/ZB if Level X1 <> 60mm

Ballast Drum Temperature	28,2	Celsius
Reactor Top Temperature	31	Celsius
Vortex Drum Flange Temperature	43,9	
Vortex Drum Bottom Temperature	43,9	Celsius
Evaporator Outlet Temperature	22,8	Celsius
Water Reservoir (CW Pump Inlet) Temp	25,2	Celsius
Measurements Time	11:26	
Purge Valve ZB Open 6 Notches	NO	Only open when needed

Abs Ch1 Temp	35,6
Abs Ch2 Temp	31,5
Abs Ch3 Temp	24,6

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) **Yes** ✓ **No** ☐

If Pressure S < 2.7 Bar(G) Jump to Transition Reference 38

Log measurements every 5 minutes

36

Pressure S Value	3	Bar Gauge
Pressure ZK Value	2,5	Bar Gauge
Pressure G Value	3	Bar Gauge
Pressure U Value	5	Bar Gauge
Ballast Drum Temperature	28,1	Celsius
Reactor Top Temperature	30,1	Celsius
Vortex Drum Flange Temperature	44	Celsius
Vortex Drum Bottom Temperature	43,4	Celsius
Evaporator Outlet Temperature	24,5	Celsius
Water Reservoir (CW Pump Inlet) Temp	25	Celsius
Measurements Time	11:36	

Adjust Q/ZB if Level X1 <> 60mm

37

Pressure S Value	3	Bar Gauge
Pressure ZK Value	2,5	Bar Gauge
Pressure G Value	3	Bar Gauge
Pressure U Value	4,8	Bar Gauge
Ballast Drum Temperature	28,7	Celsius
Reactor Top Temperature	30	Celsius
Vortex Drum Flange Temperature	43,7	
Vortex Drum Bottom Temperature	42,1	Celsius
Evaporator Outlet Temperature	24,2	Celsius
Water Reservoir (CW Pump Inlet) Temp	25,4	Celsius
Measurements Time	11:45	
Purge Valve ZB Open 6 Notches	NO	Only open when needed

Ambient Temp	27,9
Ambient Humidity	40
Abs Ch1 Temp	35,9
Abs Ch2 Temp	32,9
Abs Ch3 Temp	26,7

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) **Yes** ✓ **No** ☐

If Pressure S < 2.7 Bar(G) Jump to Transition Reference 38

Log measurements every 5 minutes

38

Pressure S Value	2,8	Bar Gauge
Pressure ZK Value	2,4	Bar Gauge
Pressure G Value	2,5	Bar Gauge
Pressure U Value	4,7	Bar Gauge
Ballast Drum Temperature	29,1	Celsius
Reactor Top Temperature	29	Celsius
Vortex Drum Flange Temperature	43,2	Celsius
Vortex Drum Bottom Temperature	42,4	Celsius
Evaporator Outlet Temperature	24,5	Celsius
Water Reservoir (CW Pump Inlet) Temp	25,5	Celsius
Measurements Time	11:54	

Adjust Q/ZB if Level X1 <> 60mm

39

Pressure S Value	2,7	Bar Gauge
Pressure ZK Value	2,3	Bar Gauge
Pressure G Value	2,5	Bar Gauge
Pressure U Value	4,7	Bar Gauge
Ballast Drum Temperature	29,1	Celsius
Reactor Top Temperature	28,8	Celsius
Vortex Drum Flange Temperature	42,2	
Vortex Drum Bottom Temperature	41,3	Celsius
Evaporator Outlet Temperature	24,8	Celsius
Water Reservoir (CW Pump Inlet) Temp	25,8	Celsius
Measurements Time	12:04	
Purge Valve ZB Open 6 Notches	NO	Only open when needed

Ambient Temp	28,5
Ambient Humidity	41
Abs Ch1 Temp	31,7
Abs Ch2 Temp	32,9
Abs Ch3 Temp	25

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) **Yes** ✓ **No** ☐

If Pressure S < 2.7 Bar(G) Jump to Transition Reference 38

40 Transition to AWG Sequence:

Transition Time 12:06 (Estimated AWG Time ~ 90 min)

Transition with Vacuum Pump staying on !!

Valve C Open ✓ Evaporator liquid overflow path opened

Valve Y Open	✓	AWG path open so NH3 Pump may keep pressure = 2Bar
Valve P Open	✓	Open vapor flowpath from evaporator to pre-absorber
Valve D Close	✓	Stop CW untill it is needed again for pressure control
Valve J Close	✓	We are evaluating the chilling effect of the evaporator with the only load being the Wally

41

Valve F Closed Completely	✓	Backpress regulator will keep 1.9 - 2.0 Bar @ V
Adjust Valve C for Press ZK = 2 Bar	✓	C just cracked open

42

Valve E Opened 50% to allow CW higher mass flow through Evaporator — Valve Open ✓

Air Coil Fan On Low Speed Setting ✓ AWG in Operation and water should be produced (if Reactor activated!) — AWG On Time 12:10

Log measurements every 5 minutes

43			44				
Pressure S Value	2,5	Bar Gauge	Pressure S Value	2,4	Bar Gauge	Ambient Temp	28,7
Pressure ZK Value	2	Bar Gauge	Pressure ZK Value	2	Bar Gauge	Ambient Humidity	38
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge		
Pressure U Value	4,5	Bar Gauge	Pressure U Value	4,7	Bar Gauge		
Ballast Drum Temperature	29	Celsius	Ballast Drum Temperature	29,4	Celsius		
Reactor Top Temperature	28,8	Celsius	Reactor Top Temperature	28,9	Celsius		
Vortex Drum Flange Temperature	36,7	Celsius	Vortex Drum Flange Temperature	32,2			
Vortex Drum Bottom Temperature	35,4	Celsius	Vortex Drum Bottom Temperature	31,2	Celsius	Abs Ch1 Temp	30,3
Evaporator Outlet Temperature	24,2	Celsius	Evaporator Outlet Temperature	25,9	Celsius	Abs Ch2 Temp	29,5
Water Reservoir (CW Pump Inlet) Temp	25	Celsius	Water Reservoir (CW Pump Inlet) Temp	25,1	Celsius	Abs Ch3 Temp	25,6
Measurements Time	12:15		Measurements Time	12:24			

45

Valve F Closed Completely	✓	Backpress regulator will keep 1.9 - 2.0 Bar @ V
Adjust Valve C for Press ZK = 2 Bar	✓	

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ?	0	
Vacuum Pump Off	✓	Pressure control reverts to CW
Valve ZG Closed	✓	Pressure control reverts to CW

Log measurements every 5 minutes

46			47				
Pressure S Value	2	Bar Gauge	Pressure S Value	2	Bar Gauge	Ambient Temp	29,3
Pressure ZK Value	1,9	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge	Ambient Humidity	38
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge		
Pressure U Value	4,5	Bar Gauge	Pressure U Value	4,5	Bar Gauge		
Ballast Drum Temperature	29,2	Celsius	Ballast Drum Temperature	29,6	Celsius		
Reactor Top Temperature	27,5	Celsius	Reactor Top Temperature	27	Celsius		
Vortex Drum Flange Temperature	31,8	Celsius	Vortex Drum Flange Temperature	28,3			
Vortex Drum Bottom Temperature	28,9	Celsius	Vortex Drum Bottom Temperature	27,2	Celsius	Abs Ch1 Temp	29,2
Evaporator Outlet Temperature	28,9	Celsius	Evaporator Outlet Temperature	27,9	Celsius	Abs Ch2 Temp	30,9
Water Reservoir (CW Pump Inlet) Temp	25,5	Celsius	Water Reservoir (CW Pump Inlet) Temp	26,5	Celsius	Abs Ch3 Temp	25,6
Measurements Time	12:30		Measurements Time	12:40			

48

Valve F Closed Completely	✓	Backpress regulator will keep 1.9 - 2.0 Bar @ V
XX Adjust Valve C for Press ZK = 2 Bar	1,9	XX

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

49			50				
Pressure S Value	2	Bar Gauge	Pressure S Value	2	Bar Gauge	Ambient Temp	29,5
Pressure ZK Value	1,9	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge	Ambient Humidity	38
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge		

Pressure U Value	4,5	Bar Gauge
Ballast Drum Temperature	30,1	Celsius
Reactor Top Temperature	27	Celsius
Vortex Drum Flange Temperature	27,2	Celsius
Vortex Drum Bottom Temperature	26,9	Celsius
Evaporator Outlet Temperature	24,5	Celsius
Water Reservoir (CW Pump Inlet) Temp	25,9	Celsius
Measurements Time	12:48	

Pressure U Value	4,5	Bar Gauge
Ballast Drum Temperature	30	Celsius
Reactor Top Temperature	27	Celsius
Vortex Drum Flange Temperature	27	
Vortex Drum Bottom Temperature	26,8	Celsius
Evaporator Outlet Temperature	24,7	Celsius
Water Reservoir (CW Pump Inlet) Temp	26	Celsius
Measurements Time	12:55	

Abs Ch1 Temp	29,8
Abs Ch2 Temp	29,4
Abs Ch3 Temp	26,9

51

Valve F Closed Completely ✓ Backpress regulator will keep 1.9 - 2.0 Bar @ V

X Adjust Valve C for Press ZK = 2 Bar 1,9 X

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

52

Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,5	Bar Gauge
Ballast Drum Temperature	30,1	Celsius
Reactor Top Temperature	26,9	Celsius
Vortex Drum Flange Temperature	27,2	Celsius
Vortex Drum Bottom Temperature	26,9	Celsius
Evaporator Outlet Temperature	24,1	Celsius
Water Reservoir (CW Pump Inlet) Temp	27,1	Celsius
Measurements Time	13:04	

53

Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,5	Bar Gauge
Ballast Drum Temperature	30,2	Celsius
Reactor Top Temperature	26,9	Celsius
Vortex Drum Flange Temperature	27	
Vortex Drum Bottom Temperature	26,7	Celsius
Evaporator Outlet Temperature	25,6	Celsius
Water Reservoir (CW Pump Inlet) Temp	26	Celsius
Measurements Time	13:14	

Ambient Temp	29,4
Ambient Humidity	37
Abs Ch1 Temp	30
Abs Ch2 Temp	29,7
Abs Ch3 Temp	26

54

Valve F Closed Completely ✓ Backpress regulator will keep 1.9 - 2.0 Bar @ V

XX Adjust Valve C for Press ZK = 2 Bar 1,9 XX

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

55

Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,4	Bar Gauge
Ballast Drum Temperature	30,3	Celsius
Reactor Top Temperature	26,5	Celsius
Vortex Drum Flange Temperature	27	Celsius
Vortex Drum Bottom Temperature	26,8	Celsius
Evaporator Outlet Temperature	24,6	Celsius
Water Reservoir (CW Pump Inlet) Temp	26	Celsius
Measurements Time	13:22	

56

Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,4	Bar Gauge
Ballast Drum Temperature	30,3	Celsius
Reactor Top Temperature	26,2	Celsius
Vortex Drum Flange Temperature	27,5	
Vortex Drum Bottom Temperature	26,9	Celsius
Evaporator Outlet Temperature	25,7	Celsius
Water Reservoir (CW Pump Inlet) Temp	26,4	Celsius
Measurements Time	13:31	

Ambient Temp	29,3
Ambient Humidity	37
Abs Ch1 Temp	29,2
Abs Ch2 Temp	29,3
Abs Ch3 Temp	26,2

57

Valve F Closed Completely ✓ Backpress regulator will keep 1.9 - 2.0 Bar @ V

Adjust Valve C for Press ZK = 2 Bar 1,9

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

58			59		
Pressure S Value	2	Bar Gauge	Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,4	Bar Gauge	Pressure U Value	4,4	Bar Gauge
Ballast Drum Temperature	31,3	Celsius	Ballast Drum Temperature	30,7	Celsius
Reactor Top Temperature	26,2	Celsius	Reactor Top Temperature	26,1	Celsius
Vortex Drum Flange Temperature	27,5	Celsius	Vortex Drum Flange Temperature	27,4	
Vortex Drum Bottom Temperature	26,9	Celsius	Vortex Drum Bottom Temperature	26,9	Celsius
Evaporator Outlet Temperature	24,5	Celsius	Evaporator Outlet Temperature	26,5	Celsius
Water Reservoir (CW Pump Inlet) Temp	26,3	Celsius	Water Reservoir (CW Pump Inlet) Temp	26,5	Celsius
Measurements Time	13:41		Measurements Time	13:50	

Ambient Temp 30,1
Ambient Humidity 38

Abs Ch1 Temp 30,2
Abs Ch2 Temp 28
Abs Ch3 Temp 26,4

60

Valve F Closed Completely ✓ Backpress regulator will keep 1.9 - 2.0 Bar @ V

Adjust Valve C for Press ZK = 2 Bar 1,9

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

61			62		
Pressure S Value	2	Bar Gauge	Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,4	Bar Gauge	Pressure U Value	4,4	Bar Gauge
Ballast Drum Temperature	31,9	Celsius	Ballast Drum Temperature	30,5	Celsius
Reactor Top Temperature	26,1	Celsius	Reactor Top Temperature	26	Celsius
Vortex Drum Flange Temperature	26,9	Celsius	Vortex Drum Flange Temperature	27,6	
Vortex Drum Bottom Temperature	26,5	Celsius	Vortex Drum Bottom Temperature	27,3	Celsius
Evaporator Outlet Temperature	26,9	Celsius	Evaporator Outlet Temperature	23,9	Celsius
Water Reservoir (CW Pump Inlet) Temp	26,8	Celsius	Water Reservoir (CW Pump Inlet) Temp	26,7	Celsius
Measurements Time	13:57		Measurements Time	14:06	

Ambient Temp 29,2
Ambient Humidity 39

Abs Ch1 Temp 29,9
Abs Ch2 Temp 30
Abs Ch3 Temp 25,6

63

Valve F Closed Completely Backpress regulator will keep 1.9 - 2.0 Bar @ V

Adjust Valve C for Press ZK = 2 Bar

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches NO Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed ✓ To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

64			65		
Pressure S Value	2	Bar Gauge	Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge	Pressure ZK Value	1,9	Bar Gauge
Pump Pressure H Value	4	Bar Gauge	Pump Pressure H Value	4	Bar Gauge
Pressure U Value	4,3	Bar Gauge	Pressure U Value	4,2	Bar Gauge
Ballast Drum Temperature	30,3	Celsius	Ballast Drum Temperature	30,6	Celsius
Reactor Top Temperature	25,9	Celsius	Reactor Top Temperature	25,5	Celsius
Vortex Drum Flange Temperature	27,6	Celsius	Vortex Drum Flange Temperature	27,5	
Vortex Drum Bottom Temperature	27,1	Celsius	Vortex Drum Bottom Temperature	27,3	Celsius
Evaporator Outlet Temperature	27,2	Celsius	Evaporator Outlet Temperature	27,5	Celsius
Water Reservoir (CW Pump Inlet) Temp	26,8	Celsius	Water Reservoir (CW Pump Inlet) Temp	26,3	Celsius
Measurements Time	14:15		Measurements Time	14:23	

Ambient Temp 25,5
Ambient Humidity 40

Abs Ch1 Temp 25,4
Abs Ch2 Temp 27,8
Abs Ch3 Temp 26,2

66

Valve F Closed Completely	✓	Backpress regulator will keep 1.9 - 2.0 Bar @ V
X Adjust Valve C for Press ZK = 2 Bar	✓ 1,9	X

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches: NO — Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed: ✓ — To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

Log measurements every 5 minutes

67			68				
Pressure S Value		Bar Gauge	Pressure S Value		Bar Gauge	Ambient Temp	
Pressure ZK Value		Bar Gauge	Pressure ZK Value		Bar Gauge	Ambient Humidity	
Pump Pressure H Value		Bar Gauge	Pump Pressure H Value		Bar Gauge		
Pressure U Value		Bar Gauge	Pressure U Value		Bar Gauge		
Ballast Drum Temperature		Celsius	Ballast Drum Temperature		Celsius		
Reactor Top Temperature		Celsius	Reactor Top Temperature		Celsius		
Vortex Drum Flange Temperature		Celsius	Vortex Drum Flange Temperature				
Vortex Drum Bottom Temperature		Celsius	Vortex Drum Bottom Temperature		Celsius	Abs Ch1 Temp	
Evaporator Outlet Temperature		Celsius	Evaporator Outlet Temperature		Celsius	Abs Ch2 Temp	
Water Reservoir (CW Pump Inlet) Temp		Celsius	Water Reservoir (CW Pump Inlet) Temp		Celsius	Abs Ch3 Temp	
Measurements Time			Measurements Time				

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Valve F Closed Completely	✓	Backpress regulator will keep 1.9 - 2.0 Bar @ V
Adjust Valve C for Press ZK = 2 Bar	1,9	

Adjust Q/ZB if Level X1 <> 60mm

Purge Valve ZB Open 6 Notches: NO — Only open when needed

If Level X1 > 60, Adjust valve Q more open to pump more liquid into Ballast

If Level X1 < 60, Adjust valve Q more closed to increase Reactor Level

Purge Valve ZB Closed: ✓ — To preserve Absorber Heat

Was it necessary to adjust Q for level control? (Mark Yes OR No) Yes ✓ No ☐

Adjust D if Pressure S <> 2.5 Bar

If Press S > 2.5 Bar, open D one more notch to increase CW flow.

If Press S < 2.5 Bar, close D one more notch to decrease CW flow.

How many Notches D is open ? 0

70 Abort Sequence (Signalling experiment is over)

Abort Time: 14:26

Gas Burner Off	✓	Heat removed (If it was on)
Vacuun Pump Off	✓	Heat removed (If it was on)
NH3 Pump off	✓	Circulation Flow stopped
Vortex Circ Pump off	✓	Absorber Disabled
Boiler Circ Pump Off	✓	Circulation Flow stopped
Valve ZB Closed	✓	Purge Stopped
Valve ZH Closed	✓	Vapor Flow stopped
Valve ZG Closed	✓	Vapor Flow stopped
Valve Q Closed	✓	Purge Stopped
Pressure S Value	2	Bar Gauge
Pressure ZK Value	1,9	Bar Gauge
Pressure V Value	2	Bar Gauge
Pressure U Value	4,1	Bar Gauge
Ballast Drum Temperature	31,9	Celsius
Reactor Top Temperature	25,5	Celsius
Vortex Drum Flange Temperature	27,3	Celsius
Vortex Drum Bottom Temperature	26,4	Celsius
Evaporator Outlet Temperature	26,9	Celsius
Water Reservoir (CW Pump Inlet) Temp	27,1	Celsius
All pumps off	✓	For preserving and accumulating gradients achieved with this start-up.
All valves closed	✓	For preserving and accumulating gradients achieved with this start-up.

Ambient Temp	28,4
Ambient Humidity	40

=> Abort Sequence Completed. The next Start-up may follow any time!