

MARINE NH3

# APPENDIX (THESIS)

Safe and effective application of ammonia as a marine fuel

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## APPENDIX A: RENEWABLE FUEL SYNTHETIC PRODUCTION COST [MJ/MJ]

Energy demand calculation:

	Liquid Methane CH4	Ethanol C2H5OH	Methanol CH3OH	Liquid Ammonia NH3	Liquid Ammonia NH3	Liquid Hydrogen H2	Compressed Hydrogen H2
Storage temperature [°C]	-164	20	20	-34	20	-253	20
Storage pressure [bar]	1	1	1	1	10	1	700
Energy [MJ]	1000	1000	1000	1000	1000	1000	1000
Energy density (LHV) [MJ/kg]	50.0	26.7	19.9	18.6	18.6	120.0	120.0
Mass [kg]	20.0	37.5	50.3	53.8	53.8	8.3	8.3
Density [kg/m3]	468	789	792	682	682	71	63
Volume [m3]	0.04	0.05	0.06	0.08	0.08	0.12	0.13
Nitrogen [kg-nitrogen] (*1)				44.2	44.2		
Air separation [MJ/kg-nitrogen]				0.2 [1]	0.2		
Air separation [MJ]				9.7	9.7		
Air separation [MJ/MJ]				9.7E-3	9.7E-3		
Carbon [kg-carbon] (*2)	15.0	19.5	26.2				
CO2 [kg-CO2] (*3)	54.9	71.6	96.0				
Air separation [MJ/kg-CO2]	6.6 [1]	6.6	6.6				
Air separation [MJ]	362.1	472.3	633.7				
Air separation [MJ/MJ]	0.36	0.47	0.63				
Hydrogen [kg-hydrogen] (*4)	10.1	9.8	9.5	9.5	9.5	8.3	8.3
Water [kg-water] (*5)	89.8	87.9	84.8	85.3	85.3	74.5	74.5
Water cleaning [MJ/kg-water]	6.5E-3 [1]	6.5E-3	6.5E-3	6.5E-3	6.5E-3	6.5E-3	6.5E-3
Water cleaning [MJ]	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Water cleaning [MJ/MJ]	5.8E-4	5.7E-4	5.5E-4	5.5E-4	5.5E-4	4.8E-4	4.8E-4
Hydrogen [kg-hydrogen] (*4)	10.1	9.8	9.5	9.5	9.5	8.3	8.3
Water splitting [MJ/kg-hydrogen]	180.7 [1]	180.7	180.7	180.7	180.7	180.7	180.7
Water splitting [MJ]	1817	1777	1714	1725	1725	1506	1506
Water splitting [MJ/MJ]	1.82	1.78	1.71	1.72	1.72	1.51	1.51
Synthesis [MJ/kg-fuel]	1.2 [1]	36.9 [2]	4.8 [1]	1.6 [1]	1.6		
Synthesis [MJ]	24	1382	241	86	86		
Synthesis [MJ/MJ]	0.02	1.38	0.24	0.09	0.09		
Compression/Cooling [MJ/kg-fuel]	5.00 [3]			0.01 [1]		40.00 [1]	17.04 [4]
Compression/Cooling [MJ]	100.0			0.5		333.3	142.0
Compression/Cooling [MJ/MJ]	0.10			5.4E-4		0.33	0.14
Total [MJ]	2303	3632	2589	1822	1821	1840	1648
Total [MJ/MJ]	2.30	3.63	2.59	1.82	1.82	1.84	1.65

- [1] S. Crolius, O. Elishav, „N-Fuels vs. C-Fuels: Nitrogen “superior” to carbon as a hydrogen carrier,” Ammonia Energy & Technion Israel Institute of Technology, 16 November 2017. [Online]. Available: <http://www.ammoniaenergy.org/n-fuels-vs-c-fuels-nitrogen-superior-to-carbon-as-a-hydrogen-carrier/>. [Geopend 9 April 2018].
- [2] Y. El Fouih and C. Bouallou, „Recycling of carbon dioxide to produce ethanol,” Elsevier (MINES ParisTech, Centre Energétique et Procédés), Paris, 2013.
- [3] PetroWiki, „Liquified natural gas (LNG),” PetroWiki, 15 January 2018. [Online]. Available: [https://petrowiki.org/Liquified\\_natural\\_gas\\_\(LNG\)#cite\\_ref-r5\\_5-1](https://petrowiki.org/Liquified_natural_gas_(LNG)#cite_ref-r5_5-1). [Geopend 9 April 2018].
- [4] S.S. Makridis, „Hydrogen storage and compression,” Department of Mechanical Engineering, University of Western Macedonia, Kozani, 2016.

#### Chemical data:

Type	Atom	g/mol	Mass % Hydrogen	Mass % Nitrogen	Mass % Carbon	Mass % Oxygen
Hydrogen	H	1.0079	100%			
Nitrogen	N	14.0067		100%		
Carbon	C	12.0107			100%	
Oxygen	O	15.9994				100%
Carbon dioxide	CO <sub>2</sub>	44.0095			27.29%	72.71%
Water	H <sub>2</sub> O	18.0153	11.19%			88.81%
Methane	CH <sub>4</sub>	16.0425	25.13%		74.87%	
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	46.0684	13.13%		52.14%	34.73%
Methanol	CH <sub>3</sub> OH	32.0419	12.58%		37.48%	49.93%
Ammonia	NH <sub>3</sub>	17.0306	17.76%	82.24%		
Hydrogen	H <sub>2</sub>	2.0159	100.00%			

#### Hydrogen utilization factor:

Methane	$CO_2 + 4H_2 \rightarrow CH_4 + H_2O$	50%
Ethanol	$2CO_2 + 6H_2 \rightarrow C_2H_5OH + 3H_2O$	50%
Methanol	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$	67%
Ammonia	$N_2 + 3H_2 \rightarrow 2NH_3$	100%

(\*1): Nitrogen mass calculated by multiplying total mass with nitrogen percentage given in chemical data table.

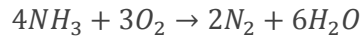
(\*2): Carbon mass calculated by multiplying total mass with carbon percentage given in chemical data table.

(\*3): Carbon dioxide mass calculated by dividing carbon mass by carbon mass percentage given in chemical data table. (Oxygen demand covered with carbon dioxide supply as carbon demand is greater or equal to oxygen demand. Furthermore, carbon dioxide supply provides 2 oxygen atoms and 1 carbon atom. Thus, carbon is dominant)

(\*4): Hydrogen mass calculated by multiplying total mass with hydrogen percentage, given in chemical data table, and dividing it by hydrogen utilization factor.

(\*5): Water mass calculated by dividing hydrogen mass with hydrogen percentage given in chemical data table.

## APPENDIX B: AMMONIA COMBUSTION



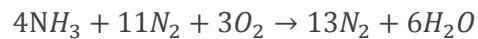
Type	-	Moles	Molecule	Phase	Enthalpy of formation [kJ/mol]	Enthalpy of formation [kJ]
Reactant	$\Delta H_f$	4	NH <sub>3</sub>	Gas	-45.9	-183.6
Reactant	$\Delta H_f$	3	O <sub>2</sub>	Gas	0.0	0.0
Product	$\Delta H_f$	2	N <sub>2</sub>	Gas	0.0	0.0
Product	$\Delta H_f$	6	H <sub>2</sub> O	Gas	-241.8	-1,450.9
	$\Delta H_r$					-1,267.3

$$\Delta H_r = \sum H_f(\text{products}) - \sum H_f(\text{reactants})$$

$\Delta H_r$ : -1,267.3 kJ Needed  
 $\Delta H_r$ : 1,267.3 kJ Released

NH<sub>3</sub>: 17.0305 g/mol  
 4NH<sub>3</sub>: 68.1221 g

NH<sub>3</sub>: 18,603 kJ/kg Lower Heating Value (LHV)



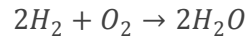
Stoichiometric combustion of 1 kg ammonia

Moles	Molecule	Mass [kg]	Specific heat [kJ/kg·K] (at 2000K)	$\Delta T$ Temperature [K]
13	N <sub>2</sub>	5.35	1.28	1,637
6	H <sub>2</sub> O	1.59	2.84	

Start T: 293 K  
 $\Delta T$ : 1,637 K  
 End: 1,930 K

Check simplified conservative approach of calculation: 2,000 > 1,930

## APPENDIX C: HYDROGEN COMBUSTION



Type	-	Moles	Molecule	Phase	Enthalpy of formation [kJ/mol]	Enthalpy of formation [kJ]
Reactant	$\Delta H_f$	2	H <sub>2</sub>	Gas	0.0	0.0
Reactant	$\Delta H_f$	1	O <sub>2</sub>	Gas	0.0	0.0
Product	$\Delta H_f$	2	H <sub>2</sub> O	Gas	-241.8	-483.6
	$\Delta H_r$					-483.6

$$\Delta H_r = \sum H_f (\text{products}) - \sum H_f (\text{reactants})$$

$\Delta H_r$ : -483.6 kJ Needed

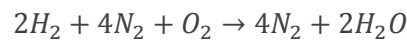
$\Delta H_r$ : 483.6 kJ Released

H<sub>2</sub>: 2.0159 g/mol

H<sub>2</sub>: 4.0318 g

H<sub>2</sub>: 119,957 kJ/kg

Lower Heating Value (LHV)



Stoichiometric combustion of 1 kg hydrogen

Moles	Molecule	Mass [kg]	Specific heat [kJ/kg·K] (at 2,300K)	$\Delta T$ Temperature [K]
4	N <sub>2</sub>	27.79	1.30	1,924
2	H <sub>2</sub> O	8.94	2.93	

Start T: 293 K

$\Delta T$ : 1,924 K

End: 2,217 K

Check simplified conservative approach of calculation: 2,300 > 2,217

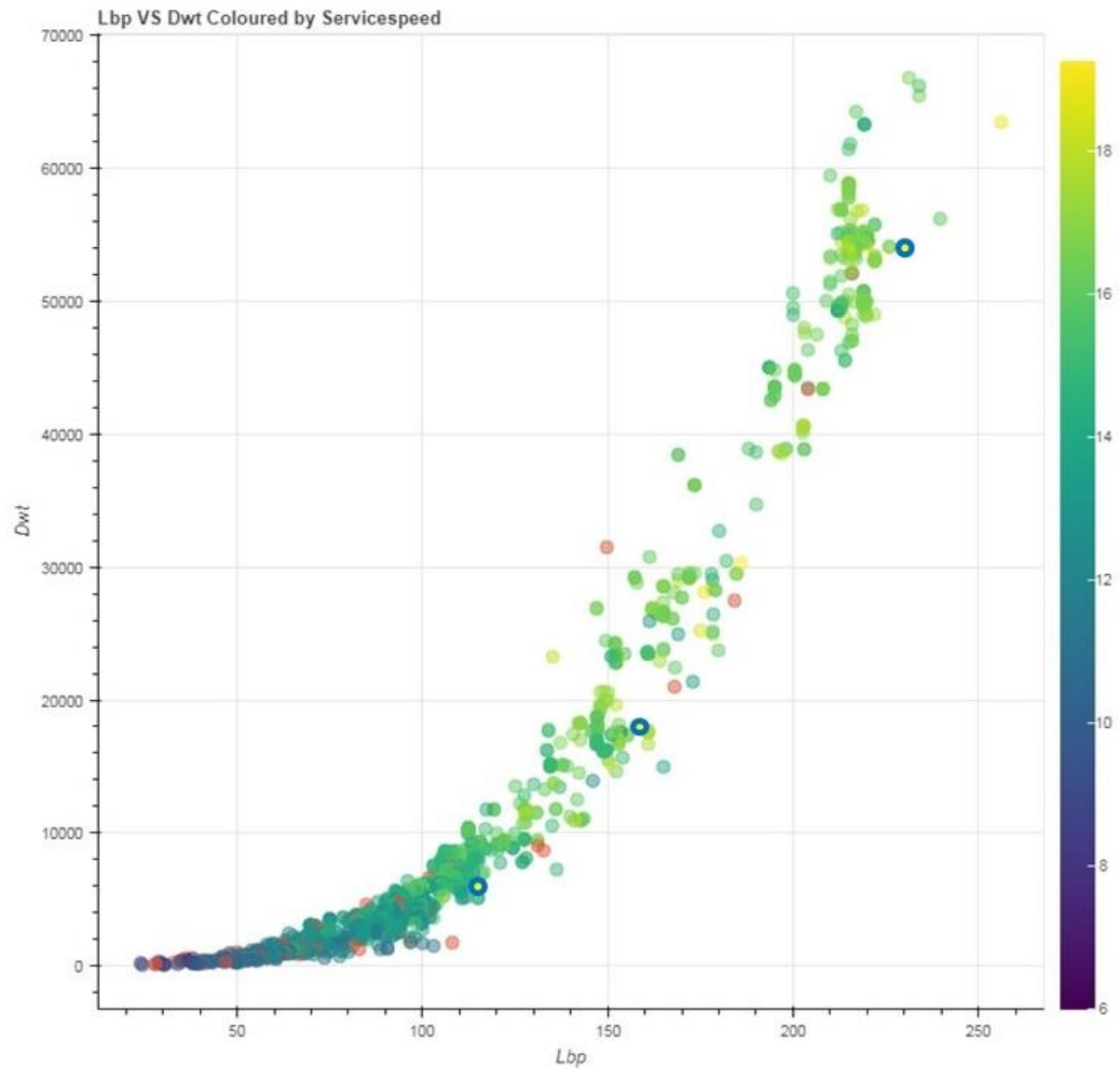
## APPENDIX D: REFERENCE VESSELS

Summary of reference vessels, LPG tankers/ammonia carriers

Lbp: Length between perpendiculars [m]

Dwt: Deadweight [ton]

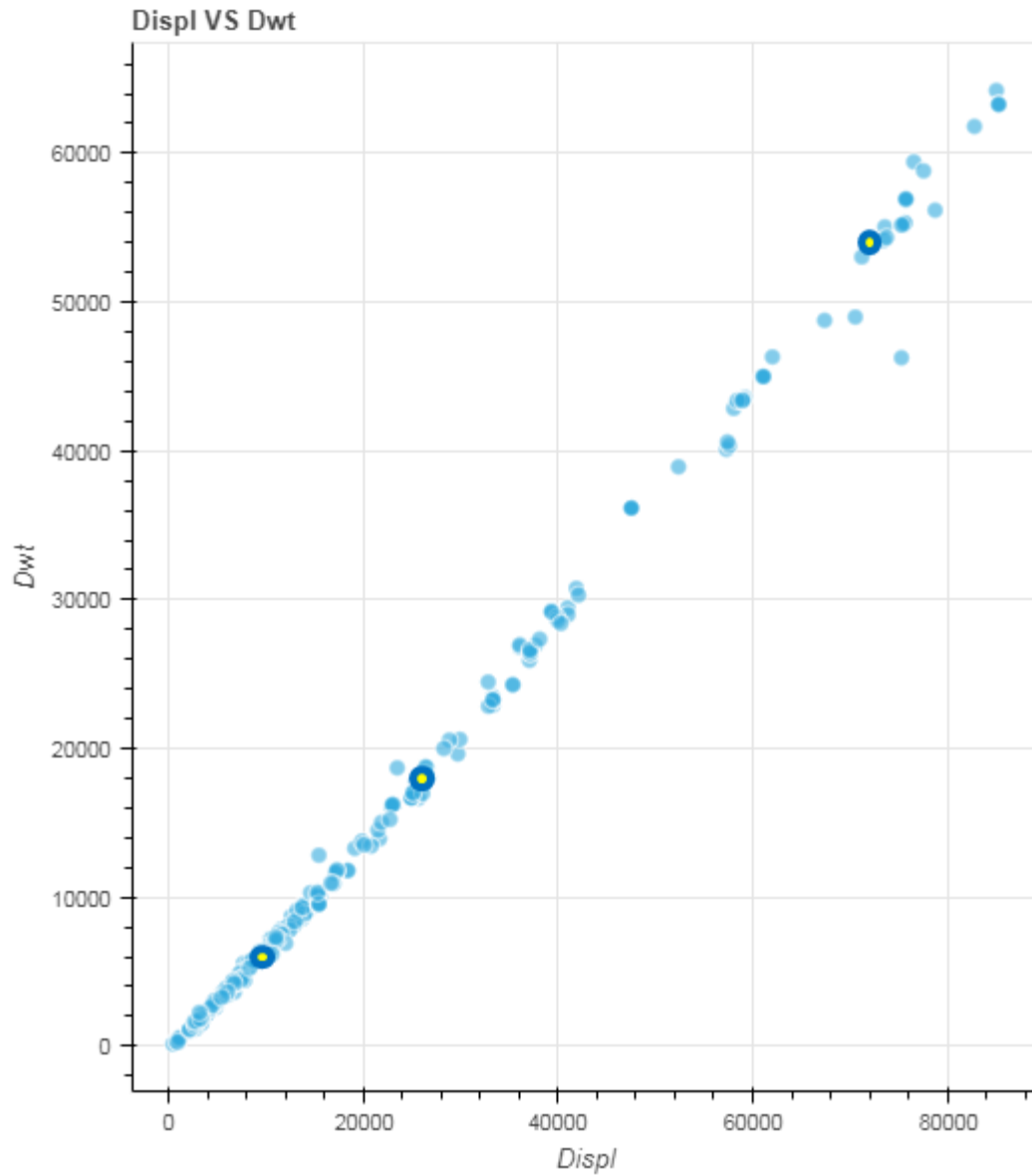
Servicespeed: Service speed [kts]



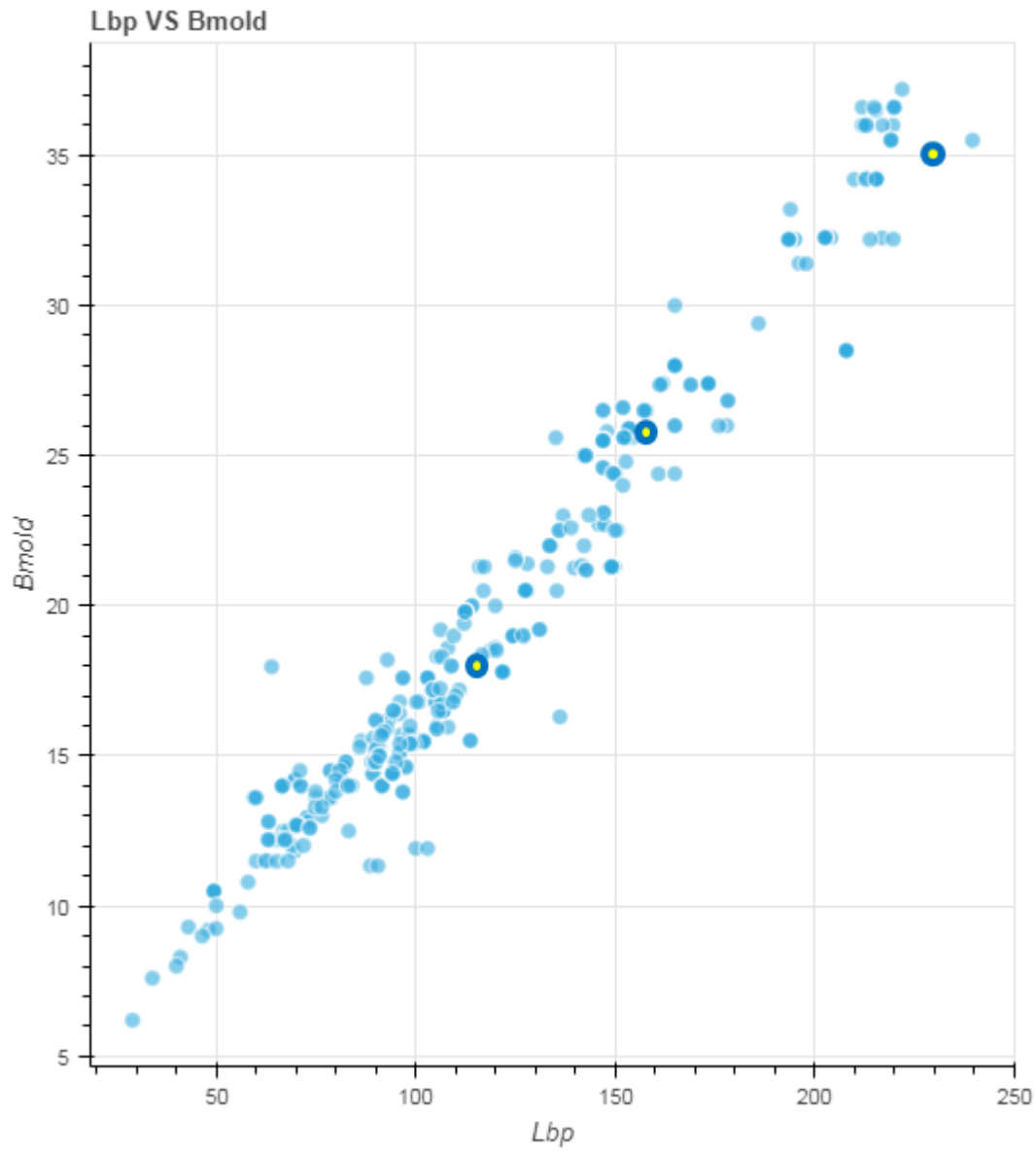


Displ: Displacement [ton]

Dwt: Deadweight [ton]

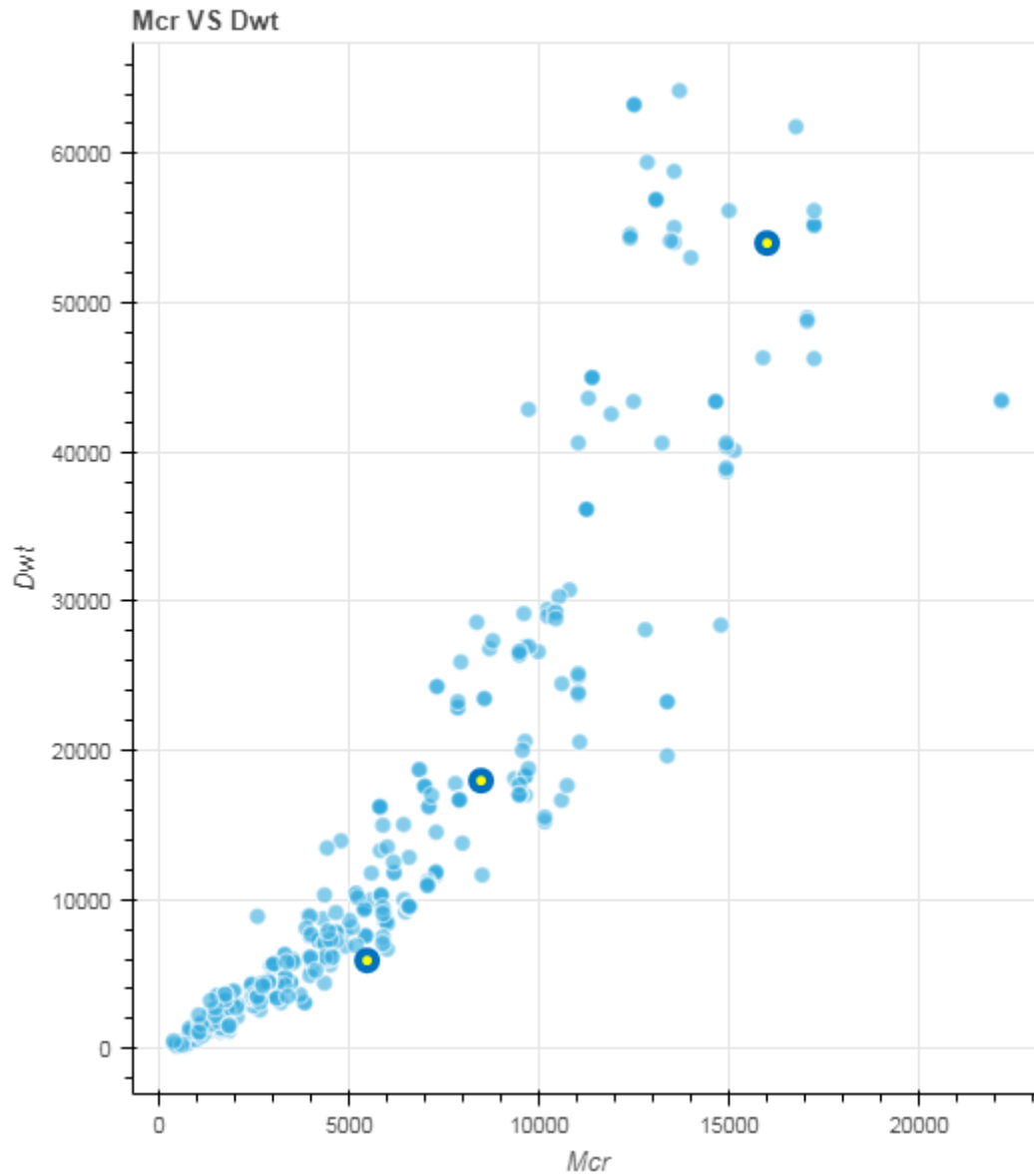


Lbp: Length between perpendiculars [m]  
Bmold: Breadth moulded [m]



Mcr: Maximum continuous rating [kW]

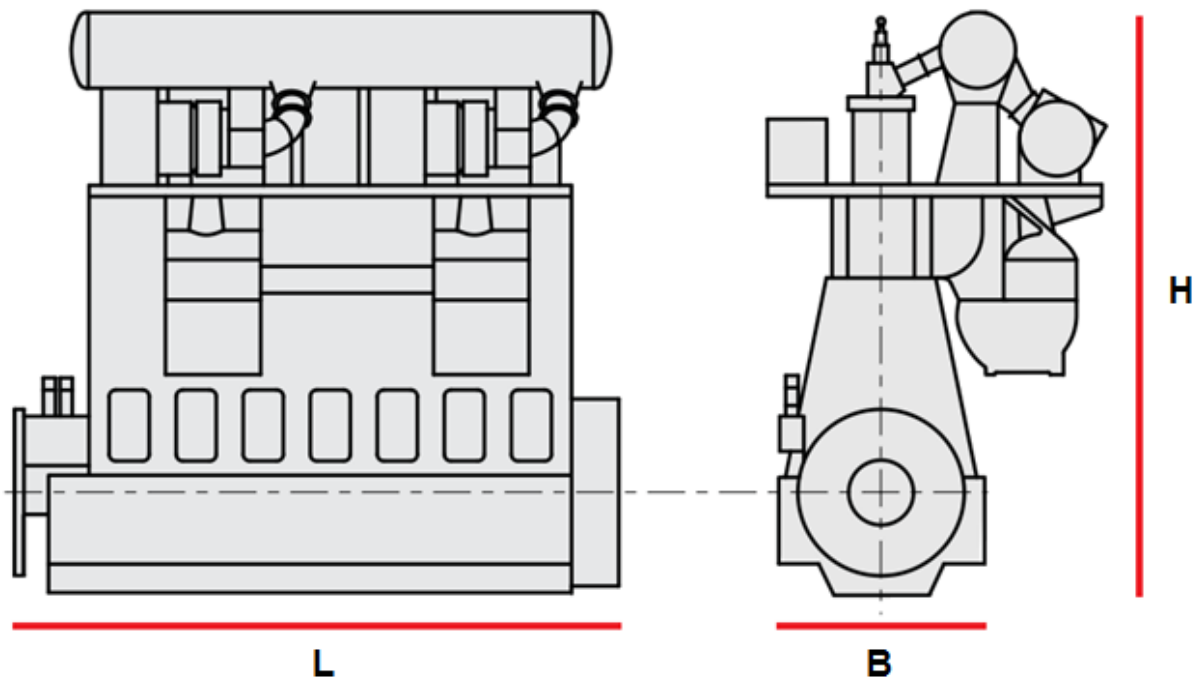
Dwt: Deadweight [ton]



## APPENDIX E: POWER DENSITY ICE (NATURAL GAS, DUAL FUEL)

Power density: Internal combustion engine (natural gas, dual fuel)

Reference: WinGD X62DF – 6 cylinders 14,310 kW



Example figure for definition of measurements only.

L [m]: 9.776

B [m]: 4.200

H [m]: 11.860

Mass [ton]: 377

Power density [kW/ton]: 38

Volumetric power density [kW/m<sup>3</sup>]: 29

## APPENDIX F: NOX EMISSIONS SMALL DIESEL ENGINES

Approximation of NOx emissions of small diesel engines/diesel-cars:

Reference car used for conversion of g/km to g/kWh: BMW 3 series (E90), 320D



Courtesy of BMW AG / Autoweek.nl

Distance [km]	1.0
Consumption [l/100 km]	5.7
Fuel volume [dm <sup>3</sup> ]	0.057
Fuel density [kg/m <sup>3</sup> ]	0.846
Fuel mass [kg]	0.048
Fuel lower heating value [MJ/kg]	42.6
Energy in [MJ/km]	2.05
Energy in [kWh/km]	0.57
Eta engine	0.30
Energy out [kWh/km]	0.17
*NOx [g/km]	1.2-1.7
NOx [g/kWh]	7.0-9.9

\*As per reference in thesis report to TNO report.

## APPENDIX G: HEAT BALANCE ICE

Calculation of heat demand evaporator and cracker, internal combustion engine at 100% power:

			Assumptions/reference:
<b>1 - Exhaust gas temperature</b>			
Engine power	14,310	[kW]	Ship 54,000 ton DWT
Engine efficiency	0.50	[-]	Ammonia hydrogen mixture
Energy consumption	28,620	[kW]	
Ammonia flow	21,751	[kJ/s]	70%v = 76%e = 95%m
Hydrogen flow	6,869	[kJ/s]	30%v = 24%e = 5%m
Ammonia mass flow	1.169	[kg/s]	
Hydrogen mass flow	0.057	[kg/s]	
Ammonia stoichiometric air mass flow	6.1	[kg/kg]	
Hydrogen stoichiometric air mass flow	34.3	[kg/kg]	
Air excess ratio	2.0	[-]	Assumed to be sufficient for complete and correct combustion
Air mass flow	18.19	[kg/s]	
Total mass flow	19.42	[kg/s]	
Mass flow exhaust gas	<b>19.42</b>	[kg/s]	
Mass flow excess air	9.10	[kg/s]	
Mass flow water vapour (ammonia)	1.86	[kg/s]	
Mass flow water vapour (hydrogen)	0.51	[kg/s]	
Mass flow nitrogen (ammonia)	6.25	[kg/s]	
Mass flow nitrogen (hydrogen)	1.59	[kg/s]	
Check - Mass flow exhaust gas	19.31	[kg/s]	Minor difference due to simplification of air (nitrogen and oxygen only)
<b>Composition exhaust gas</b>			
Air	47%	[-]	
Water vapour	12%	[-]	
Nitrogen	41%	[-]	
<b>Specific heat</b>			
			Conservative simplified approach cp: 700K
Air	1.075	[kJ/kg K]	Engineeringtoolbox.com
Water vapour	2.080	[kJ/kg K]	Engineeringtoolbox.com
Nitrogen	1.098	[kJ/kg K]	Engineeringtoolbox.com
Specific heat exhaust gas	<b>1.208</b>	[kJ/kg K]	
Exhaust gas heat availability	<b>8,586</b>	[kW]	30% Energy consumption [P.van Maanen, Scheepsdieselmotoren]
Start Temperature fuel and air mixture	298	[K]	
Delta Temperature exhaust gas	<b>368</b>	[K]	$\Delta T = \frac{Q}{m \cdot c_p}$
Temperature exhaust gas	666	[K]	
Temperature exhaust gas	393	[°C]	

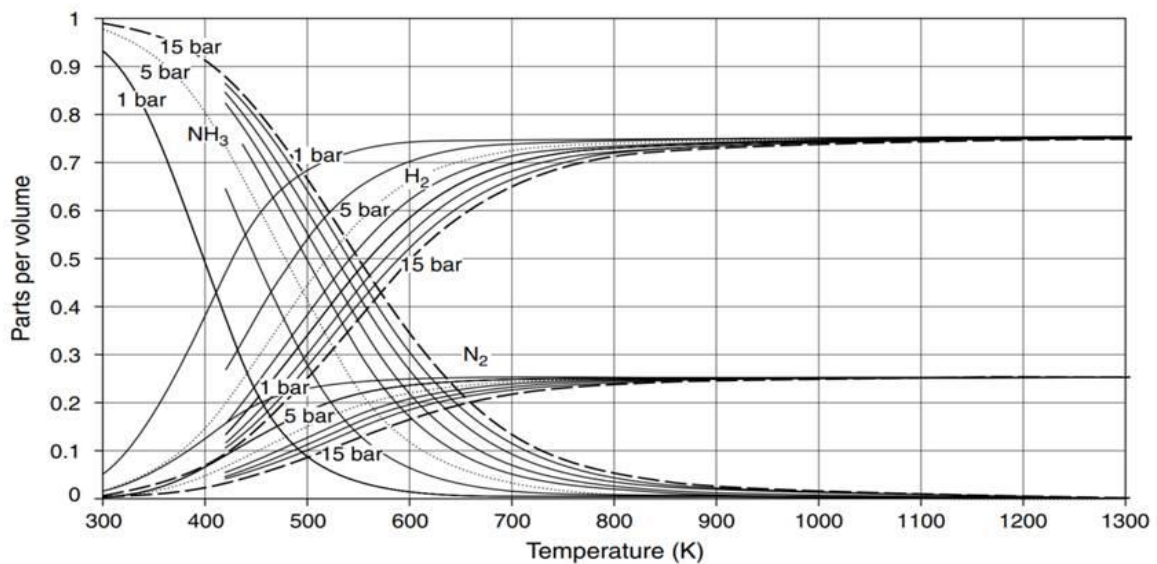
## 2 -Ammonia vapourization

### Demand

Direct ammonia flow	1.169	[kg/s]
Direct hydrogen flow	0.057	[kg/s]
Indirect ammonia flow	0.322	[kg/s]
Total ammonia flow	1.492	[kg/s]

### Supply

Boil-off	0.895	[kg/s]	0.06 kg/h per ton ammonia Proton Ventures guideline
Additional (to be vapourized)	1.492	[kg/s]	Conservative approach, boil-off assumed 0 for worst case: sailing back with only fuel
Ammonia heat of evaporation	1,372	[kJ/kg]	Engineeringtoolbox.com
Exhaust heat consumption	2,047	[kW]	



Ammonia crackers V. Hacker and K. Kordesch Volume 3 Part 2 pp 121-127, John Wiley & Sons, Ltd, Chichester, 2003

<b>3 - Ammonia cracking</b>			1 bar 500K (91% effective)
Input cracker ammonia flow	0.355	[kg/s]	Indirect flow + 10% of indirect flow from direct flow
<b><u>Temperature increase</u></b>			
Start Temperature ammonia flow	239	[K]	
End Temperature ammonia flow	500	[K]	Check: Lower than exhaust gas temperature
Delta Temperature ammonia flow	261	[K]	
Specific heat ammonia gas	2.483	[kJ/kg K]	Conservative simplified approach cp: 500K Engineeringtoolbox.com
Exhaust heat consumption part 1	230	[kW]	
<b><u>Cracking</u></b>			
Heat demand cracking ammonia	2,695	[kJ/kg]	Derived from enthalpy of formation, Engineeringtoolbox.com
Exhaust heat consumption part 2	956	[kW]	
<b><u>Total</u></b>			
Exhaust heat consumption	1,186	[kW]	
<b>4 - Balance</b>			
<b><u>Supply</u></b>			
Exhaust gas heat supply	8,586	[kW]	
<b><u>Demand</u></b>			
Exhaust gas heat vapourization	2,047	[kW]	
Exhaust gas heat cracking	1,186	[kW]	
<b><u>Remainder</u></b>			
Exhaust gas heat remainder	5,354	[kW]	Considered sufficient to account for heat losses



## APPENDIX H: LESS INCOME CALCULATION

Less income calculation:

Case		
Single trip	5,000	[nm]
Retour (Autonomy)	10,000	[nm]
Speed	16	[kts]
Duration retour	625	[hours]
DWT	54,000	[ton]

		Base	NH3			
		Conventional	ICE	PEMFC	AFC	SOFC
Operational point (average)	[kW]	12,942	12,280	13,398	13,122	13,122
Output	[kWh]	8,088,750	7,675,000	8,373,750	8,201,250	8,201,250
Output	[MJ]	29,119,500	27,630,000	30,145,500	29,524,500	29,524,500
Eta	[-]	50%	51.6%	50.7%	50%	60%
LHV fuel	[MJ/ton]	40,000	18,600	18,600	18,600	18,600
Fuel mass	[ton]	1,456	2,879	3,197	3,175	2,646
Fuel margin	[-]	10%	10%	10%	10%	10%
DWT fuel	[ton]	1,602	3,167	3,516	3,492	2,910
DWT other	[ton]	300	300	300	300	300
DWT cargo	[ton]	52,098	50,533	50,184	50,208	50,790

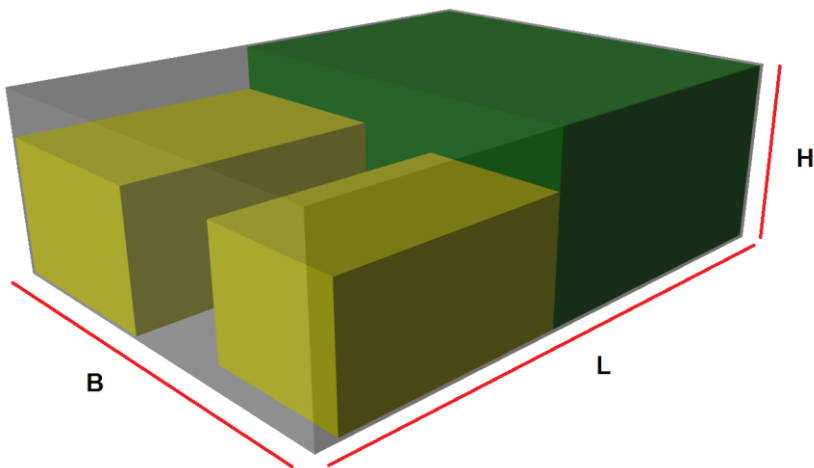
  

1 year	Conventional	ICE	PEMFC	AFC	SOFC
OPEX fuel	€7,571,000				
OPEX fuel total part	25%				
OPEX total	€30,284,000				
ΔOPEX (excl: less income)	€8,236,538				
OPEX base	€22,047,462				
OPEX total/DWT cargo per ton	€581				
Less cargo [ton]	-	1,565	1,915	1,891	1,309
Less income	€-	€909,801	€1,113,040	€1,089,960	€760,639

## APPENDIX I: POWER DENSITY PEMFC

Power density: PEMFC

Reference: Ballard FCveloCity-HD100 100 kW



	Fuel cell module	Coolant subsystem	Air subsystem
L [m]:	0.869	0.737	0.676
B [m]:	1.200	0.529	0.418
H [m]:	0.506	0.379	0.352
Mass [kg]:	285	44	61

PEMFC (added margin 5mm each side)

L [m]: 1.616

B [m]: 1.210

H [m]: 0.516

Mass [ton]: 0.390

Power density [kW/ton]: 256

Volumetric power density [kW/m<sup>3</sup>]: 99

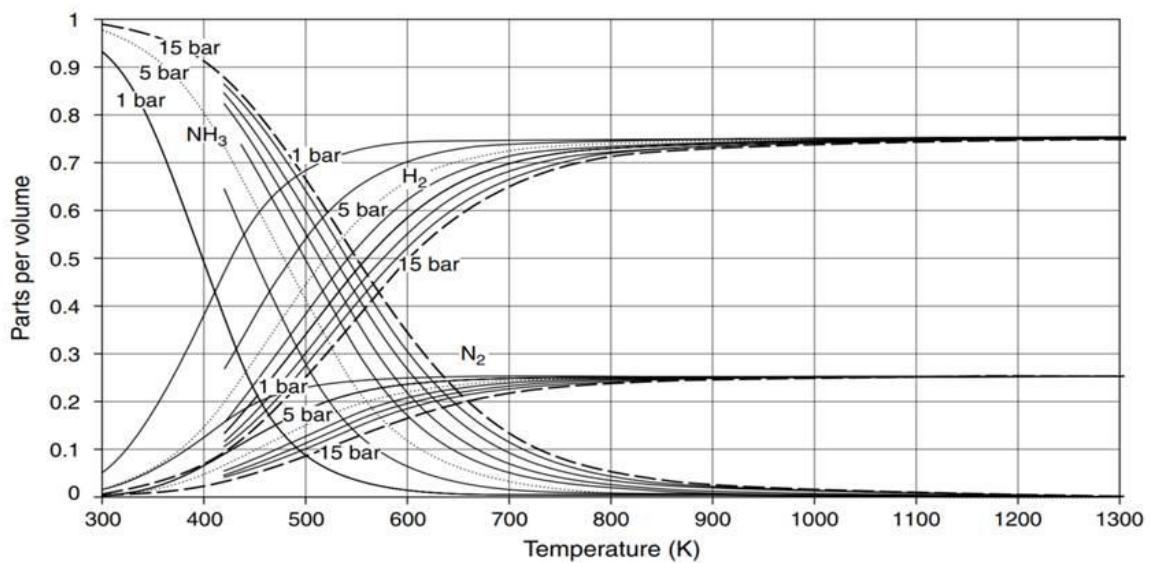
## APPENDIX J: AMMONIA FLOW BURNER, EVAPORATOR AND CRACKER PEMFC

Calculation of burner demand at operational design point PEMFC:

			Assumptions/source:
<b>1 - Fuel demand</b>			
PEMFC power	13,398	[kW]	Ship 54,000 ton DWT
PEMFC efficiency	0.55	[-]	Hydrogen
Energy consumption	24,360	[kW]	
Hydrogen flow	24,360	[kJ/s]	
Hydrogen mass flow	0.203	[kg/s]	
Ammonia fuel mass flow	1.143	[kg/s]	
<b>2 - Ammonia cracking</b>			
Ammonia fuel flow	1.143	[kg/s]	
<b>Temperature increase</b>			
Start Temperature ammonia flow	239	[K]	
End Temperature ammonia flow	700	[K]	
Delta Temperature ammonia flow	461	[K]	
Specific heat ammonia gas	2.937	[kJ/kg K]	Conservative simplified approach cp: 700K Engineeringtoolbox.com
Burner consumption part 1	1,548	[kW]	
<b>Cracking</b>			
Heat demand cracking ammonia	2,695	[kJ/kg]	Derived from enthalpy of formation, Engineeringtoolbox.com
Burner consumption part 2	3,081	[kW]	Minor difference with 3,093 kW due to rounding up calculation figures
<b>Total</b>			
Burner consumption total	4,629	[kW]	
<b>3 - Burner</b>			
<b>Demand</b>			
Burner demand	4,629	[kW]	
Burner effectiveness	0.90	[-]	10% heat loss
Ammonia burner flow	5,144	[kW]	
Ammonia burner flow	0.277	[kg/s]	

Calculation of evaporator and cracker flow, PEMFC at 100% power:

			Assumptions/source:
<b>1 - Fuel demand</b>			
PEMFC power	15,000	[kW]	Ship 54.000 ton DWT
PEMFC efficiency	0.55	[-]	Hydrogen
Energy consumption	27,273	[kW]	
Hydrogen flow	27,273	[kJ/s]	
Hydrogen mass flow	0.227	[kg/s]	
Ammonia fuel mass flow	1.280	[kg/s]	



Ammonia crackers V. Hacker and K. Kordesch Volume 3 Part 2 pp 121-127, John Wiley & Sons, Ltd, Chichester, 2003

<b>2 - Ammonia cracking</b>			
Ammonia fuel flow	1.280	[kg/s]	
<b>Temperature increase</b>			
Start Temperature ammonia flow	239	[K]	
End Temperature ammonia flow	700	[K]	
Delta Temperature ammonia flow	461	[K]	
Specific heat ammonia gas	2.937	[kJ/kg K]	Conservative simplified approach cp: 700K Engineeringtoolbox.com
Burner consumption part 1	1,733	[kW]	
<b>Cracking</b>			
Heat demand cracking ammonia	2,695	[kJ/kg]	Derived from enthalpy of formation, Engineeringtoolbox.com
Burner consumption part 2	3,450	[kW]	
<b>Total</b>			
Burner consumption total	5,183	[kW]	

**3 - Burner**

<b>Demand</b>			
Burner demand	5,183	[kW]	
Burner effectiveness	0.90	[-]	10% heat loss
Ammonia burner flow	5,759	[kW]	
Ammonia burner flow	0.310	[kg/s]	

**4 - Ammonia vapourization**

<b>Demand</b>			
Ammonia fuel flow	1.280	[kg/s]	
Ammonia burner flow	0.310	[kg/s]	
Total ammonia flow	1.590	[kg/s]	
<b>Supply</b>			
Boil-off	0.895	[kg/s]	0.06 kg/h per ton ammonia Proton Ventures guideline
Additional (to be vapourized)	1.590	[kg/s]	Conservative approach, boil-off assumed 0 for worst case: sailing back with only fuel

## APPENDIX K: POWER DENSITY AFC

Power density: AFC

Reference: GenCell A5 4 kW (fuel cell generator only)

Box measurement estimations:

L [m]: 1.200

B [m]: 0.600

H [m]: 1.000

Mass [ton]: 0.500

Power density [kW/ton]: 8

Volumetric power density [kW/m<sup>3</sup>]: 4

## APPENDIX L: AMMONIA FLOW EVAPORATOR AFC

Calculation of evaporator and cracker flow, AFC at 100% power:

			Assumptions/source:
<b>1 - Fuel demand</b>			
AFC power	15,000	[kW]	Ship 54,000 ton DWT
AFC efficiency	0.50	[-]	Ammonia
Energy consumption	30,000	[kW]	
Ammonia mass flow	1.613	[kg/s]	
<b>2 -Ammonia vapourization</b>			
<b><u>Demand</u></b>			
Ammonia flow	1.613	[kg/s]	
<b><u>Supply</u></b>			
Boil-off	0.895	[kg/s]	0.06 kg/h per ton ammonia Proton Ventures guideline
Additional (to be vapourized)	1.613	[kg/s]	Conservative approach, boil-off assumed 0 for worst case: sailing back with only fuel

## APPENDIX M: POWER DENSITY SOFC

Power density: SOFC

Reference: SOLIDpower BlueGEN 1.50 kW (AC), 1.67 kW (DC)

Box measurements:

L [m]: 0.660

B [m]: 0.600

H [m]: 1.010

Mass [ton]: 0.195

Assumed 50% covers fuel cell module, air subsystem and cooling subsystem as discussed in thesis report.

Power density [kW/ton]: 17

Volumetric power density [kW/m<sup>3</sup>]: 8



## APPENDIX N: AMMONIA FLOW EVAPORATOR SOFC

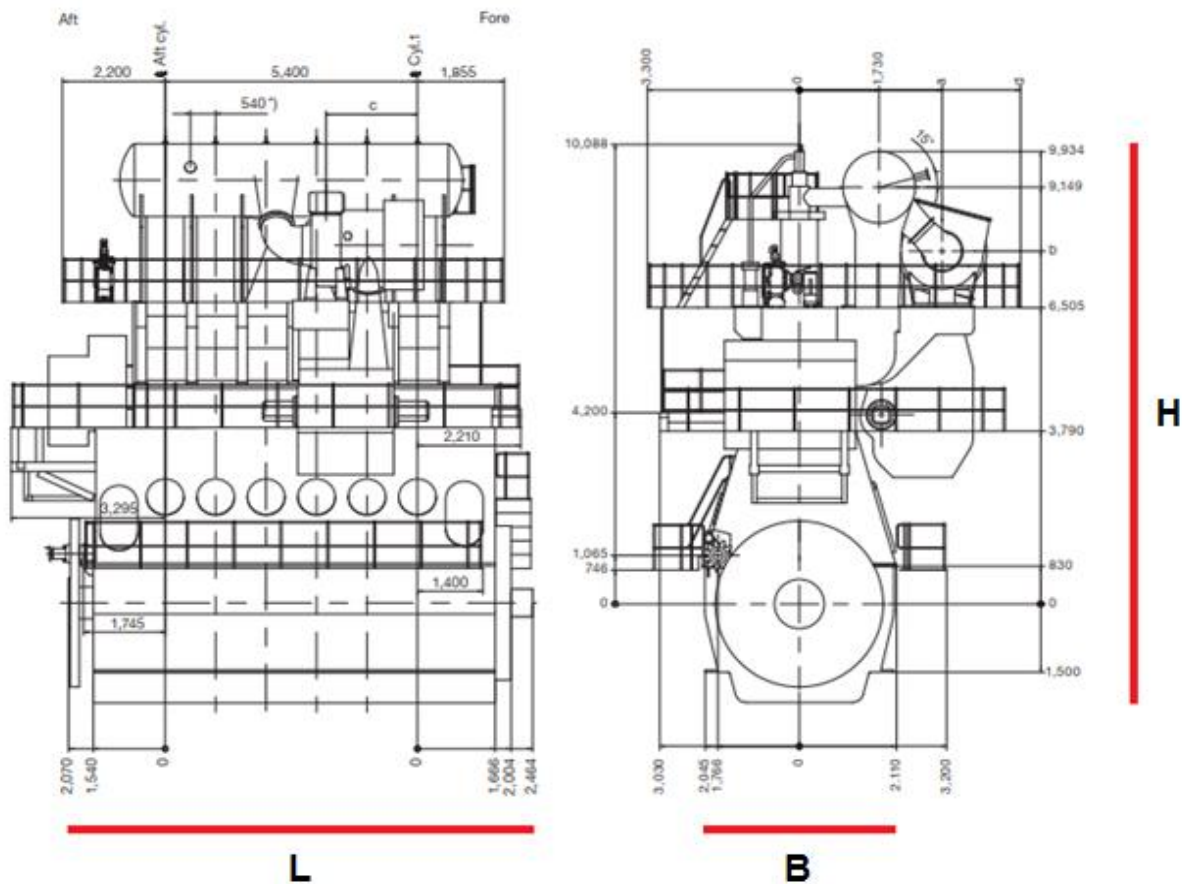
Calculation of evaporator flow, SOFC at 100%:

			Assumptions/source:
<b>1 - Fuel demand</b>			
SOFC power	15,000	[kW]	Ship 54,000 ton DWT
SOFC efficiency	0.60	[-]	Ammonia
Energy consumption	25,000	[kW]	
Ammonia mass flow	1.344	[kg/s]	
<b>2 -Ammonia vapourization</b>			
<b><u>Demand</u></b>			
Ammonia flow	1.344	[kg/s]	
<b><u>Supply</u></b>			
Boil-off	0.895	[kg/s]	0.06 kg/h per ton ammonia Proton Ventures guideline
Additional (to be vapourized)	1.344	[kg/s]	Conservative approach, boil-off assumed 0 for worst case: sailing back with only fuel

## APPENDIX O: POWER DENSITY ICE (CONVENTIONAL)

Power density: Internal combustion engine (conventional)

Reference: MAN G60ME – 6 cylinders 16,080 kW



Example figure for definition of measurements only.

L [m]: 9.934

B [m]: 4.155

H [m]: 12.257

Mass [ton]: 453

Power density [kW/ton]: 35

Volumetric power density [kW/m<sup>3</sup>]: 32

## APPENDIX P: COST CALCULATION 6K & 18K TON DWT

Cost calculations 6,000 ton DWT:

### General data: ICE (NH3) & Conventional

	[kWe]	[kW]
Main engine		5,500
Engine margin 10%		5,377
Engine margin 15%		5,693
Operational point		4,839
Proppeller shaft		4,500
Hotel	130	147
Re-liq.	0	0
Main engine support	170	192

Main engine running time	6500	[h]
Main engine output	31,455,882	[kWh]
Main engine output	113,241,176	[MJ]
Ammonia	11,799	[ton]
OR		
Low sulphur 0.5% HFO	5,662	[ton]

## Less income:

## Case

Single trip	2,000	[nm]
Retour (Autonomy)	4,000	[nm]
Speed	14	[kts]
Duration retour	286	[hours]
DWT	6,000	[ton]

		Base	NH3
		Conventional	ICE
Operational point (average)	[kW]	4,839	4,839
Output	[kWh]	1,382,571	1,382,571
Output	[MJ]	4,997,257	4,997,257
Eta	[-]	50.0%	51.6%
LHV fuel	[MJ/ton]	40,000	18,600
Fuel mass	[ton]	249	519
Fuel margin	[-]	10%	10%
DWT fuel	[ton]	274	570
DWT other	[ton]	100	100
DWT cargo	[ton]	5,626	5,330

1 year	Conventional	ICE
OPEX fuel	€2,831,029	
OPEX fuel total part	25%	
OPEX total	€11,324,116	
ΔOPEX (excl: less income)	€3,074,765	
OPEX base	€8,249,351	
OPEX total/DWT cargo per ton	€2,013	
Less cargo [ton]	-	297
Less income	€-	€597,185

**ΔCAPEX: Scenario 1**

	ICE (NH3)	Conventional
Main engine	€2,200,000	€2,200,000
Cracker	€1,502,795	€-
Evaporator	€1,166,108	€-
DeNOx	€220,000	€220,000
ΔCAPEX	€5,088,903	€2,420,000

**ΔOPEX (1 year): Scenario 1**

	ICE (NH3)	Conventional
Main engine	€55,000	€55,000
Cracker	€15,028	€-
Evaporator	€11,661	€-
Fuel	€10,029,070	€2,831,029
DeNOx	€188,735	€188,735
Less income	€597,185	€-
ΔOPEX	€10,896,679	€3,074,765

**ΔCAPEX: Scenario 4  
(400 €/ton NH3 & 100 €/ton CO2)**

	ICE (NH3)	Conventional
Main engine	€2,200,000	€2,200,000
Cracker	€1,502,795	€-
Evaporator	€1,166,108	€-
DeNOx	€220,000	€220,000
ΔCAPEX	€5,088,903	€2,420,000

**ΔOPEX (1 year): Scenario 4  
(400 €/ton NH3 & 100 €/ton CO2)**

	ICE (NH3)	Conventional
Main engine	€55,000	€55,000
Cracker	€15,028	€-
Evaporator	€11,661	€-
Fuel	€4,719,562	€4,594,195
DeNOx	€188,735	€188,735
Less income	€597,185	€-
ΔOPEX	€5,587,172	€4,837,930

Cost calculations 18,000 ton DWT:

**General data:  
ICE (NH3)**

	[kWe]	[kW]
Main engine		8,000
Engine margin 10%		7,750
Engine margin 15%		8,206
Operational point		6,975
Proppeller shaft		6,500
Hotel	180	204
Re-liq.	0	0
Main engine support	240	271
Main engine running time	6500	[h]
Main engine output	45,338,235	[kWh]
Main engine output	163,217,647	[MJ]
Ammonia	17,006	[ton]

**General data:  
Conventional**

	[kWe]	[kW]
Main engine		8,500
Engine margin 10%		8,215
Engine margin 15%		8,698
Operational point		7,394 50% 6,998 50%
Proppeller shaft		6,500
Hotel	180	204
Re-liq.	350	396
Main engine support	260	294
Main engine running time	6500	[h]
Main engine output	46,772,059	[kWh]
Main engine output	168,379,412	[MJ]
Low sulphur 0.5% HFO	8,419	[ton]

**Less income:  
Case**

Single trip	4,000	[nm]
Retour (Autonomy)	8,000	[nm]
Speed	15	[kts]
Duration retour	533	[hours]
DWT	18,000	[ton]

		Base	NH3
		Conventional	ICE
Operational point (average)	[kW]	7196	4,839
Output	[kWh]	3,837,867	1,382,571
Output	[MJ]	13,816,320	4,997,257
Eta	[-]	50.0%	51.6%
LHV fuel	[MJ/ton]	40,000	18,600
Fuel mass	[ton]	691	519
Fuel margin	[-]	10%	10%
DWT fuel	[ton]	760	1,535
DWT other	[ton]	200	200
DWT cargo	[ton]	17,040	16,265

1 year	Conventional	ICE
OPEX fuel	€4,209,485	
OPEX fuel total part	25%	
OPEX total	€16,837,940	
ΔOPEX (excl: less income)	€4,575,118	
OPEX base	€12,262,822	
OPEX total/DWT cargo per ton	€988	
Less cargo [ton]	-	775
Less income	€-	€765,792

**ΔCAPEX: Scenario 1**

	ICE (NH3)	Conventional
Main engine	€3,200,000	€3,400,000
Cracker	€2,185,884	€-
Evaporator	€1,696,157	€-
DeNOx	€320,000	€340,000
ΔCAPEX	€7,402,041	€3,740,000

**ΔOPEX (1 year): Scenario 1**

	ICE (NH3)	Conventional
Main engine	€80,000	€85,000
Cracker	€21,859	€-
Evaporator	€16,962	€-
Fuel	€14,455,176	€4,209,485
DeNOx	€272,029	€280,632
Less income	€765,792	€-
ΔOPEX	€15,611,818	€4,575,118

**ΔCAPEX: Scenario 4  
(400 €/ton NH3 & 100 €/ton CO2)**

	ICE (NH3)	Conventional
Main engine	€3,200,000	€3,400,000
Cracker	€2,185,884	€-
Evaporator	€1,696,157	€-
DeNOx	€320,000	€340,000
ΔCAPEX	€7,402,041	€3,740,000

**ΔOPEX (1 year): Scenario 4  
(400 €/ton NH3 & 100 €/ton CO2)**

	ICE (NH3)	Conventional
Main engine	€80,000	€85,000
Cracker	€21,859	€-
Evaporator	€16,962	€-
Fuel	€6,802,436	€6,831,153
DeNOx	€272,029	€280,632
Less income	€765,792	€-
ΔOPEX	€7,959,078	€7,196,785

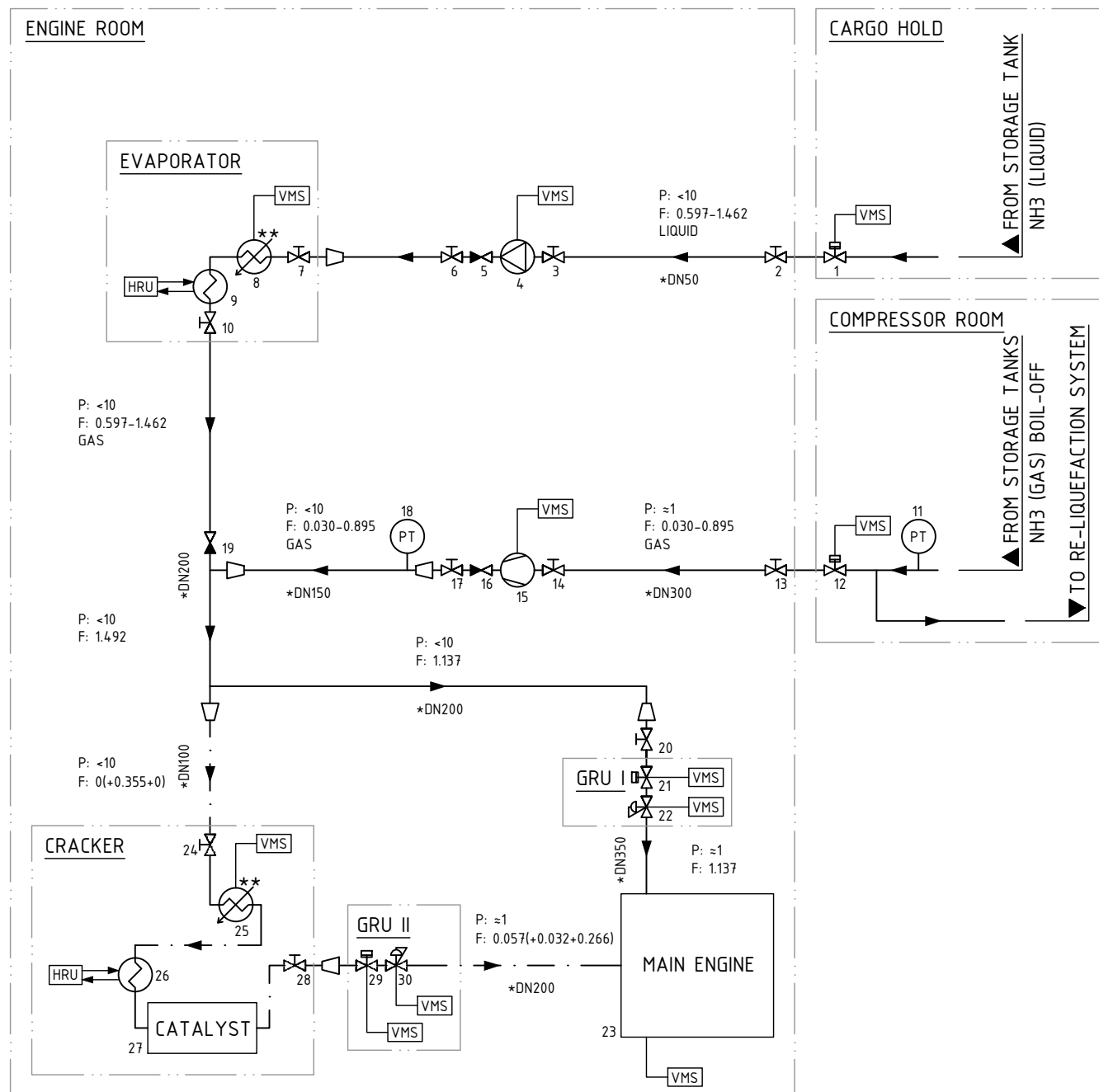


Cost comparisons (Conventional vs ICE (NH3)):

Scenario 1		DWT [ton]		
		6,000	18,000	54,000
ICE (NH3)	ΔCAPEX	€5,088,903	€7,402,041	€13,240,400
	ΔOPEX (1 year)	€10,896,679	€15,611,818	€27,050,261
	ΔTCO	€277,505,880	€397,697,493	€689,496,925
Conventional	ΔCAPEX	€2,420,000	€3,740,000	€7,075,200
	ΔOPEX (1 year)	€3,074,765	€4,575,118	€8,236,538
	ΔTCO	€79,289,118	€118,117,941	€212,988,650

Scenario 4 (400 €/ton NH3 & 100 €/ton CO2)		DWT [ton]		
		6,000	18,000	54,000
ICE (NH3)	ΔCAPEX	€5,088,903	€7,402,041	€13,240,400
	ΔOPEX (1 year)	€5,587,172	€7,959,078	€13,611,481
	ΔTCO	€144,768,192	€206,378,984	€353,527,425
Conventional	ΔCAPEX	€2,420,000	€3,740,000	€7,075,200
	ΔOPEX (1 year)	€4,837,930	€7,196,785	€12,955,838
	ΔTCO	€123,368,246	€183,659,627	€330,971,158

## APPENDIX Q: DIAGRAM NH3 FUEL SYSTEM (TECHNICAL BASIS)



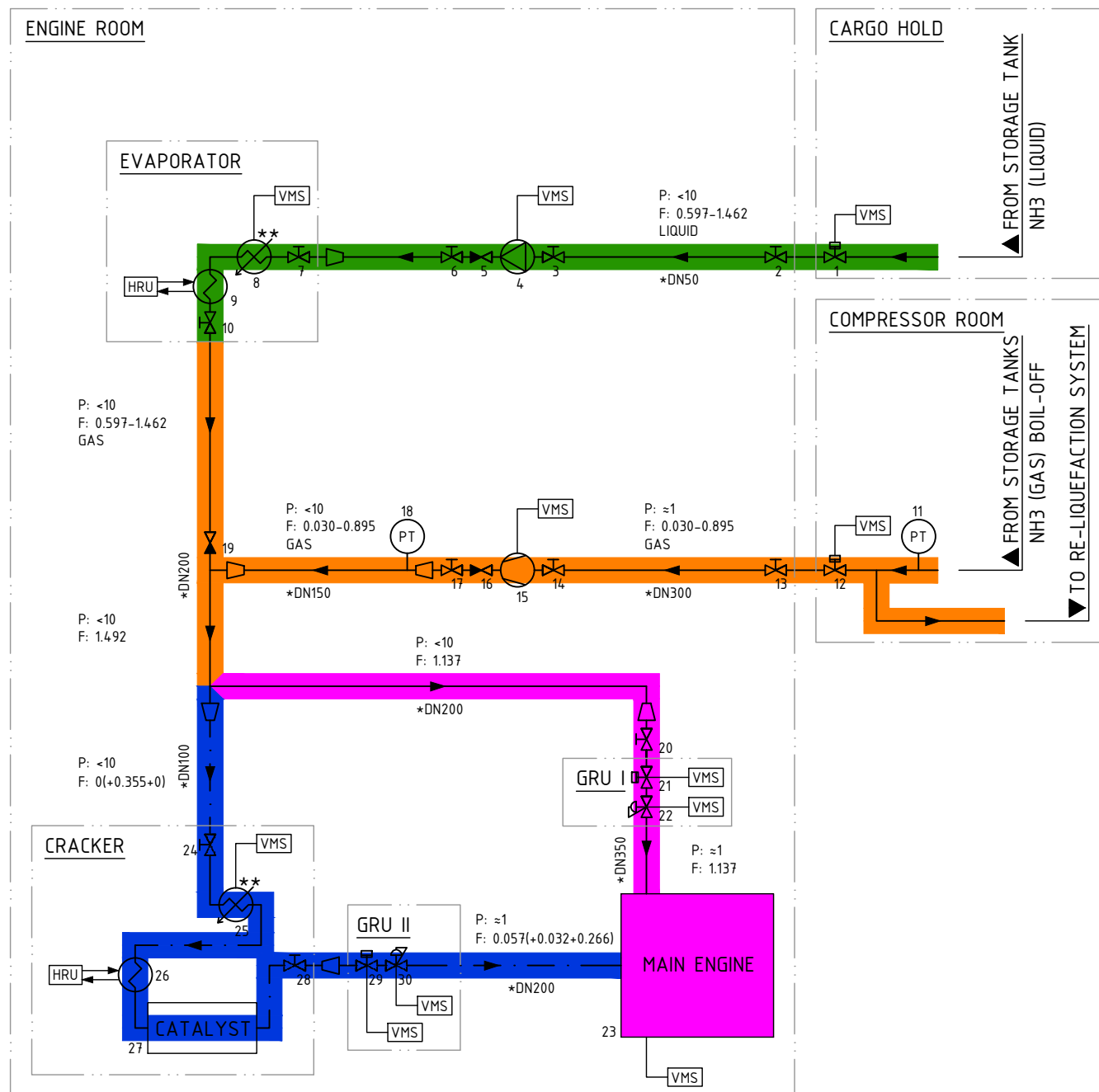
SYMBOLS					
	HAND OPERATED VALVE		REMOTE OPERATED VALVE		
	NON RETURN VALVE		PRESSURE REGULATING VALVE		
	REDUCER		PRESSURE TRANSMITTER		
	COMPRESSOR		CENTRIFUGAL PUMP		
	HEAT EXCHANGER		HEATER		

LEGEND					
<p>— NH3 FUEL</p> <p>- - - H2(+NH3+N2) FUEL</p>					

NOTES					
<p>PIPE INDICATION:  P: PRESSURE bar  F: FLOW kg/s  STATE OF MATTER (GAS, UNLESS NOTED OTHERWISE)</p> <p>HRU: EXHAUST GAS HEAT RECOVERY UNIT  GRU: GAS REGULATING UNIT  VMS: VESSEL MANAGEMENT SYSTEM (POWER SUPPLY AND CONTROL)</p> <p>*) PROVISIONAL DIMENSIONS  **) START-UP POWER ONLY</p> <p>INERT GAS SYSTEM TO EMPTY FUEL LINES FOR MAINTENANCE TO BE ADDED</p>					
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412
REV.	DESCRIPTION	DRAWN	CHECK.	APPR.	DATE
CLIENT PROJECT NO.:		CLIENT DRAWING NO.:			
CLIENT: -		YARD NO.: -	CLASS NO.: -		
PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY			
TITLE: DIAGRAM NH3 FUEL SYSTEM (TECHNICAL BASIS)					
PROJECTION: 	DIM. UNIT: mm	COPYRIGHT OF C-JOB, WHOSE PROPERTY THIS DOCUMENT REMAINS. NO PART THEREOF MAY BE DISCLOSED, COPIED, DUPLICATED OR IN ANY OTHER WAY MADE USE OF EXCEPT WITH THE APPROVAL OF C-JOB.	REV.: A	SHEET: 1-1	SCALE: N.A.
		FORMAT: A2			



### COLOUR CODING

- NODE 1: MAIN LIQUID AMMONIA SUPPLY
- NODE 2: MAIN GASEOUS AMMONIA SUPPLY
- NODE 3: AMMONIA ENGINE SUPPLY
- NODE 4: HYDROGEN ENGINE SUPPLY

### SYMBOLS

	HAND OPERATED VALVE		REMOTE OPERATED VALVE
	NON RETURN VALVE		PRESSURE REGULATING VALVE
	REDUCER		PRESSURE TRANSMITTER
	COMPRESSOR		CENTRIFUGAL PUMP
	HEAT EXCHANGER		HEATER

### LEGEND

- NH3 FUEL
- H2(+NH3+N2) FUEL

### NOTES

PIPE INDICATION:  
P: PRESSURE bar  
F: FLOW kg/s  
STATE OF MATTER (GAS, UNLESS NOTED OTHERWISE)

HRU: EXHAUST GAS HEAT RECOVERY UNIT  
GRU: GAS REGULATING UNIT  
VMS: VESSEL MANAGEMENT SYSTEM (POWER SUPPLY AND CONTROL)

- \*) PROVISIONAL DIMENSIONS
- \*\*\*) START-UP POWER ONLY

INERT GAS SYSTEM TO EMPTY FUEL LINES FOR MAINTENANCE TO BE ADDED

REV.	DESCRIPTION	DRAWN	CHECK.	APPR.	DATE
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412

CLIENT PROJECT NO.: \_\_\_\_\_ CLIENT DRAWING NO.: \_\_\_\_\_



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CLIENT: -	YARD NO.: -	CLASS NO.: -
PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY
TITLE: DIAGRAM NH3 FUEL SYSTEM (TECHNICAL BASIS)		
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FORMAT: A2		

## APPENDIX R: FAILURE MODES RISK ASSESSMENT 1

Failure modes risk assessment 1:

<b>Cause:</b>	Identified in system	Various	Various
<b>General Description:</b>	Partial or complete equipment function failure	Leakage	Blockage
<b>Component:</b>	<b>Failure Modes:</b>		
Piping	None, passive equipment	External leakage	None, passive equipment
Hand operated valve	Blocking flow OR unable to stop flow	External leakage	Blocking flow
Non return valve	Blocking flow OR unable to stop counter flow	External leakage	Blocking flow
Remote operated valve	Blocking flow OR unable to stop flow	External leakage	Blocking flow
Pressure regulating valve	Unable to regulate pressure (too high/low) AND/OR blocking flow	External leakage	Blocking flow
Pump	Unable to provide flow OR unable to stop flow	External leakage	Blocking flow
Compressor	Unable to provide flow OR unable to stop flow	External leakage	Blocking flow
Pressure transmitter	Unable to indicate pressure (too high/low or not at all)	External leakage	None
Heater	Unable to provide heat or unable to stop heat supply	External leakage	None
Heat exchanger	Blocking flow AND unable to transfer heat	External leakage OR internal leakage	Blocking flow
Catalyst	None, passive equipment	External leakage	Blocking flow
Main engine	Unable to provide mechanical power OR unable to stop mechanical power supply	External leakage	Blocking flow

Failure Mode:	Fire	Flooding	Blackout
Component:	Effects:		
Piping	Increase in temperature and pressure within system	Exposed to water (pressure)	None
Hand operated valve			None
Non return valve			None
Remote operated valve			Shut down if installed with fail close
Pressure regulating valve			Loss of pressure regulation
Pump			Shut down loss of flow
Compressor			Shut down loss of flow
Pressure transmitter			Shut down
Heater			Shut down loss of heat supply
Heat exchanger			Indirect loss of heat supply
Catalyst		None	
Main engine		Shut down complete loss of mechanical power supply	

## APPENDIX S: RISK ASSESSMENT 1

Risk assessment 1:

### Nodes

- 1-S-XX Main liquid ammonia supply
- 2-S-XX Main gaseous ammonia supply
- 3-S-XX Ammonia engine supply
- 4-S-XX Hydrogen engine supply
- 5-S-XX Entire system

### Subsection

- 1-1-XX Routing in Cargo Hold
- 1-2-XX Routing from Cargo Hold to Engine Room
- 1-3-XX Routing in Engine Room
  
- 2-1-XX Routing in Compressor Room
- 2-2-XX Routing from Compressor Room to Engine Room
- 2-3-XX Routing in Engine Room
  
- 3-1-XX Routing in Engine Room
  
- 4-1-XX Routing in Engine Room
  
- 5-1-XX Entire system

### Risk ID number

- N-S-01 Risk 01
- N-S-02 Risk 02

Green marked text in the mitigation column is a mitigation already mentioned in a previous risk of its corresponding subsection.

Reference	Failure Mode	Cause	Effect	Detection	Original Risk Ranking	Mitigation	Overall Assessment	Final Risk Ranking
1-1-01	Completely unable to open valve 1	VMS error/bug	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
1-1-02	Completely unable to close valve 1	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	A4	-	-	A4
1-1-03	Ammonia leakage in cargo hold	Various	Cargo hold exposed with liquid and gaseous ammonia	-	E2	1. Add ammonia detection 2. Add ventilation 3. Add redundancy in supply line	Ammonia detection alerts crew and enables them to close valve 1 stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Redundancy assures operation can continue reducing the impact.	C2
1-1-04	Fire in cargo hold	Various	Increase in temperature and pressure within system	Pressure transmitter storage tank	E1	1. Add redundancy in supply line from other source located in different cargo hold 2. Add pressure transmitter 3. Add pressure relieve system	Pressure transmitter alerts crew. Valve 1 can be closed to isolate pressure and temperature in the system. Ammonia can be released by means of the pressure relieve system after valve 1. The pressure buildup before valve 1 can be reduced by the pressure relieve system of the storage tank. Fire can be suppressed by cutting oxygen supply to cargo hold. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
1-1-05	Flooding and ammonia leakage in cargo hold	Ship collision	Cargo hold and environment exposed with liquid and gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side. 2. Add ammonia detection 3. Add flow detection 4. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close valve 1 limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
1-2-01	Ammonia leakage in unidentified area (between cargo hold and engine room)	Various	Unidentified area (between cargo hold and engine room) exposed with liquid and gaseous ammonia	-	E4	1. Locate piping in separate trunk 2. Add ammonia detection 3. Add ventilation 4. Add redundancy in supply line	Locating piping in separate trunk reduces the likelihood and impact of leakage. Ammonia detection alerts crew and enables them to close valve 1 stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Redundancy assures operation can continue reducing the impact.	C2



1-2-02	Fire in unidentified area (between cargo hold and engine room)	Various	Increase in temperature and pressure within system	-	E3	1. Locate piping in separate trunk 2. Add pressure transmitter 3. Add pressure relieve system 4. Add redundancy in supply line	Locating piping in separate trunk reduces the likelihood for exposure to fire. Pressure transmitter alerts crew and enables them to close valve 1 stopping the ammonia supply. Pressure relieve system release remaining ammonia to reduce impact. Redundancy assures operation can continue reducing the impact.	C2
1-2-03	Flooding and ammonia leakage in unidentified area (between cargo hold and engine room)	Ship collision	Unidentified area (between cargo hold and engine room) and environment exposed with liquid and gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side. 2. Add ammonia detection 3. Add flow detection 4. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close valve 1 limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
1-3-01	Completely unable to open valve 2	Various	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
1-3-02	Completely unable to close valve 2	Various	Flow continuous	-	B4	1. Add flow detection	Flow detection alerts crew flow has not stopped yet and should be stopped by closing another valve, for example valve 3. Flow detection also alerts crew repairs are required.	A4
1-3-03	Completely unable to (re)start pump 4	VMS error/bug	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
1-3-04	Completely unable to stop pump 4	VMS error/bug	Flow continuous	-	B4	1. Add flow detection	Flow detection alerts crew flow has not stopped yet and should be stopped by closing a valve, for example valve 2. Flow detection also alerts crew repairs are required.	A4
1-3-05	Completely unable to allow flow valve 5	Various	Unable to supply fuel to engine	-	D3	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A3
1-3-06	Completely unable to stop counterflow valve 5	Various	Counter flow in inactive pump	-	B3	1. Add flow detection	Flow detection alerts crew of counter flow and should be stopped by closing another valve, for example valve 3.	A3
1-3-07	Completely unable to supply heat heater 8	VMS error/bug	Unable to supply fuel to engine	-	D3	1. Add temperature transmitter 2. Add pressure transmitter 3. Add redundancy in supply line	Temperature monitoring and pressure transmitter alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A3
1-3-08	Completely unable to stop heat supply heater 8	VMS error/bug	Temperature and pressure increase of fuel/gaseous ammonia supply	-	B4	1. Add temperature transmitter 2. Add pressure transmitter	Temperature monitoring and pressure transmitter alerts crew repairs are required and switch off HRU with heat exchanger to prevent overheating/high pressures.	A4

1-3-09	Complete blockage of flow and completely unable to transfer heat heat exchanger 9	Contamination	Unable to supply fuel to engine	-	D2	1. Add flow detection 2. Add temperature transmitter 3. Add pressure transmitter 4. Add redundancy in supply line	Temperature monitoring, pressure transmitter and flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A2
1-3-10	Leaking ammonia in HRU from heat exchanger 9	Various	Buildup of ammonia contamination in HRU	-	B3	1. Add ammonia detection in HRU return line	Ammonia detection alerts crew HRU is contaminated and that repairs are required.	A3
1-3-11	Ammonia leakage in engine room	Various	Engine room exposed with liquid and gaseous ammonia	-	E4	1. Locate piping outside of engine room 2. Add ammonia detection 3. Add ventilation 4. Add remote operated isolation valve 5. Add redundancy in supply line	Locating piping in separate space reduces the likelihood and impact of leakage. Ammonia detection alerts crew and enables them to close the added remote operated isolation valve stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Redundancy assures operation can continue reducing the impact.	C2
1-3-12	Fire in engine room	Various	Increase in temperature and pressure within system	-	E4	1. Locate piping outside of engine room 2. Add pressure transmitter 3. Add temperature monitoring 4. Add pressure relieve system 5. Add remote operated isolation valve 6. Add redundancy in supply line	Locating piping in space trunk reduces the likelihood for exposure to fire. Pressure transmitter and temperature monitoring alerts crew and enables them to close the added remote operated isolation valve stopping the ammonia supply. Pressure relieve system releases remaining ammonia to reduce impact. Redundancy assures operation can continue reducing the impact.	C2
1-3-13	Flooding and ammonia leakage in piping in engine room	Ship collision	Engine room and environment exposed with liquid and gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side. 2. Add ammonia detection 3. Add flow detection 4. Add remote operated isolation valve 5. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close the added remote operated isolation valve stopping limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
2-1-01	Completely unable to indicate pressure pressure transmitter 11	Various	Unable to regulate compressor for fuel and reliquefaction system. Pressure build up in storage tank engaging pressure relieve system of storage tank	-	C4	1. Add double redundant pressure transmitters	With 3 pressure transmitters in total 2 will always indicate the correct pressure when 1 fails. Impact reduced as correct operation is covered with 3 pressure transmitters.	A4
2-1-02	Completely unable to open valve 12	VMS error/bug	Unable to use boil-off for fuel, boil-off will be reliquefied	Pressure transmitter and reliquefaction system	A4	-	-	A4
2-1-03	Completely unable to close valve 12	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	A4	-	-	A4

2-1-04	Ammonia leakage in compressor room	Various	Compressor room exposed with liquid and gaseous ammonia	-	E2	1. Add ammonia detection 2. Add ventilation	Ammonia detection alerts crew and enables them to close valve 12 stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia.	C2
2-1-05	Fire in compressor room	Various	Increase in temperature and pressure within system	Pressure transmitter	E1	1. Add pressure relieve system	Pressure transmitter alerts crew. Valve 12 can be closed to isolate pressure and temperature in the system. Ammonia can be released by means of the pressure relieve system after valve 21. The pressure buildup before valve 12 can be reduced by the pressure relieve system of the storage tank. Fire can be suppressed by cutting oxygen supply to cargo hold. Likelihood to low for additional mitigation.	D1
2-2-01	Ammonia leakage in unidentified area (between cargo hold and engine room)	Various	Unidentified area (between compressor room and engine room) exposed with gaseous ammonia	-	E4	1. Locate piping in separate trunk 2. Add ammonia detection 3. Add ventilation	Locating piping in separate trunk reduces the likelihood and impact of leakage. Ammonia detection alerts crew and enables them to close valve 11 stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia.	C2
2-2-02	Fire in unidentified area (between compressor room and engine room)	Various	Increase in temperature and pressure within system	-	E3	1. Locate piping in separate trunk 2. Add pressure transmitter 3. Add pressure relieve system	Locating piping in separate trunk reduces the likelihood for exposure to fire. Pressure transmitter alerts crew and enables them to close valve 1 stopping the ammonia supply. Pressure relieve system release remaining ammonia to reduce impact. Redundancy assures operation can continue reducing the impact.	C2
2-2-03	Flooding and ammonia leakage in unidentified area (between compressor room and engine room)	Ship collision	Unidentified area (between compressor room and engine room) and environment exposed with liquid and gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side. 2. Add ammonia detection 3. Add flow detection	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close valve 11 limiting the impact. Likelihood to low for additional mitigation.	D1
2-3-01	Completely unable to open valve 13	Various	Unable to use boil-off for fuel, boil-off will be reliquefied	Pressure transmitter and reliquefication system	A4	-	-	A4
2-3-02	Completely unable to close valve 13	Various	Flow is stopped by inactive equipment in supply line	-	A4	-	-	A4
2-3-03	Completely unable to start compressor 15	VMS error/bug	Unable to use boil-off for fuel, boil-off will be reliquefied	Pressure transmitter and reliquefication system	A4	-	-	A4
2-3-04	Completely unable to stop compressor 15	VMS error/bug	Flow continuous	-	B4	1. Add flow detection	Flow detection alerts crew flow has not stopped yet and should be stopped by closing another valve, for example valve 17. Flow detection also alerts crew repairs are required.	A4

2-3-05	Completely unable to allow flow valve 16	Various	Unable to use boil-off for fuel, boil-off will be reliquefied	Pressure transmitter and reliquefication system	A3	-	-	A3
2-3-06	Completely unable to stop counterflow valve 16	Various	Pressure and flow fluctuations in system	-	B3	1. Add flow detection	Flow detection alerts crew and enables them to close valve 12 to stop counter flow.	A3
2-3-07	Completely unable to allow flow valve 19	Various	Unable to supply fuel to engine	-	D3	1. Add flow detection 2. Add redundancy in supply line	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A3
2-3-08	Completely unable to stop counterflow valve 19	Various	Minor amount of back flow when pump 4 is inactive as non return valve 5 will prevent continuous back flow	-	A3	-	-	A3
2-3-09	Ammonia leakage in engine room	Various	Engine room exposed with gaseous ammonia	-	E4	1. Locate piping outside of engine room 2. Add ammonia detection 3. Add ventilation 4. Add remote operated isolation valves 5. Add redundancy in supply line	Locating piping in separate space reduces the likelihood and impact of leakage. Ammonia detection alerts crew and enables them to close the added remote operated isolation valves stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Redundancy assures operation can continue reducing the impact.	C2
2-3-10	Fire in engine room	Various	Increase in temperature and pressure within system	-	E4	1. Locate piping outside of engine room 2. Add pressure relieve system 3. Add remote operated isolation valves 4. Add redundancy in supply line	Locating piping in space trunk reduces the likelihood for exposure to fire. Pressure transmitter alerts crew and enables them to close the added remote operated isolation valves stopping the ammonia supply. Pressure relieve system releases remaining ammonia to reduce impact. Redundancy assures operation can continue reducing the impact.	C2
2-3-11	Flooding and ammonia leakage in piping in engine room	Ship collision	Engine room and environment exposed with gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side 2. Add ammonia detection 3. Add flow detection 4. Add remote operated isolation valves 5. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close the added remote operated isolation valves stopping limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
3-1-01	Completely unable to open valve 21	VMS error/bug	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
3-1-02	Completely unable to close valve 21	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	A4	-	-	A4

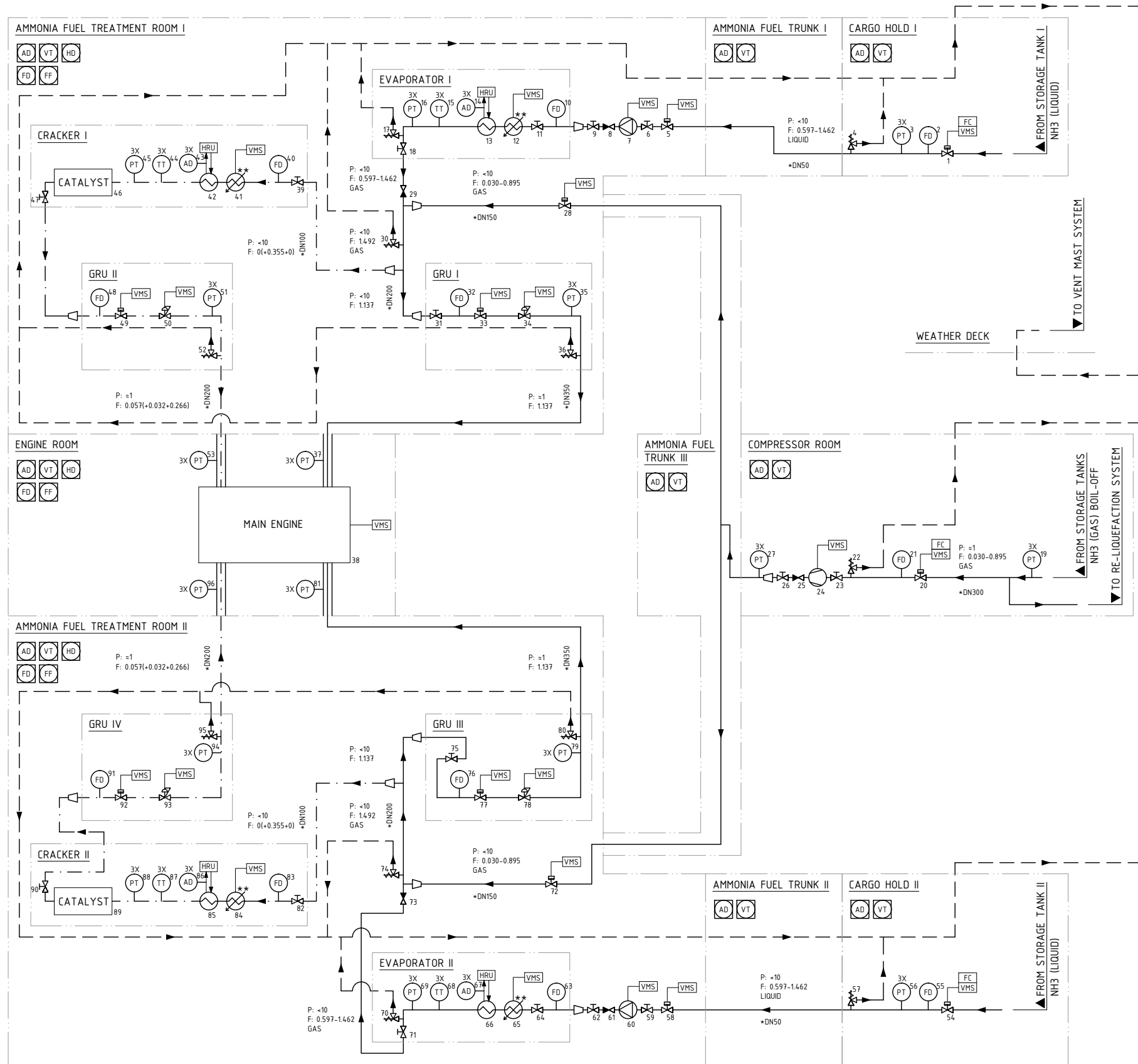
3-1-03	Completely unable to regulate pressure valve 22 blocking flow	VMS error/bug	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
3-1-04	Completely unable to regulate pressure valve 22 supplying high pressure	VMS error/bug	Too high pressure in fuel supply to engine	-	D4	1. Add pressure transmitter 2. Add pressure relieve system 3. Add redundancy in supply line	Pressure transmitter alerts crew and enables them to close valve 21. Pressure relieve system releases the excess ammonia to prevent too high pressures for the engine. Redundancy assures operation can start reducing the impact.	B4
3-1-05	Shut down/failure main engine 23	Various	Loss of power for propulsion and PTO	VMS	E2	-	Likelihood too low for mitigation.	E2
3-1-06	Ammonia leakage in engine room	Various	Engine room exposed with gaseous ammonia	-	E4	1. Locate piping outside of engine room as much as possible 2. Add double walled piping for ammonia fuel supply in engine room 3. Add pressure transmitter to monitor double walled piping 4. Add ammonia detection 5. Add ventilation 6. Add redundancy in supply line	Locating piping in separate space as much as possible reduces the likelihood and impact of leakage. Ammonia detection alerts crew and enables them to close the added remote operated isolation valve stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Redundancy assures operation can continue reducing the impact. Adding double walled piping and pressure transmitter limits impact and likelihood for a leakage in the engine room.	C2
3-1-07	Fire in engine room	Various	Increase in temperature and pressure within system	-	E4	1. Locate piping outside of engine room as much as possible 2. Add pressure transmitter 3. Add pressure relieve system 4. Add remote operated isolation valve 5. Add fire detection system 6. Add fire fighting system	Locating piping in separate space as much as possible reduces the likelihood for exposure to fire. Pressure transmitter alerts crew and enables them to close the added remote operated isolation valves if needed stopping the ammonia supply. Pressure relieve system releases remaining ammonia to reduce impact. Fire detection activates the firefighting system limiting the damage in the engine room.	C4
3-1-08	Flooding and ammonia leakage in piping in engine room	Ship collision	Engine room and environment exposed with gaseous ammonia	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side 2. Add ammonia detection 3. Add flow detection 4. Add remote operated isolation valves 5. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia detection alerts crew and enables them to close the added remote operated isolation valves stopping limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1

4-1-01	Completely unable to supply heat heater 25	VMS error/bug	Unable to supply fuel to engine	-	D3	1. Add temperature transmitter 2. Add pressure transmitter 3. Add redundancy in supply line	Temperature monitoring and pressure transmitter alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A3
4-1-02	Completely unable to stop heat supply heater 25	VMS error/bug	Temperature and pressure increase of fuel/gaseous ammonia supply	-	B4	1. Add temperature transmitter 2. Add pressure transmitter	Temperature monitoring and pressure transmitter alerts crew repairs are required and switch off HRU with heat exchanger to prevent overheating/high pressures.	A4
4-1-03	Complete blockage of flow and completely unable to transfer heat heat exchanger 26	Contamination	Unable to supply fuel to engine	-	D2	1. Add flow detection 2. Add temperature transmitter 3. Add pressure transmitter 4. Add redundancy in supply line	Temperature monitoring, pressure transmitter and flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A2
4-1-04	Leaking ammonia in HRU from heat exchanger 26	Various	Buildup of ammonia contamination in HRU	-	B3	1. Add ammonia detection in HRU return line	Ammonia detection alerts crew HRU is contaminated and that repairs are required.	A3
4-1-05	Complete blockage of flow and completely unable to accelerate ammonia cracking catalyst 27	Contamination	Unable to supply fuel to engine	-	D2	1. Add flow detection 2. Add redundancy in supply line	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A2
4-1-06	Completely unable to open valve 29	VMS error/bug	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
4-1-07	Completely unable to close valve 29	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	A4	-	-	A4
4-1-08	Completely unable to regulate pressure valve 30 blocking flow	Various	Unable to supply fuel to engine	-	D4	1. Add redundancy in supply line 2. Add flow detection	Flow detection alerts crew repairs are required. Redundancy assures operation can start reducing the impact.	A4
4-1-09	Completely unable to regulate pressure valve 30 supplying high pressure	Various	Too high pressure in fuel supply to engine	-	D4	1. Add pressure transmitter 2. Add pressure relieve system 3. Add redundancy in supply line	Pressure transmitter alerts crew and enables them to close valve 29. Pressure relieve system releases the excess ammonia & hydrogen to prevent too high pressures for the engine. Redundancy assures operation can start reducing the impact.	B4

4-1-10	Ammonia & hydrogen leakage in engine room	Various	Engine room exposed with gaseous ammonia & hydrogen	-	E4	1. Locate piping outside of engine room as much as possible 2. Add double walled piping for ammonia & hydrogen fuel supply in engine room 3. Add pressure transmitter to monitor double walled piping 4. Add ammonia & hydrogen detection 5. Add ventilation 6. Add redundancy in supply line	Locating piping in separate space as much as possible reduces the likelihood and impact of leakage. Ammonia and hydrogen detection alerts crew and enables them to close the added remote operated isolation valve stopping the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia & hydrogen. Redundancy assures operation can continue reducing the impact. Adding double walled piping and pressure transmitter limits impact and likelihood for a leakage in the engine room.	C2
4-1-11	Fire in engine room	Various	Increase in temperature and pressure within system	-	E4	1. Locate piping outside of engine room as much as possible 2. Add pressure transmitter 3. Add pressure relieve system 4. Add remote operated isolation valve 5. Add fire detection system 6. Add fire fighting system	Locating piping in separate space as much as possible reduces the likelihood for exposure to fire. Pressure transmitter alerts crew and enables them to close the added remote operated isolation valves if needed stopping the ammonia & hydrogen supply. Pressure relieve system releases remaining ammonia & hydrogen to reduce impact. Fire detection activates the firefighting system limiting the damage in the engine room.	C4
4-1-12	Flooding and ammonia & hydrogen leakage in piping in engine room	Ship collision	Engine room and environment exposed with gaseous ammonia & hydrogen	-	E3	1. Route piping with sufficient distance from shell, for example at least B/5 away from side 2. Add ammonia & hydrogen detection 3. Add flow detection 4. Add remote operated isolation valves 5. Add redundancy in supply line	Distance in pipe routing from shell reduces likelihood. Flow and ammonia & hydrogen detection alerts crew and enables them to close the added remote operated isolation valves stopping limiting the impact. Redundancy assures operation can continue reducing the impact. Likelihood too low for additional mitigation.	D1
5-1-01	Overall blackout	Various	Shut down of all systems and free unregulated flow of ammonia	-	E2	1. Add fail close on main supply valves	The fail close will close the valves once there is loss of power stopping the ammonia flow towards the engine room reducing the impact.	D2

## APPENDIX T: DIAGRAM NH3 FUEL SYSTEM (2X 100%)





SYMBOLS			
	HAND OPERATED VALVE		REMOTE OPERATED VALVE
	NON RETURN VALVE		PRESSURE REGULATING VALVE
	REDUCER		PRESSURE RELIEVE VALVE
	COMPRESSOR		PUMP
	HEAT EXCHANGER		HEATER
	FLOW DETECTOR		PRESSURE TRANSMITTER
	AMMONIA DETECTOR		TEMPERATURE TRANSMITTER
	SPACE: AMMONIA DETECTION		SPACE: HYDROGEN DETECTION
	SPACE: FIRE DETECTION		SPACE: VENTILATION
	SPACE: FIRE FIGHTING SYSTEM		

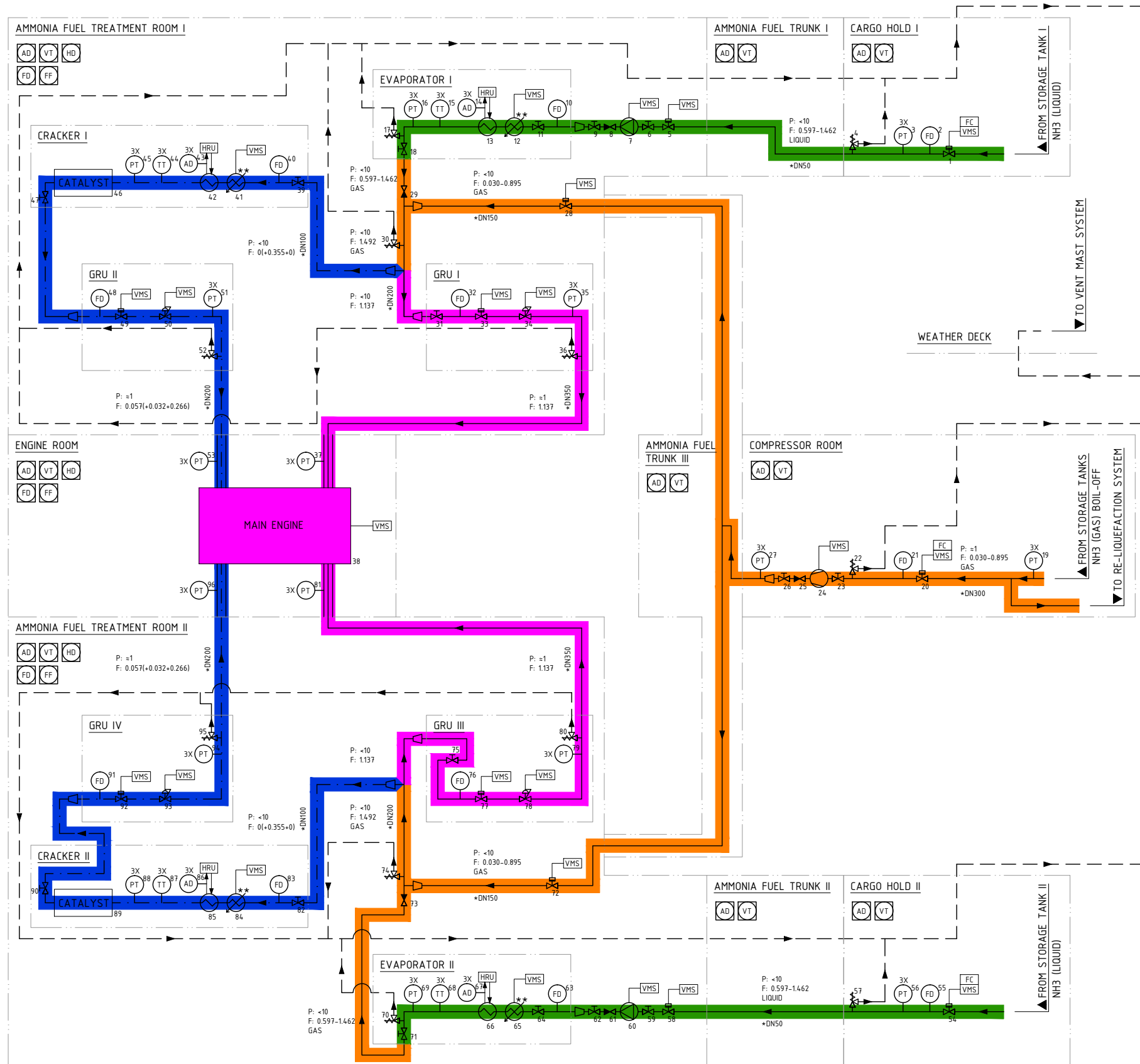
LEGEND	
	NH3 FUEL
	H2+(NH3+N2) FUEL
	AIR/GAS VENT
	NH3 FUEL DOUBLE WALLED
	H2+(NH3+N2) FUEL DOUBLE WALLED

- NOTES**
- PIPE INDICATION:  
P: PRESSURE bar  
F: FLOW kg/s  
STATE OF MATTER (GAS, UNLESS NOTED OTHERWISE)
- HRU: EXHAUST GAS HEAT RECOVERY UNIT  
GRU: GAS REGULATING UNIT  
VMS: VESSEL MANAGEMENT SYSTEM (POWER SUPPLY AND CONTROL)  
FC: FAIL CLOSE, CLOSES VALVE IN CASE OF BLACK OUT
- \*1) PROVISIONAL DIMENSIONS
  - \*\*1) START-UP POWER ONLY
- 1) SYSTEM DESIGN BASED ON ZERO LEAKAGE IN NORMAL OPERATIONAL CONDITIONS, FURTHER ANALYSIS REQUIRED TO CONTINUE DEVELOPMENT OF SYSTEM, FOR EXAMPLE BY MEANS OF QUANTITATIVE ANALYSIS
  - 2) ALL SPACE SYSTEMS, TRANSMITTERS AND DETECTORS CONNECTED WITH VMS
  - 3) REDUNDANCY OF SPACE SYSTEMS TO BE REVIEWED AND ALERT CAPABILITIES OF SPACE SYSTEMS IN CASE OF FAILURE TO BE INCLUDED
  - 4) INERT GAS SYSTEM TO EMPTY FUEL LINES FOR MAINTENANCE TO BE ADDED
  - 5) ALL FUEL PIPING TO BE ROUTED B/S FROM OUTER SHELL
  - 6) VENTILATION INTAKES TO BE LOCATED OUTSIDE HAZARDOUS AREAS
  - 7) HAZARDOUS AREAS OF VENTILATION EXHAUSTS TO BE DETERMINED
  - 8) HAZARDOUS AREA AND MEASURES TO MONITOR FLOW/ACTIVITY OF VENT MAST TO BE REVIEWED
  - 9) ADDITIONAL MEASURES FOR MITIGATION OF AMMONIA VENTILATION EITHER BY WATER SPRAY OR FLARING TO BE REVIEWED

REV.	DESCRIPTION	DRAWN	CHECK	APPR.	DATE
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412

CLIENT PROJECT NO.: \_\_\_\_\_ CLIENT DRAWING NO.: \_\_\_\_\_

 T: +31 (0) 88 024 37 00 I: www.c-job.com E: info@c-job.com	CLIENT: -	YARD NO.: -	CLASS NO.: -
	PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY
TITLE: DIAGRAM NH3 FUEL SYSTEM (2X 100%)			
PROJECTION: 	DIM. UNIT: mm	REVISIONS: THIS DOCUMENT REMAINS THE PROPERTY OF C-JOB. NO PART THEREOF MAY BE DISCLOSED, COPIED, REPRODUCED OR IN ANY OTHER WAY MADE USE OF EXCEPT WITH THE APPROVAL OF C-JOB.	SCALE: A 1-1
FORMAT: A1		SHEET: 1-1	



COLOUR CODING				
<span style="color: green;">■</span>	NODE 1: MAIN LIQUID AMMONIA SUPPLY			
<span style="color: orange;">■</span>	NODE 2: MAIN GASEOUS AMMONIA SUPPLY			
<span style="color: magenta;">■</span>	NODE 3: AMMONIA ENGINE SUPPLY			
<span style="color: blue;">■</span>	NODE 4: HYDROGEN ENGINE SUPPLY			

SYMBOLS			
	HAND OPERATED VALVE		REMOTE OPERATED VALVE
	NON RETURN VALVE		PRESSURE REGULATING VALVE
	REDUCER		PRESSURE RELIEVE VALVE
	COMPRESSOR		PUMP
	HEAT EXCHANGER		HEATER
	FLOW DETECTOR		PRESSURE TRANSMITTER
	AMMONIA DETECTOR		TEMPERATURE TRANSMITTER
	SPACE: AMMONIA DETECTION		SPACE: HYDROGEN DETECTION
	SPACE: FIRE DETECTION		SPACE: VENTILATION
	SPACE: FIRE FIGHTING SYSTEM		

LEGEND	
	NH3 FUEL
	H2+(NH3+N2) FUEL
	AIR/GAS VENT
	NH3 FUEL DOUBLE WALLED
	H2+(NH3+N2) FUEL DOUBLE WALLED

NOTES
PIPE INDICATION: P: PRESSURE bar F: FLOW kg/s STATE OF MATTER (GAS, UNLESS NOTED OTHERWISE)
HRU: EXHAUST GAS HEAT RECOVERY UNIT GRU: GAS REGULATING UNIT VMS: VESSEL MANAGEMENT SYSTEM (POWER SUPPLY AND CONTROL) FC: FAIL CLOSE, CLOSES VALVE IN CASE OF BLACK OUT
+1) PROVISIONAL DIMENSIONS
+*) START-UP POWER ONLY
1) SYSTEM DESIGN BASED ON ZERO LEAKAGE IN NORMAL OPERATIONAL CONDITIONS, FURTHER ANALYSIS REQUIRED TO CONTINUE DEVELOPMENT OF SYSTEM, FOR EXAMPLE BY MEANS OF QUANTITATIVE ANALYSIS
2) ALL SPACE SYSTEMS, TRANSMITTERS AND DETECTORS CONNECTED WITH VMS
3) REDUNDANCY OF SPACE SYSTEMS TO BE REVIEWED AND ALERT CAPABILITIES OF SPACE SYSTEMS IN CASE OF FAILURE TO BE INCLUDED
4) INERT GAS SYSTEM TO EMPTY FUEL LINES FOR MAINTENANCE TO BE ADDED
5) ALL FUEL PIPING TO BE ROUTED B/S FROM OUTER SHELL
6) VENTILATION INTAKES TO BE LOCATED OUTSIDE HAZARDOUS AREAS
7) HAZARDOUS AREAS OF VENTILATION EXHAUSTS TO BE DETERMINED
8) HAZARDOUS AREA AND MEASURES TO MONITOR FLOW/ACTIVITY OF VENT MAST TO BE REVIEWED
9) ADDITIONAL MEASURES FOR MITIGATION OF AMMONIA VENTILATION EITHER BY WATER SPRAY OR FLARING TO BE REVIEWED

REV.	DESCRIPTION	DRAWN	CHECK	APPR.	DATE
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412

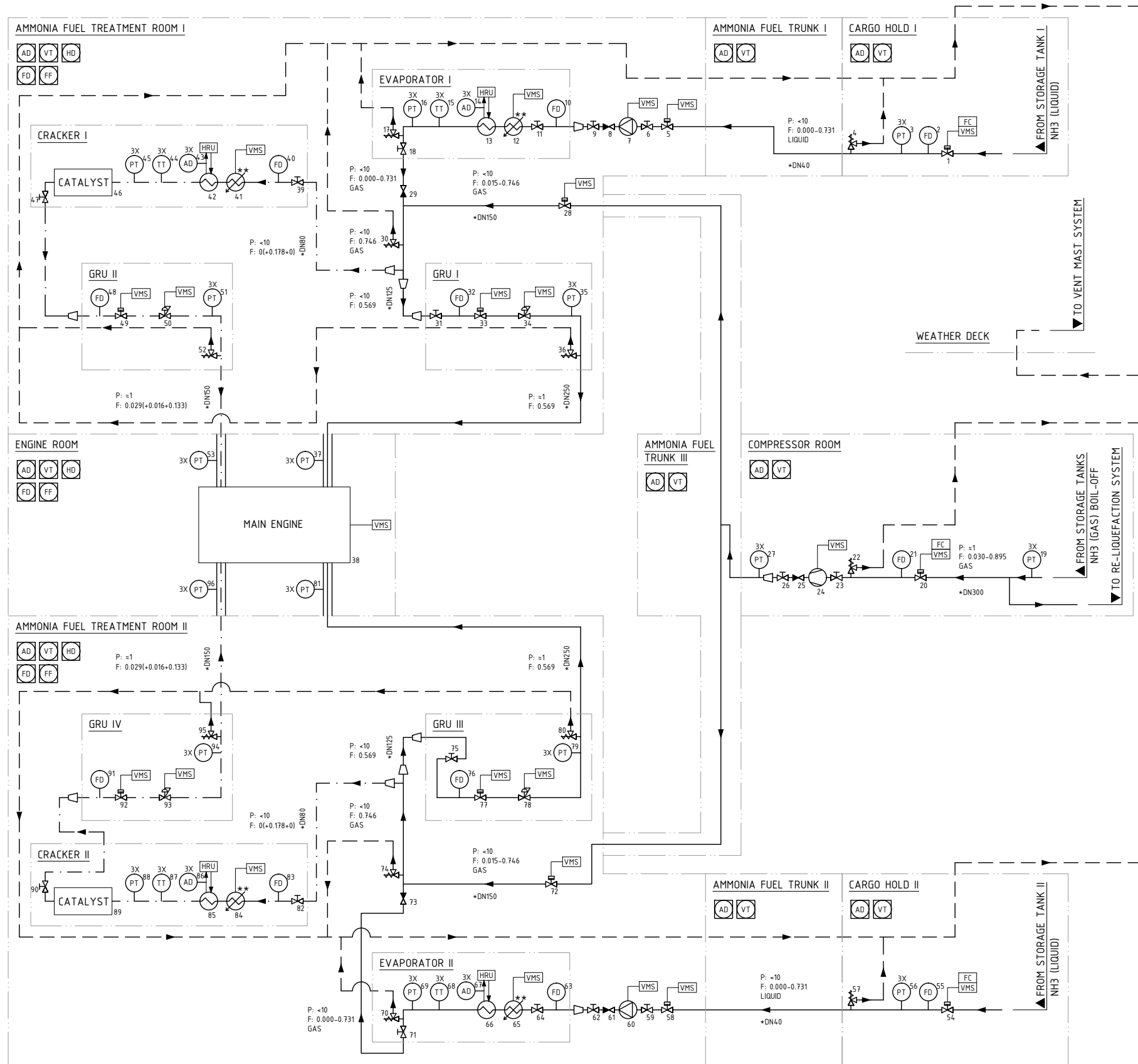
  

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CLIENT: -	YARD NO.: -	CLASS NO.: -
PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY
TITLE: DIAGRAM NH3 FUEL SYSTEM (2X 100%)		
PROJECTION:	DIM. UNIT: mm	FORMAT: A1
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## APPENDIX U: DIAGRAM NH3 FUEL SYSTEM (2X 50%)



SYMBOLS			
	HAND OPERATED VALVE		REMOTE OPERATED VALVE
	NON RETURN VALVE		PRESSURE REGULATING VALVE
	REDUCER		PRESSURE RELIEVE VALVE
	COMPRESSOR		PUMP
	HEAT EXCHANGER		HEATER
	FLOW DETECTOR		PRESSURE TRANSMITTER
	AMMONIA DETECTOR		TEMPERATURE TRANSMITTER
	SPACE: AMMONIA DETECTION		SPACE: HYDROGEN DETECTION
	SPACE: FIRE DETECTION		SPACE: VENTILATION
	SPACE: FIRE FIGHTING SYSTEM		

LEGEND	
	NH3 FUEL
	H2+(NH3+N2) FUEL
	AIR/GAS VENT
	NH3 FUEL DOUBLE WALLED
	H2+(NH3+N2) FUEL DOUBLE WALLED

**NOTES**

PIPE INDICATION:  
P: PRESSURE bar  
F: FLOW kg/s  
STATE OF MATTER (GAS, UNLESS NOTED OTHERWISE)

HRU: EXHAUST GAS HEAT RECOVERY UNIT  
GRU: GAS REGULATING UNIT  
VMS: VESSEL MANAGEMENT SYSTEM (POWER SUPPLY AND CONTROL)  
FC: FAIL CLOSE, CLOSES VALVE IN CASE OF BLACK OUT

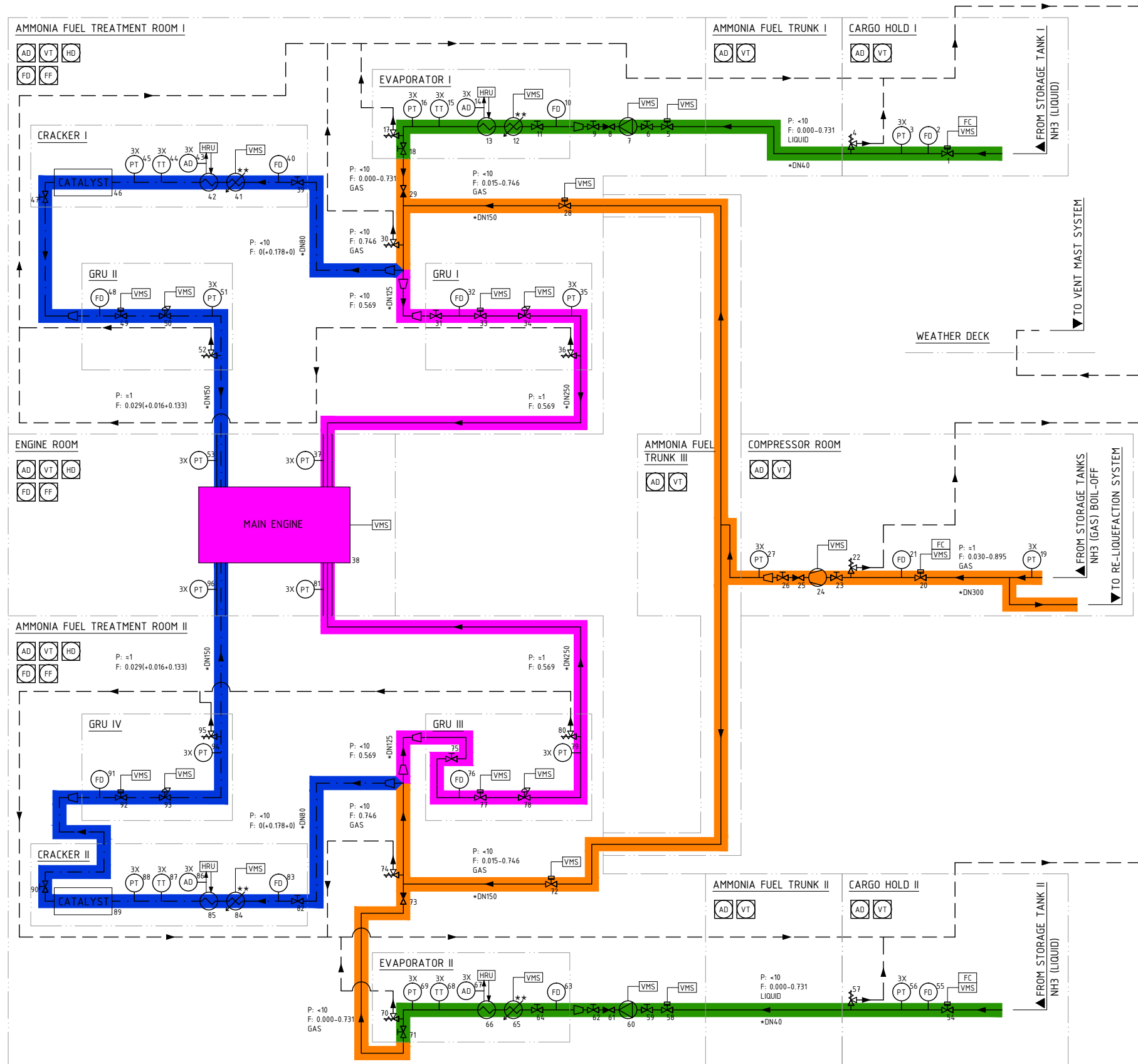
\*1) PROVISIONAL DIMENSIONS  
\*\*1) START-UP POWER ONLY

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3) REDUNDANCY OF SPACE SYSTEMS TO BE REVIEWED AND ALERT CAPABILITIES OF SPACE SYSTEMS IN CASE OF FAILURE TO BE INCLUDED  
4) INERT GAS SYSTEM TO EMPTY FUEL LINES FOR MAINTENANCE TO BE ADDED  
5) ALL FUEL PIPING TO BE ROUTED B/S FROM OUTER SHELL  
6) VENTILATION INTAKES TO BE LOCATED OUTSIDE HAZARDOUS AREAS  
7) HAZARDOUS AREAS OF VENTILATION EXHAUSTS TO BE DETERMINED  
8) HAZARDOUS AREA AND MEASURES TO MONITOR FLOW/ACTIVITY OF VENT MAST TO BE REVIEWED  
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REV.	DESCRIPTION	DRAWN	CHECK	APPR.	DATE
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412

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	PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY
TITLE: DIAGRAM NH3 FUEL SYSTEM (2X 50%)			
PROJECTION: 	DIM. UNIT: mm	REVISIONS: THIS DOCUMENT REMAINS NO PART THEREOF MAY BE DISCLOSED, COPIED, REPRODUCED OR IN ANY OTHER WAY MADE USE OF EXCEPT WITH THE APPROVAL OF C-JOB	REV.: A
SHEET: 1-1		SCALE: N.A.	FORMAT: A1



COLOUR CODING				
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<span style="color: magenta;">█</span>	NODE 3: AMMONIA ENGINE SUPPLY			
<span style="color: blue;">█</span>	NODE 4: HYDROGEN ENGINE SUPPLY			

SYMBOLS			
	HAND OPERATED VALVE		REMOTE OPERATED VALVE
	NON RETURN VALVE		PRESSURE REGULATING VALVE
	REDUCER		PRESSURE RELIEVE VALVE
	COMPRESSOR		PUMP
	HEAT EXCHANGER		HEATER
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LEGEND	
	NH3 FUEL
	H2+(NH3+N2) FUEL
	AIR/GAS VENT
	NH3 FUEL DOUBLE WALLED
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NOTES
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6) VENTILATION INTAKES TO BE LOCATED OUTSIDE HAZARDOUS AREAS
7) HAZARDOUS AREAS OF VENTILATION EXHAUSTS TO BE DETERMINED
8) HAZARDOUS AREA AND MEASURES TO MONITOR FLOW/ACTIVITY OF VENT MAST TO BE REVIEWED
9) ADDITIONAL MEASURES FOR MITIGATION OF AMMONIA VENTILATION EITHER BY WATER SPRAY OR FLARING TO BE REVIEWED

REV.	DESCRIPTION	DRAWN	CHECK	APPR.	DATE
A	GENERAL UPDATE	NDV	PL	WZ	20190503
0	FIRST ISSUE	NDV	PL	WZ	20190412

CLIENT PROJECT NO.:	CLIENT DRAWING NO.:
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CLIENT: -	YARD NO.: -	CLASS NO.: -
PROJECT NUMBER: 16.104	DRAWING NUMBER: 999-301	STATUS: PRELIMINARY
TITLE: DIAGRAM NH3 FUEL SYSTEM (2X 50%)		
PROJECTION:	DIM. UNIT: mm	SCALE: 1-1
FORMAT: A1	SHEET: 1-1	SCALE: N.A.

## APPENDIX V: FAILURE MODES RISK ASSESSMENT 2

Failure modes risk assessment 2:

<b>Cause:</b>	Identified in system	Various	Various
<b>General Description:</b>	Partial or complete equipment function failure	Leakage	Blockage
<b>Component:</b>	<b>Failure Modes:</b>		
Piping	None, passive equipment	External leakage	None, passive equipment
Hand operated valve	Blocking flow OR unable to stop flow	External leakage	Blocking flow
Non return valve	Blocking flow OR unable to stop counter flow	External leakage	Blocking flow
Remote operated valve	Blocking flow OR unable to stop flow	External leakage	Blocking flow
Pressure regulating valve	Unable to regulate pressure (too high/low) AND/OR blocking flow	External leakage	Blocking flow
Pressure relieve valve	Not relieving pressure at high pressures OR unwanted pressure release at normal conditions	External leakage	None
Pump	Unable to provide flow OR unable to stop flow	External leakage	Blocking flow
Compressor	Unable to provide flow OR unable to stop flow	External leakage	Blocking flow
Pressure transmitter	Unable to indicate pressure (too high/low or not at all)	External leakage	None
Flow detector	Unable to indicate flow (too high/low or not at all)	External leakage	None
Ammonia detector	Unable to indicate ammonia concentration (too high/low or not at all)	External leakage	None
Temperature transmitter	Unable to indicate temperature (too high/low or not at all)	External leakage	None
Heater	Unable to provide heat or unable to stop heat supply	External leakage	None

Heat exchanger	Blocking flow AND unable to transfer heat	External leakage OR internal leakage	Blocking flow
Catalyst	None, passive equipment	External leakage	Blocking flow
Main engine	Unable to provide mechanical power OR unable to stop mechanical power supply	External leakage	Blocking flow
Space systems	Unable to perform function	-	-

Failure Mode:	Fire	Flooding	Blackout
Component:	Effects:		
Piping	Increase in temperature and pressure within system	Exposed to water (pressure)	None
Hand operated valve			None
Non return valve			None
Remote operated valve			Shut down if installed with fail close
Pressure regulating valve			Loss of pressure regulation
Pressure relieve valve			None
Pump			Shut down loss of flow
Compressor			Shut down loss of flow
Pressure transmitter			Shut down
Flow detector			Shut down
Ammonia detector			Shut down
Temperature transmitter			Shut down
Heater			Shut down loss of heat supply
Heat exchanger			Indirect loss of heat supply
Catalyst			None
Main engine			Shut down complete loss of mechanical power supply
Space system	-	-	Shut down



## APPENDIX W: RISK ASSESSMENT 2

Risk assessment 2:

Nodes

- 1-S-XX Main liquid ammonia supply
- 2-S-XX Main gaseous ammonia supply
- 3-S-XX Ammonia engine supply
- 4-S-XX Hydrogen engine supply
- 5-S-XX Entire system

Subsection

- 1-1-XX Routing in Cargo Hold I
- 1-2-XX Routing in Fuel Trunk I
- 1-3-XX Routing in Fuel Treatment Room I
  
- 2-1-XX Routing in Compressor Room
- 2-2-XX Routing in Fuel Trunk III
- 2-3-XX Routing in Fuel Treatment Room I
  
- 3-1-XX Routing in Fuel Treatment Room I
- 3-2-XX Routing in Engine Room
  
- 4-1-XX Routing in Fuel Treatment Room I
- 4-2-XX Routing in Engine Room
  
- 5-1-XX Entire system

Risk ID number

- N-S-01 Risk 01
- N-S-02 Risk 02

Reference	Failure Mode	Cause	Effect	Detection	Assessment	Risk Ranking
1-1-01	Completely unable to open valve 1	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
1-1-02	Completely unable to close valve 1	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
1-1-03	No/Wrong measurements flow detector 2	Various	Wrong information flow on single point	Different readings compared to other flow detectors	Other detectors can be used to verify actual measurement.	A4
1-1-04	No/Wrong measurements pressure transmitter 3	Various	Wrong information pressure on single point	Different readings compared to other pressure transmitters	Other pressure transmitters can be used to verify actual measurement.	A4
1-1-05	Unwanted opening of pressure relieve valve 4	Various	Gaseous ammonia sent to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia sent to vent mast, supply can be cut by closing valve 1. Furthermore switch to second supply line to continue operation.	B2
1-1-06	Ammonia leakage in Cargo Hold I	Various	Cargo Hold I exposed with liquid and gaseous ammonia	Ammonia detection	Leakage can be limited by cutting supply by closing valve 1 and switching to second supply line to continue operation.	C2
1-1-07	Fire in Cargo Hold I	Various	Increase in temperature and pressure within system	Pressure transmitters	Valve 1 can be closed to isolate pressure and temperature in the system. Ammonia can be released by means of the pressure relieve system after valve 1. The pressure buildup before valve 1 can be reduced by the pressure relieve system of the storage tank. Fire can be suppressed by cutting oxygen supply to cargo hold. Operation can continue by switching to second supply line.	D1

1-1-08	Flooding and ammonia leakage in Cargo Hold I	Ship collision	Cargo hold and environment exposed with liquid and gaseous ammonia	Flow and ammonia detection	Closing valve 1 limits impact. Operation can continue by switching to second supply line.	D1
1-2-01	Ammonia leakage in Ammonia Fuel Trunk I	Various	Ammonia Fuel Trunk I exposed with liquid and gaseous ammonia	Ammonia detection	Closing valve 1 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Operation can continue by switching to second supply line.	C2
1-2-02	Fire in Ammonia Fuel Trunk I	Various	Increase in temperature and pressure within system	Pressure transmitters	Closing valve 1 stops the ammonia supply. Pressure relieve system release remaining ammonia to reduce impact. Operation can continue by switching to second supply line.	C2
1-2-03	Flooding and ammonia leakage in Ammonia Fuel Trunk I	Ship collision	Ammonia Fuel Trunk I and environment exposed with liquid and gaseous ammonia	Flow and ammonia detection	Closing valve 1 limits the impact. Operation can continue by switching to second supply line.	D1
1-3-01	Completely unable to open valve 5	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
1-3-02	Completely unable to close valve 5	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
1-3-03	Completely unable to (re)start pump 7	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
1-3-04	Completely unable to stop pump 7	VMS error/bug	Flow continuous	Flow detection	Flow can be blocked closing valve 9	A4
1-3-05	Completely unable to allow flow valve 8	Various	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A3
1-3-06	Completely unable to stop counterflow valve 8	Various	Limited counter flow in inactive pump as remainder is stopped by non return valve 29	Flow detection	Valve 6 can be closed to stop the limited counter flow	A3
1-3-07	No/Wrong measurements flow detector 10	Various	Wrong information pressure on single point.	Different readings compared to other flow detectors	Other detectors can be used to verify actual measurement.	A4

1-3-08	Completely unable to supply heat heater 12	VMS error/bug	Unable to supply fuel to engine	Temperature transmitter	Switch to second supply line to continue operation.	A3
1-3-09	Completely unable to stop heat supply heater 12	VMS error/bug	Temperature and pressure increase of fuel/gaseous ammonia supply	Temperature transmitter	Switch off HRU or switch to second fuel supply line	A4
1-3-10	Complete blockage of flow and completely unable to transfer heat heat exchanger 13	Contamination	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A2
1-3-11	Leaking ammonia in HRU from heat exchanger 13	Various	Buildup of ammonia contamination in HRU	Ammonia detection	Operation can continue. Depending on the severeness operation can continue by switching to second supply line so repairs can be done immediately.	A3
1-3-12	No/Wrong measurements ammonia detector 14	Various	Wrong information ammonia leakage on single point.	Different readings compared to other ammonia detectors	Other detectors can be used to verify actual measurement.	A4
1-3-13	No/Wrong measurements temperature transmitter 15	Various	Wrong information temperature on single point.	Different readings compared to other temperature transmitters	Other temperature transmitters can be used to verify actual measurement.	A4
1-3-14	No/Wrong measurements pressure transmitter 16	Various	Wrong information pressure on single point.	Different readings compared to other pressure transmitters	Other pressure transmitters can be used to verify actual measurement.	A4
1-3-15	Unwanted opening of pressure relieve valve 17	Various	Gaseous ammonia send to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia send to vent mast, supply can be cut by closing valve 5. Furthermore switch to second supply line to continue operation.	B2

1-3-16	Ammonia leakage in Ammonia Fuel Treatment Room I	Various	Ammonia Fuel Treatment Room I exposed with liquid and gaseous ammonia	Ammonia detection	Closing valve 5 and 1 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Operation can continue by switching to second supply line.	C2
1-3-17	Fire in Ammonia Fuel Treatment Room I	Various	Increase in temperature and pressure within system	Pressure transmitters and fire detection system	Closing valve 1 stops the ammonia supply. Pressure relieve system release remaining ammonia and fire detection system activates fire fighting system to reduce impact. Operation can continue by switching to second supply line.	C2
1-3-18	Flooding and ammonia leakage in Ammonia Fuel Treatment Room I	Ship collision	Ammonia Fuel Treatment Room I and environment exposed with liquid and gaseous ammonia	Flow and ammonia detection	Closing valve 5 and 1 limits the impact. Operation can continue by switching to second supply line.	D1
2-1-01	No/Wrong measurements pressure transmitter 19	Various	Wrong information pressure on single point	Different readings compared to other pressure transmitters	Other pressure transmitters can be used to verify actual measurement.	A4
2-1-02	Completely unable to open valve 20	VMS error/bug	Unable to use boil-off for fuel, boil-off will be reliquefied	Flow detection	-	A4
2-1-03	Completely unable to close valve 20	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
2-1-04	No/Wrong measurements flow detector 21	Various	Wrong information flow on single point	Different readings compared to other flow detectors	Other detectors can be used to verify actual measurement.	A4
2-1-05	Unwanted opening of pressure relieve valve 22	Various	Gaseous ammonia send to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia send to vent mast, supply can be cut by closing valve 20.	B2
2-1-06	Completely unable to start compressor 24	VMS error/bug	Unable to use boil-off for fuel, boil-off will be reliquefied	Flow detection	-	A4

2-1-07	Completely unable to stop compressor 24	VMS error/bug	Flow continuous	Flow detection	Flow can be stopped by closing valve 26.	A4
2-1-08	Completely unable to allow flow valve 25	Various	Unable to use boil-off for fuel, boil-off will be reliquefied	Flow detection	-	A3
2-1-09	Completely unable to stop counterflow valve 25	Various	Limited counter flow towards inactive compressor	Flow detection	Valve 23 or 20 can be closed to stop the counter flow.	A3
2-1-10	Ammonia leakage in Compressor Room	Various	Compressor Room exposed with gaseous ammonia	Ammonia detection	Leakage can be limited by cutting supply by closing valve 20.	C2
2-1-11	Fire in Compressor Room	Various	Increase in temperature and pressure within system	Pressure transmitters	Valve 20 can be closed to isolate pressure and temperature in the system. Ammonia can be released by means of the pressure relieve system after valve 20. The pressure buildup before valve 20 can be reduced by the pressure relieve system of the storage/re-liquefaction system. Fire can be suppressed by cutting oxygen supply to cargo hold.	D1
2-2-01	Ammonia leakage in Ammonia Fuel Trunk III	Various	Ammonia Fuel Trunk I exposed with gaseous ammonia	Ammonia detection	Closing valve 20 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia.	C2
2-2-02	Fire in Ammonia Fuel Trunk III	Various	Increase in temperature and pressure within system	Pressure transmitter	Closing valve 20 stops the ammonia supply. Pressure relieve system release remaining ammonia to reduce impact.	C2

2-2-03	Flooding and ammonia leakage in Ammonia Fuel Trunk III	Ship collision	Ammonia Fuel Trunk I and environment exposed with gaseous ammonia	Flow and ammonia detection	Closing valve 20 and 28 limits the impact.	D1
2-3-01	Completely unable to open valve 28	VMS error/bug	Unable to use boil-off for fuel, boil-off will be reliquefied	Flow detection	-	A4
2-3-02	Completely unable to close valve 28	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
2-3-03	Completely unable to allow flow valve 29	Various	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A3
2-3-04	Completely unable to stop counterflow valve 29	Various	Minor amount of back flow when pump 7 is inactive as non return valve 8 will prevent continuous back flow	Flow detection	Valve 18 can be closed to stop the limited counter flow	A3
2-3-05	Unwanted opening of pressure relieve valve 30	Various	Gaseous ammonia send to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia send to vent mast, supply can be cut by closing valve 28 and 5. Furthermore switch to second supply line to continue operation.	B2
2-3-06	Ammonia leakage in Ammonia Fuel Treatment Room I	Various	Ammonia Fuel Treatment Room I exposed with gaseous ammonia	Ammonia detection	Closing valve 28 and 5 or 28 and 20 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Operation can continue by switching to second supply line.	C2

2-3-07	Fire in Ammonia Fuel Treatment Room I	Various	Increase in temperature and pressure within system	Pressure transmitters and fire detection system	Closing valve 28, 20, 5 and 1 stops the ammonia supply. Pressure relieve system release remaining ammonia and fire detection system activates fire fighting system to reduce impact. Operation can continue by switching to second supply line.	C2
2-3-08	Flooding and ammonia leakage in Ammonia Fuel Treatment Room I	Ship collision	Ammonia Fuel Treatment Room I and environment exposed with gaseous ammonia	Flow and ammonia detection	Closing valve 28 and 5 or 28 and 20 limits the impact. Operation can continue by switching to second supply line.	D1
3-1-01	No/Wrong measurements flow detector 32	Various	Wrong information flow on single point	Different readings compared to other flow detectors	Other detectors can be used to verify actual measurement.	A4
3-1-02	Completely unable to open valve 33	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
3-1-03	Completely unable to close valve 33	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
3-1-04	Completely unable to regulate pressure valve 34 blocking flow	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
3-1-05	Completely unable to regulate pressure valve 34 supplying high pressure	VMS error/bug	Too high pressure in fuel supply to engine	Pressure transmitter	Pressure relieve system releases the excess ammonia to prevent too high pressures for the engine. Switch to second supply line to continue operation.	B4
3-1-06	Unwanted opening of pressure relieve valve 36	Various	Gaseous ammonia send to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia send to vent mast, supply can be cut by closing valve 33. Switch to second supply line to continue operation.	B2



3-1-07	Ammonia leakage in Ammonia Fuel Treatment Room I	Various	Ammonia Fuel Treatment Room I exposed with gaseous ammonia	Ammonia detection	Closing valve 33 or 28 and 5 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Operation can continue by switching to second supply line.	C2
3-1-08	Fire in Ammonia Fuel Treatment Room I	Various	Increase in temperature and pressure within system	Pressure transmitters and fire detection system	Closing valve 33, 28, 20, 5 and 1 stops the ammonia supply. Pressure relieve system release remaining ammonia and fire detection system activates fire fighting system to reduce impact. Operation can continue by switching to second supply line.	C2
3-1-09	Flooding and ammonia leakage in Ammonia Fuel Treatment Room I	Ship collision	Ammonia Fuel Treatment Room I and environment exposed with gaseous ammonia	Flow and ammonia detection	Closing valve 33 or 28 and 5 limits the impact. Operation can continue by switching to second supply line.	D1
3-2-01	Shut down/failure main engine 38	Various	Loss of power for propulsion and PTO	VMS	Likelihood too low for additional mitigation.	E2
3-2-02	Ammonia leakage in Engine Room (single penetration)	Various	Pressure increase in double walled piping in Engine Room due to entrance of gaseous ammonia	Pressure transmitter	Close valve 33 and switch to second supply line to continue operation.	A3
3-2-03	Ammonia leakage in Engine Room (double penetration)	Various	Engine Room exposed with gaseous ammonia	Pressure transmitter and ammonia detection	Closing valve 33 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia. Operation can continue by switching to second supply line.	C2

3-2-04	Fire in Engine Room	Various	Increase in temperature and pressure within system	Fire detection	Fire detection activates fire fighting system to reduce impact. Close remote operated valves if needed. Trapped ammonia with closed valves is released by means of pressure relieve valves.	C4
3-2-05	Flooding and ammonia leakage in Engine Room	Ship collision	Engine room and environment exposed with gaseous ammonia	Flow and ammonia detection	Closing valve 33 limits the impact. Operation can continue by switching to second supply line.	D1
4-1-01	No/Wrong measurements flow detector 40	Various	Wrong information flow on single point	Different readings compared to other flow detectors	Other detectors can be used to verify actual measurement.	A4
4-1-02	Completely unable to supply heat heater 41	VMS error/bug	Unable to supply fuel to engine	Temperature transmitter	Switch to second supply line to continue operation.	A3
4-1-03	Completely unable to stop heat supply heater 41	VMS error/bug	Temperature and pressure increase of fuel/gaseous ammonia supply	Temperature transmitter	Switch off HRU or switch to second fuel supply line	A4
4-1-04	Complete blockage of flow and completely unable to transfer heat heat exchanger 42	Contamination	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A2
4-1-05	Leaking ammonia in HRU from heat exchanger 42	Various	Buildup of ammonia contamination in HRU	Ammonia detection	Operation can continue. Depending on the severeness operation can continue by switching to second supply line so repairs can be done immediately.	A3
4-1-06	No/Wrong measurements ammonia detector 43	Various	Wrong information ammonia leakage on single point.	Different readings compared to other ammonia detectors	Other detectors can be used to verify actual measurement.	A4
4-1-07	No/Wrong measurements temperature transmitter 44	Various	Wrong information temperature on single point.	Different readings compared to other temperature transmitters	Other temperature transmitters can be used to verify actual measurement.	A4

4-1-08	No/Wrong measurements pressure transmitter 45	Various	Wrong information pressure on single point.	Different readings compared to other pressure transmitters	Other pressure transmitters can be used to verify actual measurement.	A4
4-1-09	Complete blockage of flow and completely unable to accelerate ammonia cracking catalyst 46	Contamination	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A2
4-1-10	Completely unable to open valve 49	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
4-1-11	Completely unable to close valve 49	VMS error/bug	Flow is stopped by inactive equipment in supply line	-	-	A4
4-1-12	Completely unable to regulate pressure valve 50 blocking flow	VMS error/bug	Unable to supply fuel to engine	Flow detection	Switch to second supply line to continue operation.	A4
4-1-13	Completely unable to regulate pressure valve 50 supplying high pressure	VMS error/bug	Too high pressure in fuel supply to engine	Pressure transmitter	Pressure relieve system releases the excess ammonia to prevent too high pressures for the engine. Switch to second supply line to continue operation.	B4
4-1-14	Unwanted opening of pressure relieve valve 52	Various	Gaseous ammonia send to vent mast	Flow detectors and pressure transmitters	Gaseous ammonia send to vent mast, supply can be cut by closing valve 49. Switch to second supply line to continue operation.	B2
4-1-15	Ammonia & hydrogen leakage in Ammonia Fuel Treatment Room I	Various	Ammonia Fuel Treatment Room I exposed with gaseous ammonia & hydrogen	Ammonia and hydrogen detection	Closing valve 49 or 28 and 5 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia and hydrogen. Operation can continue by switching to second supply line.	C2

4-1-16	Fire in Ammonia Fuel Treatment Room I	Various	Increase in temperature and pressure within system	Pressure transmitters and fire detection system	Closing valve 49, 28, 20, 5 and 1 stops the ammonia and hydrogen supply. Pressure relieve system release remaining ammonia and fire detection system activates fire fighting system to reduce impact. Operation can continue by switching to second supply line.	C2
4-1-17	Flooding and ammonia & hydrogen leakage in piping in Ammonia Fuel Treatment Room I	Ship collision	Ammonia Fuel Treatment Room I and environment exposed with gaseous ammonia & hydrogen	Flow, ammonia and hydrogen detection	Closing valve 49 or 28 and 5 limits the impact. Operation can continue by switching to second supply line.	D1
4-2-01	Ammonia and hydrogen leakage in Engine Room (single penetration)	Various	Pressure increase in double walled piping in Engine Room due to entrance of gaseous ammonia and hydrogen	Pressure transmitter	Close valve 53 and switch to second supply line to continue operation.	A3
4-2-02	Ammonia and hydrogen leakage in Engine Room (double penetration)	Various	Engine Room exposed with gaseous ammonia & hydrogen	Pressure transmitter, ammonia and hydrogen detection	Closing valve 53 stops the leakage. Ventilation reduces the impact of the limited amount of spilled ammonia and hydrogen. Operation can continue by switching to second supply line.	C2
4-2-03	Fire in Engine Room	Various	Increase in temperature and pressure within system	Fire detection	Fire detection activates fire fighting system to reduce impact. Close remote operated valves if needed. Trapped ammonia and hydrogen, with closed valves, is released by means of pressure relieve valves.	C4

4-2-04	Flooding and ammonia and hydrogen leakage in Engine Room	Ship collision	Engine Room and environment exposed with gaseous ammonia & hydrogen	Flow, ammonia and hydrogen detection	Closing valve 49 limits the impact. Operation can continue by switching to second supply line.	D1
5-1-01	Overall blackout	Various	Shut down of all systems and closing of valve 1, 20 and 54	-	Likelihood too low for additional mitigation.	D2