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HACCP STUDY FOR THE HYPERTHERMOPHILIC LIQUEFACTION UNIT

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1 HACCP STUDY FOR THE HYPERTHERMOPHILIC LIQUEFACTION UNIT

The HACCP study in this TN was prepared according to the protocol submitted by the ESA. The protocol is divided in 4 steps and 9 tasks.

Task 1: Definition of the scope, the objectives of hazard analysis and the hazard analysis planning

The HACCP study is done for the hyperthermophilic liquefaction unit, as depicted in figure 1. It is an open system. Feed containing solid particles enters the fermentor; an effluent stream leaves the fermentor. A fresh dialysate stream enters the system and leaves the system loaded with dissolved organic carbon. Steam or electricity is used to heat the system. A cooling fluid might become necessary as well. A stirrer and a pump have to be driven by electric or mechanic power supply.

The general working principle is a microbial degradation of fibrous matter at high temperatures (90 °C – 100 °C), which ensures the integrity of the degrading consortium and a fast solubilization of solid matter in a equilibrium controlled liquefaction step. The liquefied solids are withdrawn over the dialysis membrane; thus shifting the equilibrium towards the liquefied products.

Table 1 shows the classification of the hazard. The classification given by the ESA was used in this protocol.

Table 1: classification of the hazards

Category	Severity	Severity of safety consequence
I	Catastrophic	Loss of life, life-threatening or permanently disabling injury or occupational illness; Loss of an element of an interfacing manned flight system; Loss of launch site facilities or loss of system; Severe detrimental environmental effects.
II	Critical	Temporarily disabling, but not life-threatening injury or illness; Major damage to flight systems or loss of or major damage to ground facilities; Major damage to public or private property; Major detrimental environmental effects.
III	Marginal	Minor injury, minor disability, minor occupational illness; Minor system or environmental damage.
IV	Negligible	Less than minor injury, disability, occupational illness; Less than minor system or environmental damage.

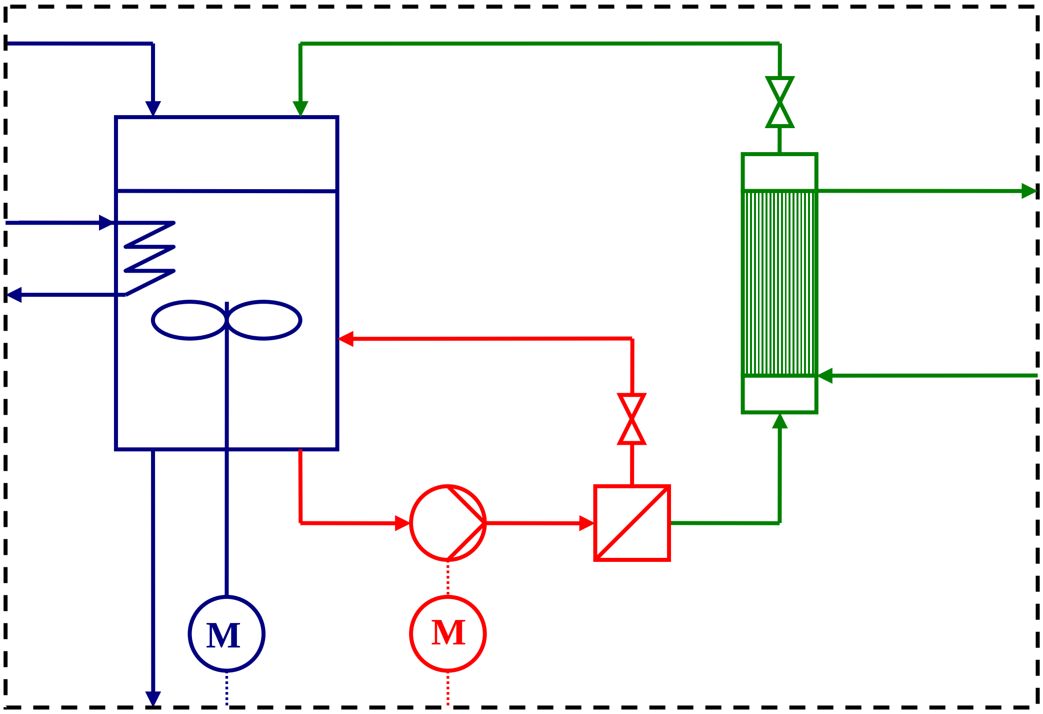

Figure 1: scheme of the hyperthermophilic liquefaction unit. The fermentor is colored blue, the filtration circuit red, the dialysis unit green.

Task 2 Definition of system baseline

The hyperthermophilc dialysis unit is designed to degrade fibrous organic matter. The degradation is done with anaerobic hyperthermophilic microorganisms at 90 °C – 100 °C. The culture medium is a mixture of organic fibrous matter, feces and water. No other ingredients such as yeast extract, organic acids or trace minerals have to be added. The medium does not need to be sterilized before entering the reactor. The solid matter concentration in the influent is approximately 2%.

The standard operation conditions are 90-100°C, pH6-7. The feed pump is set to maintain a hydraulic retention time of 4 d. The level of dissolved organic carbon in the fermentor is 500-1000 mg/L, the concentration of VFA is 50-200 mg/L, and the amount of total solids is 20-30 g/L. The loaded dialysate contains 300-800 mg/L DOC. The agitation of the stirrer is set to a slow mixing.

Task 3 Identification of hazard manifestations

Hazards are classified in physical, chemical, and biological hazards.

Table 2 shows the hazard matrix for the three sub systems. From this hazard matrix the hazard manifestation list, shown in table 3 is derived.

Table 2: Hazard matrix

Generic hazards	Subsystem elements		
	Reactor	**MF/UF**	**Dialysis**
Physical hazards			
-Power supply failure	X	X	-
-Steam supply failure	X	-	-
-High Temperature	X	X	X
-High Pressure	X	X	X
-Freezing	-	X	X
-Integrity problems	X	X	X
Biological hazards			
-Fouling	-	X	X
Chemical hazards			
-Toxicity	X	-	-

The hazards in table 2 are most important and most likely hazards that will endanger the hyperthermophilic liquefaction plant. Most of the hazards are of physical nature. Just one chemical hazard is listed here: the introduction or production of toxic compounds into / in the reactor. And even the production of toxic compounds will occur due to a physical hazard (increase of temperature). The only biological hazard is the formation of biofilms on different surfaces in the hyperthermophilic liquefaction unit. A biological hazard, that can occour at lower temperatures, such as the contamination with other bacteria is non-existant for the hyperthermophilc culture. At first the hyperthermophilc culture was enriched on a medium containing fecal matter. Mesophilc microorganisms are not able to endanger the hyperthermophilic consortium, if the temperature of the reactor is kept at hyperthermophilic conditions. Secondly, the introduction of new microorganisms able to grow at hyperthermophilic anaerobic conditions will not endanger the liquefaction. Unlike the mesophilic culture, where a contamination of the culture with methanogenic microorganisms will be disastrous because it will shift the product spectrum from VFA to methane, such contamination cannot occur at 90 °C. Literature knows no microorganisms producing methane from acetic acid at hyperthermophilc conditions. Only two microorganisms are currently known, which are able to degrade acetic acid anaerobically at hyperthermophilic conditions. These organisms are *Ferroglobus placidus*, isolated by Hafenbrandl et al. of the group of Huber and Stetter at the university of Regensburg (Germany) and *Geoglobus ahangari*, isolated by Kashefi and Lovley of the university of Massachusetts (MA, USA). However both microorganisms need stoiciometrical amounts of Fe^{3+} as electron acceptor and grow to negligible cell densities (10^5 cells / mL) in suspension cultures. A contamination with other hyperthermophilc microorganisms able to grow on the substrate will not endanger the plant but increase its efficiency instead. In waste water plants this is a common phenomenon. For example the UASB reactor, which needs a granular biomass, will develop this biomass after a

certain time by accumulating the granular-forming microorganisms from the feed. An accumulation of a biomass, which is not able to degrade the substrate will not happen, neither in a UASB-reactor nor in a hyperthermophilic dialysis-reactor. These microorganisms will simply pass the reactor, but will not accumulate.
As a consequence of this, the physical hazards are of predominant nature here, whereas the chemical and biological hazards are less important. The TN therefore focuses on the physical hazards.

Table 3: Hazard manifestation list

Mission phase	Subsystem	Hazard manifestation	
Normal operation	Reactor	HM1.1	Power supply failure – stirrer will not work
		HM1.2	Steam supply failure – temperature will decrease
		HM1.3	Toxic substances enter the fermentor / are produced in the fermentor
		HM1.4	Temperature control failure – temperature will increase or decrease
		HM1.5	Reactor outlet plugs – increase of reactor pressure
		HM1.6	After temperature control failure – reactor freezes
		HM1.7	Fatigue fracture of vessel or stirrer; seal breaks – reactor liquid and/or gas escapes into the environment
	MF/UF-System	HM2.1	Power supply failure – Filtration circuit will not run
		HM2.2	Fouling will plug the MF/UF Membrane
		HM2.3	High temperature – Membrane material can be damaged – pump seal will be damaged – Biomass can suffer
		HM2.4	High pressure – Membrane can break, pump seal can break
		HM2.5	Freezing – piping can freeze in cold environment
		HM2.6	Membrane breakage – fatigue fracture of membrane material; leaking of pipes
	Dialysis system	HM3.1	Biofilm growth on both sides of hollow fibers – reduction of membrane performance
		HM3.2	High temperature – membrane material will be damaged
		HM3.3	High pressure – moderate pressure gradients over the membrane will destroy the membrane

		HM3.4	Freezing – piping can freeze in cold environment
		HM3.5	Membrane breakage – fatigue fracture of membrane material; leaking of pipes

Task 4 Identification and classification of the hazard scenarios

Hazard manifestations comprise of causes effects and consequences. Causes, effects, and consequences are listed separately in tables 4, 5, and 6. Table 7 lists all hazard manifestations; the causes, effects and consequences of a hazard, the symptoms and propagation and reaction times. The likelihood of the scenarios is not given here. It depends on design criteria, which will be set during detail engineering.

Table 4: List of causes		
Hazard manifestation	**Cause**	
HM1.1	CA1.1	Power supply failure
	CA1.2	Maintenance works
	CA1.3	Breaking of stirrer seal
	CA1.4	Breaking of stirrer bearings
HM1.2	CA1.5	Steam supply failure
	CA1.6	Cooling fluid supply failure
HM1.3	CA1.7	Detergents/Disinfectants enter the fermentor
	CA1.8	High loads of easy degradable substrate enter the fermentor
	CA1.9	Toxic substances are formed at high temperature surfaces
HM1.4	CA1.10	Temperature control failure
HM1.5	CA1.11	Sedimentation of substrate and biomass
	CA1.12	Fouling closes the outlet lines
HM1.6	CA1.10	Temperature control failure
HM1.7	CA1.13	Fatigue fracture of stirrer / stirrer shaft
	CA1.14	Fatigue fracture of vessel
	CA1.15	Leaking of vessel seals
HM2.1	CA2.1	Power supply failure
	CA2.2	Pump failure
	CA2.3	Pump maintenance works
HM2.2	CA2.4	Fouling reduces permeate stream
HM2.3	CA2.5	Hot circuit stream melts membrane material
HM2.4	CA2.6	High trans-membrane pressure destroys the membrane
	CA2.7	Valve or piping in retentate stream downstream of the Filtration unit is closed
HM2.5	CA2.8	Changes in temperature of environment
HM2.6	CA2.9	Leaking of pipe seals
	CA2.10	Fatigue fracture of membrane material
	CA2.11	Leaking of membrane seals
	CA2.12	Microorganisms grow through membrane
HM3.1	CA3.1	Biofilm formation in the dialysate circuit
HM3.2	CA3.2	Hot circuit stream melts membrane material
HM3.3	CA3.3	Pressure gradient over the membrane destroys membrane
	CA3.4	Valve downstream of dialysis unit is closed
HM3.4	CA3.5	Changes in temperature of environment
HM3.5	CA3.6	Leaking of pipe seals
	CA3.7	Fatigue fracture of membrane material
	CA3.8	Leaking of membrane seals

Table 5: Lists of effects		
Causes	**effect**	
CA1.1	EF1.1	Stirrer stops, Biomass and solid particles settle down in the fermentor
CA1.2		
CA1.3		
CA1.4		
CA1.5	EF1.2	Fermentor cools down and reaches environmental temperature after a long time
CA1.6	EF1.3	Fermentor has to be cooled against environment
	EF1.4	Temperature in the fermentor increases, Biomass becomes reversibly inactive
	EF1.5	Fermentor liquid boils, Biomass becomes irreversibly inactive
CA1.7	EF1.6	Biomass becomes reversibly intoxicated
	EF1.7	Biomass becomes irreversibly intoxicated
CA1.8	EF1.8	pH in the fermentor drops due to rapid substrate degradation to VFAs, Biomass performance decreases
CA1.9	EF1.9	Toxic fumes leave the fermentor with the off-gas
	EF1.7	Biomass becomes irreversibly inactive
CA1.10	EF1.2	Fermentor cools down and reaches environmental temperature after a long time
	EF1.3	Fermentor has to be cooled against environment
	EF1.4	Temperature in the fermentor increases
CA1.11	EF1.1	Stirrer stops, Biomass and solid particles settle down in the fermentor, pressure increase in the fermentor
CA1.12	EF1.10	Pressure increase in the fermentor
CA1.13	EF1.1	Stirrer stops, Biomass and solid particles settle down in the fermentor
CA1.14	EF1.11	Loss of fermentation liquid/gas to environment
CA1.15	EF1.11	Loss of fermentation liquid/gas to environment
CA2.1	EF2.1	Breakdown of filtration circuit
CA2.2		
CA2.3		
CA2.4	EF2.2	Volume flow to dialysis unit decreases
	EF2.3	Biofilm particles can detach form piping / membrane and plug the dialysis module
CA2.5	EF2.4	MF/UF-membrane is destroyed, loss of filtration
	EF2.5	Membrane seals are destroyed, leakage of sludge to the environment
CA2.6	EF2.4	MF/UF-membrane is destroyed, loss of filtration
	EF2.5	Membrane seals are destroyed, leakage of sludge to the environment
	EF2.6	Burst disk opens and relieves filtration circuit to

		reactor
CA2.7	EF2.4	MF/UF-membrane is destroyed, loss of filtration
	EF2.5	Membrane seals are destroyed, leakage of sludge to the environment
	EF2.6	Burst disk opens and relieves filtration circuit to reactor
CA2.8	EF2.7	Filtration circuit freezes, pipes burst
CA2.9	EF2.8	Loss of retentate to environment
CA2.10	EF2.4	MF/UF-membrane is destroyed, loss of filtration
CA2.11	EF2.8	Loss of retentate to environment
CA2.12	EF2.9	Hyperthermophilic MO enter the dialysate stream
	EF2.10	Hyperthermophilic biofilm formation in dialysis unit
CA3.1	EF3.1	Plugging of dialysis unit in housing stream
	EF3.2	Lowering of dialysis performance
CA3.2	EF3.3	Dialysis membrane is destroyed, loss of dialysis
	EF3.4	Dialysis seals are destroyed, leakage of filtrate/dialysate to the environment
CA3.3	EF3.5	Convective flow from/to fermentor
	EF3.3	Dialysis membrane is destroyed, loss of dialysis
CA3.4	EF3.3	Dialysis membrane is destroyed, loss of dialysis
	EF3.6	Convective flow from fermentor to dialysate
CA3.5	EF3.7	Freezing of dialysate circuit / pipes burst
CA3.6	EF3.8	Loss of dialysate to environment
CA3.7	EF3.3	Dialysis membrane is destroyed, loss of dialysis
CA3.8	EF3.8	Loss of dialysate to environment

Table 6: List of consequences		
effect	**Consequence**	
EF1.1	CO1.1	Plugging of fermentor outlet
	CO1.2	Boiling of fermentor liquid due to temperature gradients
	CO1.3	Formation of toxic reaction products in the fermentor
	CO1.4	Hyperthermophilic biomass dies
	CO1.5	Temporary shutdown of hyperthermophilic liquefaction unit
EF1.2	CO1.6	Liquefaction performance decreases
	CO1.7	Fermentation broth freezes
	CO1.4	Hyperthermophilic biomass dies
EF1.3	CO1.8	Heat intake from the environment
EF1.4	CO1.9	Biomass becomes reversibly inactive
EF1.5	CO1.10	Biomass becomes irreversibly inactive
	CO1.5	Temporary shutdown of hyperthermophilic liquefaction unit

EF1.6	CO1.9	Biomass becomes reversibly inactive
EF1.7	CO1.10	Biomass becomes irreversibly inactive
	CO1.5	Temporary shutdown of hyperthermophilic liquefaction unit
EF1.8	CO1.11	pH of hyperthermophilic fermentor drops
	CO1.9	Biomass becomes reversibly inactive
EF1.9	CO1.12	Intoxication of phototrophic compartment
	CO1.13	Accumulation of non-degradable compounds in the loop
EF1.10	CO1.14	Opening of safety valve / burst disc, loss of fermentation liquid/gas to the environment
EF1.11	CO1.15	Contamination of environment with hyperthermophilic MO
	CO1.16	Loss of carbon/nitrogen/sulfur/phosphor/oxygen/water to the environment
	CO1.17	Loss of hyperthermophilic liquefaction unit
EF2.1	CO2.1	Accumulation of VFA in the fermentor
	CO2.2	Drop of pH in the fermentor, biomass becomes reversibly inactive
	CO2.3	nutrient flow to phototrophic compartment stops
	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF2.2	CO2.1	Accumulation of VFA in the fermentor
	CO2.2	Drop of pH in the fermentor, biomass becomes reversibly inactive
	CO2.5	nutrient flow to phototrophic compartment decreases
	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF2.3	CO2.6	Increase of dialysis unit inlet pressure
	CO2.7	Breakage of dialysis membrane
	CO2.8	Plugging of dialysis membrane
	CO2.9	Replacement of dialysis-membrane
	CO2.1	Accumulation of VFA in the fermentor
	CO2.2	Drop of pH in the fermentor, biomass becomes reversibly inactive
	CO2.3	nutrient flow to phototrophic compartment stops
	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF2.4	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
	CO2.9	Replacement of MF/UF-membrane
EF2.5	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
	CO2.10	Replacement of MF/UF-membrane seals

EF2.6	CO2.11	Replacement of burst disk
EF2.7	CO2.12	Replacement of piping
	CO2.13	Irreversible loss of hyperthermophilic liquefaction unit
EF2.8	CO2.14	Loss of Water in the system
	CO2.15	Loss of carbon/nitrogen/sulfur in the system
	CO2.16	Loss of CO_2 in the system
	CO2.17	Contamination of environment with hyperthermophilic MO
EF2.9	CO2.18	Contamination of phototrophic reactor with hyperthermophilic MO
EF2.10	CO2.9	Replacement of dialysis-membrane
	CO2.1	Accumulation of VFA in the fermentor
	CO2.2	Drop of pH in the fermentor, biomass becomes reversibly inactive
	CO2.3	nutrient flow to phototrophic compartment stops
	CO2.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF3.1	CO3.1	Accumulation of VFA in the fermentor
	CO3.2	Drop of pH in the fermentor
	CO3.3	nutrient flow to phototrophic compartment stops
	CO3.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF3.2	CO3.1	Accumulation of VFA in the fermentor
	CO3.2	Drop of pH in the fermentor
	CO3.3	nutrient flow to phototrophic compartment stops
	CO3.4	Temporary shutdown of hyperthermophilic liquefaction unit
EF3.3	CO3.4	Temporary shutdown of hyperthermophilic liquefaction unit
	CO3.5	Replacement of dialysis membrane
EF3.4	CO3.4	Temporary shutdown of hyperthermophilic liquefaction unit
	CO3.6	Replacement of dialysis membrane seals
EF3.5	CO3.7	Liquid level in fermentor drops
	CO3.8	Liquid level in fermentor rises
EF3.6	CO3.7	Liquid level in fermentor drops
EF3.7	CO3.9	Replacement of dialysis pipings
	CO3.10	Loss of hyperthermophilic liquefaction unit
EF3.8	CO3.11	Loss of water to environment
	CO3.12	Loss of carbon/sulfur/nitrogen/oxygen to environment
	CO3.13	Contamination of environment with hyperthermophilic MO

Table 7: Hazard scenario list for normal operation				
Hazard manifestation	**Cause - Effects - Consequences**	**Consequence severity**	**Observable symptoms**	**Propagation and reaction time**
HM1.1	CA1.1-EF1.1-CO1.1,	III	Stirrer stops, Blackout, Liquid level in fermentor rises	PT: 1 s RT: 30 min
	CA1.1-EF1.1-CO1.2	III	Stirrer stops, Detection of complex molecules in off-gas, Heat transfer into fermentor decreases, Temperature in reactor changes	PT:1 s RT: 1 d
	CA1.1-EF1.1-CO1.3	III	Detection of complex molecules in off-gas	PT: 30 min RT: 5 min
	CA1.1-EF1.1-CO1.4	II	Decrease in fermentor performance	PT: 1 w RT: 1 d
	CA1.1-EF1.1-CO1.5	II	-	-
	CA1.2-EF1.1-CO1.1	III	-	-
	CA1.2-EF1.1-CO1.2	III	-	-
	CA1.2-EF1.1-CO1.3	III	-	-
	CA1.2-EF1.1-CO1.4	II	-	-
	CA1.2-EF1.1-CO1.5	II	-	-
	CA1.3-EF1.1-CO1.1	III	Stirrer stops, Blackout, Liquid level in fermentor rises, Leaking of fermentor liquid into the environment	PT: 1 s RT: 30 min
	CA1.3-EF1.1-CO1.2	III	Stirrer stops, Detection of complex molecules in off-gas, Heat transfer into fermentor decreases, Temperature in reactor changes Leaking of fermentor liquid into environment	PT:1 s RT: 1 d
	CA1.3-EF1.1-	III	Detection of complex	PT: 30 min

	CO1.3		molecules in off-gas, Leaking of fermentor liquid into the environment	RT: 5 min
	CA1.3-EF1.1-CO1.4	II	Decrease in fermentor performance, Leaking of fermentor liquid into the environment	PT: 1 w RT: 1 d
	CA1.3-EF1.1-CO1.5	II	-	-
	CA1.4-EF1.1-CO1.1	III	Stirrer stops or slows down, Blackout, Liquid level in fermentor rises,	PT: 1 s RT: 30 min
	CA1.4-EF1.1-CO1.2	III	Stirrer stops or slows down, Detection of complex molecules in off-gas, Heat transfer into fermentor decreases, Temperature in reactor changes	PT:1 s RT: 1 d
	CA1.4-EF1.1-CO1.3	III	Detection of complex molecules in off-gas	PT: 30 min RT: 5 min
	CA1.4-EF1.1-CO1.4	II	Decrease in fermentor performance	PT: 1 w RT: 1 d
	CA1.4-EF1.1-CO1.5	II	-	-
HM1.2	CA1.5-EF1.2-CO1.6	III	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 1 d
	CA1.5-EF1.2-CO1.7	II	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 2 w
	CA1.5-EF1.2-CO1.4	II	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 2 w
	CA1.6-EF1.3-CO1.8	IV	Temperature of fermentor increases, heat balance is not closed	PT: 1 h RT: 12 h
	CA1.6-EF1.4-CO1.9	III	Temperature of fermentor increases, fermentor performance decreases	PT: 1 h RT: 2 h
	CA1.6-EF1.5-CO1.10	II	Temperature of fermentor increases, fermentor performance decreases	PT: 1 h RT: 1 h
HM1.3	CA1.7-EF1.6-CO1.9	III	Fermentor performance decreases	PT: 3d RT: -

	CA1.7-EF1.7-CO1.10	II	Fermentor performance decreases	PT: 3 d RT: -
	CA1.7-EF1.7-CO1.5	II	-	-
	CA1.8-EF1.8-CO1.11	IV	pH in fermentor drops	PT: 12 h RT: 3 d
	CA1.8-EF1.8-CO1.9	III	pH in fermentor drops, fermentor performance decreases	PT: 12 h RT: 3 d
	CA1.9-EF1.9-CO1.12	II	Performance of phototrophic compartment decreases	PT: 1 d RT: 1 d
	CA1.9-EF1.7-CO1.10	II	Fermentor performance decreases	PT: 3 d RT: -
HM1.4	CA1.10-EF1.2-CO1.6	III	Fermentor performance decreases, temperature of fermentor decreases	PT: 12 h RT: 1 d
	CA1.10-EF1.2-CO1.7	II	Stirrer stops, temperature of fermentor drops to 0°C	PT: 1 w RT: 1 w
	CA1.10-EF1.2-CO1.4	II	Fermentor performance decreases	PT: 3 d RT: 1 w
	CA1.10-EF1.3-CO1.8	IV	Heat balance is not closed	PT: 12 h RT: 1 d
	CA1.10-EF1.4-CO1.9	III	Fermentor performance decreases, Temperature of fermentor increases	PT: 30 min RT 45 min
HM1.5	CA1.11-EF1.1-CO1.1	III	Stirrer stops, Liquid level in fermentor rises	PT: 1 s RT: 30 min
	CA1.11-EF1.1-CO1.2	III	Stirrer stops, Detection of complex molecules in off-gas, Heat transfer into fermentor decreases, Temperature in reactor changes	PT:1 s RT: 1 d
	CA1.11-EF1.1-CO1.3	III	Detection of complex molecules in off-gas	PT: 30 min RT: 5 min
	CA1.11-EF1.1-CO1.4	II	Decrease in fermentor performance	PT: 1 w RT: 1 d
	CA1.11-EF1.1-CO1.5	II	-	-
	CA1.12-EF1.10-CO1.14	II *	Abrupt decreases of fermentor pressure,	PT: 1 s RT: 1d
HM1.6	CA1.10-EF1.2-CO1.6	III	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 1 d

	CA1.10-EF1.2-CO1.7	II	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 2 w
	CA1.10-EF1.2-CO1.4	II	Decrease in fermentor temperature, Decrease in fermentor performance	PT: 1 h RT: 2 w
	CA1.10-EF1.3-CO1.8	IV	Heat balance is not closed	PT: 12 h RT: 1 d
	CA1.10-EF1.4-CO1.9	III	Fermentor performance decreases, Temperature of fermentor increases	PT: 30 min RT 45 min
HM1.7	CA1.13-EF1.1-CO1.1	III	Stirrer speed increases, Detection of complex molecules in off-gas, Heat transfer into fermentor decreases, Temperature in reactor changes	PT:1 s RT: 1 d
	CA1.13-EF1.1-CO1.2	III	Detection of complex molecules in off-gas	PT: 30 min RT: 5 min
	CA1.13-EF1.1-CO1.3	III	Decrease in fermentor performance,	PT: 1 w RT: 1 d
	CA1.13-EF1.1-CO1.4	II	Decrease in fermentor performance	PT: 1 w RT: 1 d
	CA1.13-EF1.1-CO1.5	II	-	-
	CA1.14-EF1.11-CO1.15	III *	-	-
	CA1.14-EF1.11-CO1.16	II	Mass balance is not closed, decrease in fermentor pressure and temperature	PT: 1 min RT: -
	CA1.14-EF1.11-CO1.17	I	-	-
	CA1.15-EF1.11-CO1.15	III *	Mass balance is not closed, leakage stream under seals	PT: 12 h RT: 1 d
	CA1.15-EF1.11-CO1.16	II	Mass balance is not closed	PT: 12 h RT: 1 d
HM2.1	CA2.1-EF2.1-CO2.1	IV	Accumulation of VFA in fermentor, blackout, filtration mass flow decreases, pump stops	PT: 1 s RT: 1 d
	CA2.1-EF2.1-CO2.2	IV	Pump stops, filtration mass flow decreases	PT: 1 h RT: 1 d
	CA2.1-EF2.1-CO2.3	III	Performance of phototrophic compartment decreases	PT: 1 d RT: 2 d

	CA2.1-EF2.1-CO2.4	II	-	-
	CA2.2-EF2.1-CO2.1	IV	Accumulation of VFA in fermentor, blackout, filtration mass flow decreases, pump stops	PT: 1 s RT: 1d
	CA2.2-EF2.1-CO2.2	IV	Pump stops, filtration mass flow decreases	PT: 1 h RT: 1 d
	CA2.2-EF2.1-CO2.3	III	Performance of phototrophic compartment decreases	PT: 1 d RT: 2 d
	CA2.2-EF2.1-CO2.4	II	-	-
	CA2.3-EF2.1-CO2.1	IV	Accumulation of VFA in fermentor, blackout, filtration mass flow decreases, pump stops	PT: 1 s RT: 1 d
	CA2.3-EF2.1-CO2.2	IV	Pump stops, filtration mass flow decreases	PT: 1 h RT: 1 d
	CA2.3-EF2.1-CO2.3	III	Performance of phototrophic compartment decreases	PT: 1 d RT: 2 d
	CA2.3-EF2.1-CO2.4	II	-	-
HM2.2	CA2.4-EF2.2-CO2.1	IV	Accumulation of VFA in fermentor, pH in fermentor drops, performance of hyperthermophilic fermentor decreases	PT: 6 m RT: 1 a
	CA2.4-EF2.2-CO2.2	IV	Accumulation of VFA in fermentor, pH in fermentor drops, performance of hyperthermophilic fermentor decreases	PT: 6 m RT: 1 a
	CA2.4-EF2.2-CO2.4	II	-	-
	CA2.4-EF2.2-CO2.5	IV	Performance of phototrophic compartment decreases, VFA / DOC in dialysate decreases	PT: 6 m RT: 1 a
	CA2.4-EF2.3-CO2.6	III	Increase of dialysis inlet pressure	PT: 1 s RT: 10 s
	CA2.4-EF2.3-CO2.7	II	Pressure of inlet / outlet dialysate / retentate is equal, volume flow from hyperthermophilic fermentor	PT: 1 s RT: -

			to phototrophic compartment	
	CA2.4-EF2.3-CO2.8	II	Increase of dialysis inlet pressure	PT: 1 s RT: 10 s
	CA2.4-EF2.3-CO2.9	II	-	-
	CA2.4-EF2.3-CO2.1	IV	pH of hyperthermophilic fermentor drops, VFA accumulate	PT: 6 m RT: 1 a
	CA2.4-EF2.3-CO2.2	IV	pH of hyperthermophilic fermentor drops, VFA accumulate	PT: 6 m RT: 1 a
	CA2.4-EF2.3-CO2.3	III	Performance of phototrophic compartment decreases, VFA / DOC in dialysate decreases	PT: 6 m RT: 1 a
	CA2.4-EF2.3-CO2.4	II	-	-
HM2.3	CA2.5-EF2.4-CO2.4	II	High temperature in dialysate circuit, Pressure of inlet / outlet dialysate / retentate is equal, volume flow from hyperthermophilic fermentor to phototrophic compartment	-
	CA2.5-EF2.4-CO2.9	II	-	-
	CA2.5-EF2.5-CO2.4	II	High temperature in dialysate circuit, leaking of filtration liquid form dialysate unit, mass balance over dialysis unit is not closed	
	CA2.5-EF2.5-CO2.10	II	-	-
HM2.4	CA2.6-EF2.4-CO2.4	II	Rapid change of pressure in dialysis unit, Pressure of inlet / outlet dialysate / retentate is equal	PT: 1s RT: -
	CA2.6-EF2.4-CO2.9	II	Rapid change of pressure in dialysis unit, Pressure of inlet / outlet dialysate / retentate is equal	-
	CA2.6-EF2.5-CO2.4	II	Rapid change of pressure in dialysis unit, leaking of	-

			filtration liquid form dialysate unit, mass balance over dialysis unit is not closed	
	CA2.6-EF2.5-CO2.10	II	Rapid change of pressure in dialysis unit, leaking of filtration liquid form dialysate unit, mass balance over dialysis unit is not closed	-
	CA2.6-EF2.6-CO2.11	II	Volume flow to environment / into relieve vessel	PT: 1s RT: -
HM2.5	CA2.8-EF2.7-CO2.12	II	Temperature of environment decreases, membrane filtration circuit stops	PT: 1 d RT: 1 d
	CA2.8-EF2.7-CO2.13	I	-	-
HM2.6	CA2.9-EF2.8-CO2.14	II	Mass balance over filtration membrane is not closed	PT: 1 m RT: 2 m
	CA2.9-EF2.8-CO2.15	III	Detection of leakage stream, Mass balance is not closed	PT: 1 a RT: 1 a
	CA2.9-EF2.8-CO2.16	II	Carbon and oxygen Mass balance is not closed, maybe detection of frozen CO_2, depending on the environment temperature / pressure	PT: 1 a RT: 1 a
	CA2.9-EF2.8-CO2.17	III *	Detection of leakage stream	PT: 1 a RT: 1 a
	CA2.10-EF2.4-CO2.4	II	-	-
	CA2.10-EF2.4-CO2.9	II	-	-
	CA2.11-EF2.8-CO2.14	II	Mass balance is not closed, detection of leakage streams	PT: 1 m RT: 2 m
	CA2.11-EF2.8-CO2.15	III	Carbon balance is not closed	PT: 1 a RT: 1 a
	CA2.11-EF2.8-CO2.16	II	Carbon and oxygen Mass balance is not closed, maybe detection of frozen CO_2, depending on the environment temperature / pressure	PT: 1 a RT: 1 a
	CA2.11-EF2.8-	III *	-	-

	CO2.17			
	CA2.12-EF2.9-CO2.18	IV	Cells in loaded dialysate stream, decrease of performances of phototrophic compartment	PT: probing interval RT: -
	CA2.12-EF2.10-CO2.1	IV	Accumulation of VFA in fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit	PT: 2 m RT: 3 m
	CA2.12-EF2.10-CO2.2	IV	Accumulation of VFA in fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit	PT: 2 m RT: 3 m
	CA2.12-EF2.10-CO2.3	III	Decrease of DOC in loaded dialysate stream	PT. 2 m RT: 3 m
	CA2.12-EF2.10-CO2.4	II	-	-
	CA2.12-EF2.10-CO2.9	II	-	-
HM3.1	CA3.1-EF3.1-CO3.1	IV	Accumulation of VFA in fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit, increase of dialysate inlet pressure	PT: 2 m RT: 3 m
	CA3.1-EF3.1-CO3.2	IV	Accumulation of VFA in fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit, increase of dialysate inlet pressure	PT: 2 m RT: 3 m
	CA3.1-EF3.1-CO3.3	III	Decrease of performance of phototrophic compartment	PT: 2 m RT: 3 m
	CA3.1-EF3.1-CO3.4	II	-	-
	CA3.1-EF3.2-CO3.1	IV	Accumulation of VFA in fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit, increase of dialysate inlet pressure	PT: 2 m RT: 3 m
	CA3.1-EF3.2-	IV	Accumulation of VFA in	PT: 2 m

	CO3.2		fermentor, drop of pH, decrease of performance of hyperthermophilic liquefaction unit, increase of dialysate inlet pressure	RT: 3 m
	CA3.1-EF3.2-CO3.3	III	Decrease of performance of phototrophic compartment	PT: 2 m RT: 3 m
	CA3.1-EF3.2-CO3.4	II	-	-
HM3.2	CA3.2-EF3.3-CO3.4	II	-	-
	CA3.2-EF3.3-CO3.5	II	-	-
	CA3.2-EF3.4-CO3.4	II	-	-
	CA3.2-EF3.4-CO3.6	II	-	-
HM3.3	CA3.3-EF3.5-CO3.7	III	Liquid level in fermentor drops, mass balance of dialysis stream over dialysis membrane is negative	PT: 5 min RT: 10 min
	CA3.3-EF3.5-CO3.8	III	Liquid level in fermentor rises, mass balance of dialysis stream over dialysis membrane is positive	PT: 5 min RT: 10 min
	CA3.3-EF3.3-CO3.4	II	-	-
	CA3.3-EF3.3-CO3.5	II	-	-
	CA3.4-EF3.3-CO3.4	II	-	-
	CA3.4-EF3.3-CO3.5	II	-	-
	CA3.4-EF3.6-CO3.7	II	Liquid level in fermentor drops, mass balance of dialysis stream over dialysis membrane is negative	PT: 5 min RT: 10 min
HM3.4	CA3.5-EF3.7-CO3.9	II	Drop of environmental temperature, higher heat demand, temperature of returning dialysate is close to 0°C	PT: 1 d RT: 1 d
	CA3.5-EF3.7-CO3.10	I	-	-

HM3.5	CA3.6-EF3.8-CO3.11	II	Mass balance is not closed, detection of leakage streams	PT: 2 m RT: 3 m
	CA3.6-EF3.8-CO3.12	III	Carbon balance is not closed	PT: 2 m RT: 3 m
	CA3.6-EF3.8-CO3.13	III *	-	-
	CA3.7-EF3.3-CO3.4	II	-	-
	CA3.7-EF3.3-CO3.5	II	-	-
	CA3.8-EF3.8-CO3.11	II	Mass balance is not closed, detection of leakage streams	PT: 2 m RT: 3 m
	CA3.8-EF3.8-CO3.12	III	Carbon balance is not closed	PT: 2 m RT: 3 m
	CA3.8-EF3.8-CO3.13	III *	-	-
* = release of MO to environment may have consequences of higher severity				

Task 5 Hazard rating

Of the listed hazard manifestations only a small number of scenarios have a severity class I (catastrophic). These scenarios are covered by the hazard manifestations HM1.7, HM2.5, and HM3.4 (fracture of vessel, freezing of pipes) and cannot be accepted. Measures to avoid these hazards will be discussed in the next task.

A lot of scenarios will lead to consequences of a class II severity (critical). A great number of them occur after a stirrer failure in the fermentor. These hazards can be avoided by two separate stirring devices or a reactor construction without a stirrer. Detailed measures are given in task 6. Also the death of the hyperthermophilic biomass is triggered by some HMs and will lead to a consequence of class II severity. This hazard can be minimized but has to be accepted. A re-inoculation might be necessary from time to time. Fracture of membranes or the seals thereof is also an acceptable hazard, if the fracture can be detected fast. The exchange of membranes, seals, and bearings must be done on a regular basis. The risk of fouling and biofilm formation can be accepted, if cleaning procedures are carried out on a regular basis.

The release of hyperthermophilic microorganisms to the environment does not represent an immediate danger to the crew and can be accepted. However there might be some political or administrational restraints of this scenario. In this case, this scenario cannot be accepted.

Task 6 Hazard reduction

In the previous task several scenarios were named, which will lead to unacceptable risks. HM1.7 includes the scenario of a vessel fracture. The likelihood of this event is very low, but the risk cannot be avoided. Regular maintenance together with a careful operation will prolog the lifetime of the vessel beyond the lifetime of the rest of the station. In terrestrial applications stirred tank reactors are designed for 30 years and often operated even longer without damage of the hull.

The scenario of freezing pipes is probably the most endangering scenario for the hyperthermophilic liquefaction unit in a cold environment well below 0°C. Once the continuous flow through the pipes stops, the pipes are prone to freezing after a short time. Even a good insulation will not stop this process, but only causes its delay. Countermeasures can be taken, such as heating of the pipes or housing of the pipes in a temperature controlled room. Further measures can be found in cold environments on earth, such as waste water plants in Siberia or the Arctic, were this risk also occurs.

Stirrer failure will lead to some class II scenarios (critical). At the moment, a stirred tank reactor is used for the hyperthermophilic liquefaction unit. Experiments in the lab showed, that the heat supply of the fermentor can cause problems, when either the heat exchanging surface or the temperature probe is covered with a thick layer of sedimented substrate particles. A good mixing of the fermentor liquid is therefore of high importance. Several types of reactors are known in the field of anaerobic wastewater treatment, such as fluidized bed, USAB, EGSB, tower reactors with gas circulation (e.g. Paques IC®), and Mammut pumps (e.g. Linde Laran®). All of these reactor types do not require the usage of a stirrer. Some of these concepts, especially fluidized bed, tower reactors and Mammut pumps, seem to be fit for operation with high solid content at hyperthermophilic conditions. A overheating of the fermentor in the case of bad mixing conditions can also be circumvented by the use of more than one temperature probe or by monitoring the heat-transfer into the fermentor medium.

The irreversible inactivation of the biomass is also a critical hazard for the operation of the system. This risk in minimized by the usage of two collecting tanks. The first tank receives the substrate and feeds a small test reactor and the second tank. The second tank feeds the hyperthermophilic liquefaction unit. If any toxic substances enter the first tank, the intoxication of the test fermentor will occur one hydraulic retention time before the intoxication of the big fermentor. This will give enough time to close the substrate supply to the hyperthermophilic liquefaction unit.

The hyperthermophilic liquefaction unit uses two membranes, which integrity have to be ensured. The best way to prevent membranes form breakage is a close monitoring of the pressure on both sides of the membrane in the inlet and outlet. High pressure gradients can occur in the form of many hazard manifestations (HM2.2, HM2.4, HM3.1, HM3.3, and HM3.5). High pressure can be circumvented by the usage of burst disks and safety valves and a stable process control system. Fouling problems are encountered by regular cleaning. In general, membrane technology is a well established field in process technology; stable and safe systems are on the market (e.g. drinking water production form sea water)

The release of hyperthermophilic microorganisms can occur in some hazard manifestations (HM1.7, HM2.4, HM2.6, HM3.3, and HM3.5) though hyperthermophilic microorganisms all belong to the group of S1 organisms and therefore do not endanger humans or animals. If the release of microorganisms into a sterile environment cannot be accepted several counter measures are possible. Instead of single seals double seals with sealing liquid must be used. Double seals with sealing liquid are state of the art in design of bioreactors for the cultivation of non-GRAS (Generally regarded as safe) organisms. Membrane seals can be housed, so that leakage streams are gathered. Burst dirks and safety valves must not open to the environment. Instead relieve tanks are necessary, which take up any streams leaving the safety vales.

Task 7 Recommendation of acceptance
The hazards, which were classified unacceptable in task 5, are all acceptable now, if the measures named in task 6 are taken. Additional loops of task 5, 6 and 7 have to be done during basic and detail engineering of the plant.

Task 8 Tracking and communication of the hazards
The identified hazards may be reduced by modifying the hardware. For instance, pressure relief valves could be mounted on the bioreactor in order to prevent overpressure and possibly fracture of the fermentor.
The HACCP has to be repeated regularly, and the staff in charge of the hardware will be trained to react to prevent the occurrence of hazards and react in case of hazard occurence.

Task 9 Acceptance of the hazards
All hazards which are currently known are acceptable.

2 BALANCE DATA FOR THE HYPERTHERMOPHILIC LIQUEFACTION UNIT

Basis for the data are 10 experiments covering a wide range of process parameters, such as temperature, pH, membrane type and area, hydraulic retention time, dialysate exchange rate, and feed concentration. The composition of the ingoing and outgoing streams is given in Tables 8-11. The provided data are calculated for a 100L- plant with an ingoing wastewater stream of 1L/h. A degradation performance of 75% is assumed. Effluent is saturated with dissolved gases (CO_2 and H_2), which are also withdrawn through the dialysis membrane. A Gas production of 0.003L/(L h) was measured. Due to the high solubility of CO_2 in the fermentation liquid the CO_2 fraction in the gas phase decreases below the stoichiometric fraction of 33% to roughly 10%. Hydrogen makes up the other 90%. (gas fractions are given in vol% or mol%)
Organically bound Oxygen and Hydrogen were not balanced, since an aqueous system is used.
A mass balance model is given in TN3.9.

Table 8: Composition of Feed

Phase	Species	Unit	Value
Solid	Carbon	[g/L]	6.4
	Nitrogen	[g/L]	0.5
	Total	[g/L]	20
	Biomass*	[g/L]	0.1
Liquid	Carbon	[g/L]	1.6
	Nitrogen	[g/L]	0.1
	VFA	[g_C/L]	0.015
	NH_4^+	[g_N/L]	0.15
Gaseous	Carbon	[g/L]	0
	Nitrogen	[g/L]	0.02
	Oxygen	[g/L]	0.006

	Hydrogen	[g/L]	0
Temperature		[°C]	25
Vol-Flow		[L/h]	1
*mesophilic			

Table 9: Composition of Effluent			
Phase	Species	Unit	Value
Solid	Carbon	[g/L]	1.6
	Nitrogen	[g/L]	0.1
	Total	[g/L]	5
	Biomass*	[g/L]	0.5
Liquid	Carbon	[g/L]	0.4
	Nitrogen	[g/L]	0.05
	VFA	[g_C/L]	0.04
	NH_4^+	[g_N/L]	0.01
Gaseous	Carbon	[g/L]	0.036
	Nitrogen	[g/L]	0
	Oxygen	[g/L]	0
	Hydrogen	[g/L]	0.001
Temperature		[°C]	90
Vol-Flow		[L/h]	1
*hyperthermophilic			

Table 10: Composition of Dialysate in			
Phase	Species	Unit	Value
Solid	Carbon	[g/L]	0
	Nitrogen	[g/L]	0
	Total	[g/L]	0
	Biomass	[g/L]	0
Liquid	Carbon	[g/L]	0.02
	Nitrogen	[g/L]	0.001
	VFA	[g_C/L]	0
	NH_4^+	[g_N/L]	0
Gaseous	Carbon	[g/L]	0
	Nitrogen	[g/L]	0
	Oxygen	[g/L]	0
	Hydrogen	[g/L]	0
Temperature		[°C]	90
Vol-Flow		[L/h]	20

Table 11: Composition of Dialysate out			
Phase	Species	Unit	Value
Solid	Carbon	[g/L]	0
	Nitrogen	[g/L]	0
	Total	[g/L]	0
	Biomass	[g/L]	0
Liquid	Carbon	[g/L]	0.3
	Nitrogen	[g/L]	0.05
	VFA	[g_C/L]	0.02
	NH_4^+	[g_N/L]	0.006
Gaseous	Carbon	[g/L]	0.03
	Nitrogen	[g/L]	0
	Oxygen	[g/L]	0
	Hydrogen	[g/L]	0.001
Temperature		[°C]	90
Vol-Flow		[L/h]	20

Table 11: Composition of biogas			
Phase	Species	Unit	Value
Solid	Carbon	[g/L]	0
	Nitrogen	[g/L]	0
	Total	[g/L]	0
	Biomass	[g/L]	0
Liquid	Carbon	[g/L]	0
	Nitrogen	[g/L]	0
	VFA	[g_C/L]	0
	NH_4^+	[g_N/L]	0
Gaseous	Carbon	[g/L]	0.04
	Nitrogen	[g/L]	0
	Oxygen	[g/L]	0
	Hydrogen	[g/L]	0.03
Temperature		[°C]	90
Vol-Flow		[L/h]	1.5