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Chemical Looping Gasification for Sustainable Production of Biofuels

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Health & Safety Risk Assessment

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1 Introduction

Brief introduction into the topic, relevance for the CLARA project.
Despite to its approach to use regenerative harmless fuels (biomasses) as input and use for production of fuels several chemicals are applied during the conditioning and further application of the intermediate products. Particular attention should also be drawn to the process itself and the potential safety risks in case of a malfunction of the unit and preventive measures. It should be taken into consideration that most of the full process chain consists of large scale units almost known. The innovative gas cleaning section consists of new combination of processes but these are also generally well known.
Finally, measures for health and safety risk mitigation are to be developed to show that there are at least no unsolvable risks.

2 Methods

Risk assessment is basically done by looking schematically of relevant risk categories. These are first described e.g. by mentioning the cause of happening, and subsequently assessed first in their possible impact. These impacts are assessed regarding their severeness following finally by describing possible / necessary mitigation measures. In most cases these mitigation measures are already known from similar application (literature, good engineering practices).

For the assessment of risks, a matrix of probability and severity is usually used. In the CLARA project the partners have commonly decided to use four levels of probability and severity (neglectable/low/medium/high or 1/2/3/4). For overall risk assessment the values for probability and severity are multiplied and the products are finally categorised into overall risk levels (see Figure 1)

	impact factor				
risk factor		1	2	3	4
	1	1	2	3	4
	2	2	4	6	8
	3	3	6	9	12
	4	4	8	12	16

Figure 1: Risk matrix

The assessment of the full-chain process has been done for the following sections, leading partner in brackets:

- Solid Fuel Treatment (CENER
- Gasification (AE, TUDA)
- Raw Gas Treatment (TUDA, RWE)
- CO-Shift, COS hydrolysis, BTX removal (TUDA, RWE)
- Sour gas cleaning (TUDA, RWE)
- Caustic wash, Sulfur recovery (RWE)
- Fischer-Tropsch Synthesis (RWE)

For each section, several sub-sections were defined if meaningful. The assessment of each has been done by using 15 risk categories (key words) like:

- Flow (no/low/high/back/misdirected)
- Temperature (low/high)
- Pressure (low/high)
- Level (low/high)
- Thermal expansion (explosion)
- Leakage
- Quality/composition of process media/utilities
- Others (e.g. utility outage)

These keywords are used as a guideline to think of possible risks, describing their origin or causes and their impact regarding health and safety to the operators.

This assessment has been done on the basis of the process flow diagrams for the individual sections by the above mentioned partners. The drafts have then been reviewed by RWE and discussed with the partners individually.

As for the pilot gasifier a detailed PID has been developed and a HAZOP has been performed under work package 5, such detailed HAZOP table was used as starting point. Risks regarding operability which are also listed in a HAZOP table were eliminated almost. Same was applicable for the raw gas cleaning, CO shift, COS hydrolysis, BTX removal and Sour gas cleaning as these sections are already built before the project started.

For the solid fuel treatment, the sulfur recovery and the FT synthesis, the above mentioned procedure has been done from the beginning (empty risk table) as these processes were developed under CLARA project on a less detailed level.

3 Results and Discussion

In the subsequent chapters the individual risk tables are shown for the different sub-sections of the CLARA process.

3.1 Solid fuel treatment

CENER prepared a first draft of the risk assessment while it was reviewed by RWE. As this is a purely solid handling system no severe risks were expected despite to possible dust explosion in case of leakages and existing ignition sources. But as this is a topic already well-known in process technology standard mitigation measures are also known and listed (see Table 1)

Table 1. Risk table for solid fuel treatment

Category	Description	Likeli-hoods	Impacts qual.	Impacts quant.	Mitigation options	Comment	Likelihood x Impact
Explosion/fire	Fire/explosion due to formation of dust clouds	1	Destruction of plant equipment, deaths/injuries of staff	4	Indication/classification of areas of explosion (ATEX)		4
					avoid flames or sparks		
					Ventilation		
chemical exposure	Aspiration of / Exposure to dust during operation, unloading of biomass, handling of product, cleaning	1	long term health impact to lunge	2	Use of wet or suction methods		2
					Periodic cleaning and general ventilation		
					Mandatory use of dust mask in cleaning tasks and other operations in which dust is generated		
Noise	Noise exposure level above the exposure limit value	1	long term deafness of staff	1	Periodical measurements in workplaces	standard topic, hearing protection and noise protection / encapsulation is obligatory	1
					Use of hearing protection.	standard topic, hearing protection and noise protection / encapsulation is obligatory	
electricity	Work on or close an electrical installation	1	Contact with voltage parts of electrical equipment	2	Warning of electrical risk in existing electrical panels	standard topic	2
					Work carried out without elctrical connection, disconnect power supply of relevant equipment	standard topic, organisational measure	
moving parts	Unblocking or maintenance operations	1	entrapment/jamming of staff in mobile parts	2	Unblocking or maintenance operations when the machines are stopped and disconnected from the power supply	standard topic, standard working procedures and safety measures before maintance work starts	2

In this section one severe risks was identified namely possible dust explosion due to possible leakages. But as this explosion will only happen if at the same time an ignition source occurs, this has to be avoided e.g. by organizational means like smoking ban, and other also already known technical measures to protect ignition.

The last three topics are more general. They are applicable for any technical installations and are not individual for the solid fuel treatment. So these topics are only mentioned here, not for the subsequent process sections.

3.2 Gasification

As mentioned in chapter 2 a very detailed HAZOP table was used as starting point for the risk assessment. It consisted of a lot of operational risks as well as of repetitions for the different subsections. All these are deleted from the list to get a less complicated overview.

Nevertheless this list is much more detailed as for any other sub-section and will not be shown here but in Annex 1: Additional Information for better readability

To get a short overview for the gasification in total, the risks per sub-section were summed up to identify most critical subsections . The values are listed in Table 2.

Table 2. Summarized risks for sub-sections of gasification

Gasifier sub-section	Value
Biomass pellet transport (e.g. from silo)	4
Biomass pellet dosing (into FR)	38
Raw Gas Cooling system	29
Reactor system (FR, AR, Loop Seals)	32
Gas Path Fluidization FR (steam/CO2)	4
Gas Path Fluidization AR (air)	2
Flue Gas AR	19
Producer Gas FR	27
Overall system	28

As expected all sub-sections dealing with or having possible connection to the fuel gas (which is toxic and combustible) show higher risk values than those dealing with air or flue gas. Although certain single risks (impact) are assessed as high or very high (see Annex 1: Additional Information), the summarized risks can be assessed to be low or medium which reflects also the low probabilities of such risks. Nevertheless, at a later stage of detailed engineering for a large-scale unit each individual risk hast to be checked again and the assessment has to be done on a much more detailed level with respect to single equipment and instruments.

3.3 Raw gas treatment

Also for raw gas treatment the most critical risks are in case of leakages leading to contact of burnable and or toxic gases to the surrounding and staff. These risks as well as possible mitigation measures are basically known.

Table 3. Risk table for raw gas treatment

Plant section	Plant sub section	Category	Description	Likelihoods	Impacts qual.	Impacts quant.	Mitigation options	Likelihood x Impact
Raw Gas Treatment (after first Cooling)	Raw gas filter	No/low flow	filter blocked	1	increase of pressure in upfront systems (gasifier)	1	Nitrogen purge including check valve, orifice and safety valve optional: redundant filter (to be evaluated during detail engineering) detection, control and alarm of purge flow	1
		Reverse flow	Compressor outage and backflow via compressor bypass/backflow duct	1	increase of pressure in upfront systems (gasifier), leakage	2	check valve	2
		High temp.	unsufficient operation of raw gas cooler	1	rupture / leakages due to high temperature	2	high alarm at raw gas cooler (upfront to filter section) supervision of cooling cycle, reserve pump	2
		High Level	outage of rotary valve	1	pressure drop increases (see blockage of filter, here due to overfill)	1	Alarm L+; raw gas switch to emergency incineration	1
			level indicator outage	1	pressure drop increases, pressure in gasifier increases	2	safety valve at gasifier / fuel reactor redundant level indicator	2
	Raw Gas Scrubber	no flow	water pump out of operation	1	no proper operation of washer	1	redundant pump, flow detection	1
				1	freeze of water, leakage of gases	3	supply of LP steam, trace heating	3
		High flow	too much steam	1	hig pressure in column	1	safety valve and orifice measurement of pressure drop via column design of equipment considering max. steam pressure	1
		High dust	malfunction of raw gas filter	1	high dust in wash / waste water	1	in Pumpen-Spec. berücksichtigen	1
	Raw gas compression	Reverse flow	compressor outage	1	reverse flow of gases to upfront systems	1	Check valve upfront intake of benzene recycle flow	1
		High pressure	blockage of compressor recycle	1	overpressure in downstream systems	2	safety valve at compressor outlet	2
		High temp.	outage of cooler	1	overheating of compressor, leakages	3	stop of compressor	3

3.4 CO shift, COS hydrolysis and BTX removal

Compared to other technologies for gas cleaning, BTX removal dealing with gases of high benzene content is an extra sub-section. But also this is generally known and same mitigation measures are to be applied as for processes with other harmful gases.

Table 4. Risk table for CO shift, COS hydrolysis and BTX removal

Plant section	Plant sub section	Category	Description	Likeli-hoods	Impacts qual.	Impacts quant.	Mitigation options	Likelihood x Impact
Shift and Hydrolysis	CO Shift	low temp	malfunction of preheating	1	malfunction of catalyst due to steam condensation	1	stop of reaktor, venting to flare	1
		Low flow	steam flow too small	1	methanation reaction occurs, high temperature, leakages	3	stop of reaktor, venting to flare	3
	COS hydrolysis	High temp.	temperature of inlet gas too high	1	malfunction of catalyst	2	stop of reaktor, venting to flare	2
BTX removal	BTX removal	High pressu	pressure control in upfront systems not sufficient	1	leakages	3	safety valve behind raw gas compressor, retention basins under biodiesel/benzene systems, gas detectors in plant and mobile	3
			high steam flow to desorber	1	leakages	3	flow control	3
		no flow	outage of pumps	1	malfunction of systems	1	redundant pumps, operation by UPS	1
		Reverse flov	backflow of condensate to cooler upfront of benzene wash	1	malfunction of cooler	1	slope of raw gas pipe in direction to benzene wash	1
		Low temp.	low ambient temperature	1	water freeze in cooling column, disrupture of pipes/seals, leakage	1	isolation of column	1
		High temp.	outage/malfunction of coolers or temperature measurement	1	high temperature in benzene gas cooler	1	high alarm at cooler exit	1
		High level	outage of pumps or level controllers	1	overfilling of vessels/columns, malfunction, spill-out	1	level alarms, sufficient size of vessels	1
		Low activity	bad separation of emulsion phases	1	malfunction of oil desorber	1	use of right chemicals / additives	1
				1	waste water quality getting worse	1		1

3.5 Sour gas cleaning, final purification and sulfur recovery

Risks in Sour gas cleaning until sulfur recovery are mainly caused by high concentration of the toxic component H2S. But as this is also well known from commercial processes mitigation measures are established and nothing new has to be developed within CLARA.

Table 5. Risk table for sour gas cleaning, final purification and sulfur recovery

Plant section	Plant sub section	Category	Description / Causes	Likeli-hoods	Impacts qual.	Impacts quant.	Mitigation options	Likelihood x Impact
Sour gas removal (SGR)	Sour gas removal (SGR)	No flow	outage of solvent pump	1	no function of sulfur removal, poor quality of syngas to caustic wash/synthesis section	1	pump control, online gas analysis, venting of gas to flare	1
			blockage of filters in solvent systems (due to salts/dust)	1	overfill of column, malfunction of column/gas cleaning	1	control of solvent quality, regular cleaning of solvent / separation of solids	1
		high temp	malfuction of coolers	1	malfunction of gas cleaning, increase of pressure (see below)	2	temperature control	2
		High pressure	malfunction of raw gas compressor, Blockage at outlet of absorber column	1	leakages, toxic gases to atmosphere	3	safety valves, pressure control, gas detectors in plant / mobile	3
Final Purification	Caustic Scrubber	high pressure	high pressure due to blockage in downstream systems or malfunktion of pressure control	1	Leakage of liquids (caustic solution)	2	safety valves, pressur econtrol, liquid collection systems, sufficient working clothes for staff	2
				1	leakage of toxic syngas	3	gas detectors in plant, mobile gas detectors for staff	3
Sulfur recovery with KMnO4	Sulfur recovery with KMnO5	other	leakage due to unproper sealing in liquid system	1	spill out of KMnO4 solution, undesired contact to skin and eyes	2	liquid collection systems, sufficient working clothes for staff	2
			leakage due to unproper sealing in gas system	1	leakage of toxic sour gas (H2S)	3	gas detectors in plant, mobile gas detectors for staff	3

3.6 FT synthesis

In FT synthesis high temperature processes are applied for toxic and combustible gases producing a mix of hydrocarbons which are water-polluting. But as it is a goal to produce these it is not meaningful to change the process to other products which might be less water-polluting. All risks are well known like for all other upfront processes mentioned above. And they all can be minimized by explicit mitigation measures – be it technically or organizationally.

Table 6. Risk table for FT synthesis

Plant section	Plant sub section	Category	Description / Causes	Likeli-hoods	Impacts qual.	Impacts quant.	Mitigation options	Likelihood x Impact
				value		value		
Final Purification	ZnO-Bed	leakage	leakage of toxic syngas	1	toxic gas system under pressure, high danger for staff	3	gas detectors in plant, mobile gas detectors for staff	3
Synthesis	FT reactor	leakage	leakage of toxic syngas	1	toxic gas system under pressure, high danger of staff	3	gas detectors in plant, mobile gas detectors for staff, propper engineering regarding operation conditions and sealings	3
			leakage of burnable gas	1	burnable gas system under pressure, explos	3	gas detectors in plant, mobile gas detectors for staff, proper engineering regarding operation conditions (safety valves and sealings)	3
			leakage of hot liquids	1	hot liquides, danger for staff	2	proper engineering regarding operation conditions, e.g. sealings (see also protection for environment by use of collection basins or tanks in case of spill-out of liquids)	2
	SMR	leakage	leakage of toxic syngas due to rupture of coil due to low steam flow inside	1	toxic gas system under pressure, high danger of staff	3	gas detectors in plant, mobile gas detectors for staff, propper engineering regarding operation conditions and sealings	3

4 Conclusions

General and individual risks have been identified by the technology partners of the CLARA project. Most severe risks refer to leakages of toxic and or combustible gases. While all these risks and necessary mitigation measures are already known from similar large scale chemical and refinery processes it is not expected that these cannot be minimized to an acceptable level. No so called “show stoppers” popped up.

When looking onto the used chemicals and process media, the only chance to avoid certain risks completely would be a change of the applied technologies. But this would only change the detailed risks, but not necessarily the number of risks or the overall severity. At least it would change the story of CLARA which is not foreseen.

5 Disclaimer

The content of this deliverable reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

Annex 1: Additional Information

Risk assessment table for gasification section (5 pages)

#	Plant section	Category	Description	Likelihoods		Impacts qual.	Impacts quant.		Mitigation options	likelihood x impact	sum of L x I per subsection
‘6.1.1	Biomass pellet transport (e.g. from silo)	LEAKAGE	Damage of wear and tear parts (e.g. compensator) in pellet supply system	low	1	Leakage of biomass pellets to surroundings	medium	2	· Check all wear parts (e.g. compensators) regularly · Replace wear parts regularly · organizational measures to protect from ignition (no smoking, no open fire, ignition avoiding tools, etc.)	2	4
					1	dust formation in plant		2		2	
‘1.2.1	Biomass pellet dosing (into FR)	NO FLOW	No flow of pellets from feeding system to FR, due to failure of dosing system (e.g. blockage, failure of screw, no pellet supply, etc.)	low	1	Termination of gasification. First: FR temperature rises, CO/H2 concentration drops Then: drop-off in AR and FR temperatures.	medium	2	· Mapping of positions of all actuators. · Mapping of activity of all screws and rotary valves · Redundant feeding system · Special equipment to prevent bridge building (vibrators, stirrers)	2	38
‘1.2.2		NO FLOW	No flow of inerting media (CO2) to feeding system	low	1	Danger of back-flow of gas from FR to dosing system	high	3	· Mapping of CO2 inerting flow · Mapping of pressure gradient between dosing system and FR	3	
‘3.2.2		HIGH FLOW	Too high flow of CO2 into dosing system	medium	2	Pressure in dosing system increases. Leakage of CO2 to surrounding	medium	2	· Stationary/Mobile Gas detectors	4	
‘4.2.1		MISDIRECTED FLOW	Inerting and pressure sealing of dosing system malfunctions. Syngas flows towards dosing system from FR	medium	2	Producer gas from FR flows towards the fuel dosing system. Danger of explosion or syngas leakage	High	3	· Supervise temperature in fuel feeding system. In case of T++ open gas path towards FR is sealed. · Mapping of flow of inerting gas into dosing system	6	
‘6.2.1		LEAKAGE	Damage of wear and tear parts (e.g. compensator) in pellet feeding system	medium	2	Leakage of dust, gases (CO2) to surroundings.	medium	2	· Check all wear parts (e.g. compensators) regularly · Replace wear parts regularly	4	
‘6.2.2		LEAKAGE	Leakage of gas through sealing	low	1	Toxic gases reach environment. Potentially hazardous environment	medium	2	· Gas alarm in plant detects gas leakage · PSA (CO/H2S detector) worn by operators	2	
‘7.2.1		LOW PRESSURE	No CO2 for inerting of dosing system, see 4.2.1	medium	2		high	3		6	
‘8.2.1		HIGH PRESSURE	Pressure in dosing system exceed max. permissible pressure	low	1	Damage of sealed containers. Risk of bursting.	high	3	· Dosing system is equipped with suitable safety relieve valve	3	
‘11.2.1		HIGH TEMPERATURE	Backflow of hot gases from FR -> increase in T in feeding system	low	1	see 4.2.1	high	3		3	
‘11.2.2		HIGH TEMPERATURE	Self-ignition of pellets -> rapid surge in temperature	low	1	Explosion in dosing system	high	3	· Safety relief valve · Temperature alarm at T+ to prevent reaching of self-ignition-T	3	
‘12.2.1		LOW LEVEL	No more pellets in feeding system	low	1	see point 1.2.1		2		2	

'1.3.1	Raw Gas Cooling system	NO FLOW	No flow of cooling medium (pump failure) in cooling system.	Low	1	T++ in flue gas tract. Overheating+damage of crucial plant components	high	3	· Redundant cooling pump · F- and T+ Alarms in cooling system · Mapping of flows/Temperatures.	3	29
'1.3.2		NO FLOW	No flow of cooling medium (blockage in fluid path) in cooling system.	Low	1	T++ in flue gas tract. Overheating+damage of crucial plant components	high	3	· Mapping of positions of all actuators. · LO for all hand actuators · F- and T+ Alarms in cooling system · Mapping of flows/Temperatures.	3	
'2.3.1		LOW FLOW	Too little flow of cooling medium in cooling system. see points 1.3.1	low	1		medium	2		2	
'4.3.1		MISDIRECTED FLOW	Leakage of cooling medium from cooling system to surroundings.	Low	1	· Liquid level in cooling system drops. Leakage of hot liquid/steam to surroundings -> danger for operators. · Risk of temperature peaks in flue gas tract due to reduced cooling power -> damage of parts.	High	3	· Map level in cooling system, emergency shut-off at ALL · Map temperature and volume flow in cooling system · Sealing-off of all measuring points with ball valves	3	
'4.3.2			Leakage of cooling medium into reactor system.	low	1	· Liquid level in cooling system drops. Leakage of hot liquid/steam to reactor -> increase in reactor pressure · Risk of temperature peaks in flue gas tract due to reduced cooling power -> damage of parts.	high	3	· Map level in cooling system, emergency shut-off at ALL · Map temperature and volume flow in cooling system · Map pressure in reactor system	3	
'7.3.1		LOW PRESSURE	Low pressure in cooling system due to leakage or other impacts	low	1	Evaporation of steam inside cooling system. Rapid increase in pressure + temperature. Danger of damage to cooling system.	high	3	· Mapping of pressure & temperature in cooling system · Safety shut-down at P--, P++ or T++	3	
'8.3.1		HIGH PRESSURE	High pressure in cooling system	Low	1	Exceeding of max. pressure in cooling system. Danger of damage to reactor parts	high	3	· Mapping of pressure & temperature in cooling system · Safety shut-down at P--, P++ or T++	3	
'9.3.1		THERMAL EXPANSION	Cooling medium is locked in (e.g. in pump)	Low	1	Increase in pressure in cooling system. Danger of damage to cooling system	High	3	· Mapping of positions of all actuators. · LO for all hand actuators	3	
'11.3.1		HIGH TEMPERATURE	Too high temperature in cooling system (e.g. failure of recooler)	Low	1	see 8.3.1	high	3		3	
'12.3.1		LOW LEVEL	Low level of cooling medium in cooling system	low	1	see point 4.3.1	high	3		3	

'2.4.1a	Reactor system (FR, AR, Loop Seals)	LOW FLOW	Low flow of fluidization medium to AR -> Fluidization still possible (e.g. issue with flow control, etc.)	Medium	2	Reduced OC entrainment from AR. AR inventory increases, FR inventory decreases. Risk of emptying of AR LS via J-Valve -> gas leakage from AR to FR	High	3	· Reactor system stabilizes itself for small changes (higher inventory -> higher entrainment) · Mapping of pressure drop in AR LS -> Alarm at L-, Safety Shut-Down at L- - · Mapping of reactor inventories, Operator reacts to changes and adjusts fluidization velocity in AR	6	
'3.4.1		HIGH FLOW	High Flow of fluidization medium to AR (e.g. issue with flow control, etc.)	medium	2	Increased entrainment of OC from AR, increased internal recirculation of OC via AR LS. Increased oxygen transport into AR. OC is oxidized to a larger degree -> Higher oxygen transport to FR. Lower syngas production. Higher temperature in AR	low	1	· Mapping of reactor inventories, Operator reacts to changes and adjusts fluidization velocity in AR · Mapping of syngas composition at FR outlet. Adjustment of air to fuel ratio by operator · Alarm at T+ in AR, Safety shut down at T++ in AR	2	
'3.4.2			High Flow of fluidization medium to AR Loop Seal (e.g. issue with flow control)	low	1	Entrainment of OC from AR LS towards AR -> AR LS is emptied. Risk of gas leakage between AR and FR. Reduced OC transport to FR. FR temperature decreases.	High	3	· Mapping of pressure drop in AR LS -> Alarm at L-, Safety Shut-Down at L- -	3	
'3.4.3			High Flow of fluidization medium to FR Loop Seal (e.g. issue with flow control)	low	1	Entrainment of OC from FR LS -> FR LS is emptied. Risk of gas leakage between AR and FR	High	3	· Mapping of pressure drop in AR LS -> Alarm at L-, Safety Shut-Down at L- -	3	
'3.4.4			High Flow of fluidization medium to J-Valve (e.g. issue with flow control)	medium	2	Emptying of AR LS towards FR -> AR LS is emptied. Risk of gas leakage between AR and FR. Increased OC transport to FR. FR temperature increases.	High	3	· Mapping of pressure drop in AR LS -> Alarm at L-, Safety Shut-Down at L- -	6	32
'7.4.2		LOW PRESSURE	Low Pressure in FR (e.g. pressure controller via syngas compressor is faulty)	low	1	Under-pressure in syngas tract. Higher risk of leakage of air into flue gas system -> Risk of explosion	medium	2	· Alarm at P- in FR, Safety-Shut down at P- in FR · O2 Sensor in syngas tract triggers emergency shut down if O2-conc. is too high	2	
'8.4.1		HIGH PRESSURE	High Pressure in AR (e.g. pressure controller via draught fan is faulty, failure of draught fan)	low	1	High-pressure in flue gas tract. Higher risk of leakage of flue gas into surroundings	low	1	· Alarm at P+ in AR, Safety-Shut down at P++ in AR · Mobile/stationary gas detectors	1	
'8.4.2			High Pressure in FR (e.g. pressure controller via syngas compressor is faulty, failure of syngas compressors)	low	1	High-pressure in syngas tract. Higher risk of leakage of raw syngas to surroundings -> Risk of explosion, Leakage of toxic gases	medium	2	· Alarm at P- in FR, Safety-Shut down at P++ in FR	2	
'11.4.1		HIGH TEMPERATURE	Too high O2 input into FR. Temperature in AR and FR increases	low	1	Temperature in AR/FR increases. Higher H2/CO content in raw syngas. Risk of reactor damage/overheating of downstream unit	low	1	· Mapping of temperatures in AR and FR · Alarm at T+ in AR/FR, Emergency shut-off at T++ in AR/FR	1	
'11.4.2			No pellets supply to FR, See 1.2.1	low	1		medium	2		2	
'11.4.3			Failure of Start-Up Burner AR	Low	1	Increase of AR Temperatures.	low	1	· Mapping of temperatures in AR · Alarm at T+ in AR, Emergency shut-off at T++ in AR	1	
'11.4.4			Failure of Start-Up Burner FR	low	1	Increase of AR temperatures. Dilution of producer gas in FR with oxygen containing flue gas -> Risk of explosion	High	3	· Mapping of temperatures in FR · Alarm at T+ in FR, Emergency shut-off at T++ in FR	3	

'8.5.1	Gas Path Fluidization FR (steam/CO2)	HIGH PRESSURE	Superheating of steam in steam line due to failure of temperature controller. Increase in pressure	low	1	Risk of damage to steam line.	Medium	2	· Pressure relief valve in steam system · Mapping of pressure in steam line. Alarm at P++	2	4
'11.5.1		HIGH TEMPERATURE	Faulty temperature controller in steam super-heater	low	1	Steam temperature increases. Higher inlet temperatures for FR. Risk of damage of steam line	medium	2	· Mapping of temperatures in steam system · Alarm at T+ in steam system	2	
'5.6.1	Gas Path Fluidization AR (air)	BACKFLOW	Failure of AR air fan. Backflow of flue gases towards air fan.	low	1	Risk of flue gas (CO/CO2) reaching atmosphere.	medium	2	· Mobile and stationary gas alarms · Gas flap upstream of AR air fan closed if air fan is switched off	2	2
'1.7.2	Flue Gas AR	NO FLOW	No flow of dust through rotary valve below AR filter.	Low	1	No extraction of dust from filter possible. Level in AR filter increases. Risk of damage of filter candles	Medium	2	· Mapping of motor speed of rotary valve · Mapping of solid level in AR filter. · Warning at L+, Alarm at L++	2	19
'1.7.3			Failure of induced draft fan.	Low	1	No flow of flue gas. Increased pressure in reactor system (-> see 8.4.1). Risk of damage to filter candles.	Low	1	· Mapping of motor speed of induced draft fan · Mapping of pressure in FR. Alarm at P+ · Safety Shut down at P++	1	
'2.7.1		LOW FLOW	Low flow of gas (N2) to AR filter cleaning system.	Low	1	Increased pressure drop over AR filter. Decreased flow of flue gas. Risk of damage of filter candles. Risk of damage of AR filter due to low pressure.	medium	2	· Mapping of pressure drop over AR filter. · Alarm at P++ · Mapping of pressure upstream of AR filter · Alarm at P--	2	
'2.7.2			Faulty pressure controller reduces motor speed of induced draft fan of AR	Low	1	Increased pressure in reactor system (see 8.4.1). Risk of damage to filter candles.	medium	2	· Mapping of motor speed of induced draft fan. Alarm at speed- · Mapping of pressure in reactor system, Alarm at P++	2	
'3.7.1		HIGH FLOW	Faulty pressure controller increases motor speed of induced draft fan of AR	Low	1	Decreased pressure in reactor system (see 8.5.1). Risk of damage to filter/ filter candles.	Medium	2	· Mapping of motor speed of induced draft fan. Alarm at speed++ · Mapping of pressure in reactor system, Alarm at P--	2	
'3.7.2			Flow from reactor system is larger than capacity of AR induced draft fan.	Low	1	Increased pressure in reactor system (see 8.4.1). Risk of damage to filter/ filter candles.	Medium	2	· Mapping of pressure in reactor system, Alarm at P--	2	
'6.7.1		LEAKAGE	Damage to AR filter candles.	Low	1	Dust reaches air draft fan (-> erosion, increased risk of damage) and atmosphere (emissions).	medium	2	· Dust detection downstream of AR filter. · Alarm if alarm limit is surpassed	2	
'11.7.1		HIGH TEMPERATURE	Problem in AR heat exchanger (e.g. dust deposition, low cooling medium flow)	Low	1	Flue gas temperature increases. Risk of damage to piping, filter or filter candles.	medium	2	· Mapping of temperature in AR flue gas tract · Alarm at T+	2	
'11.7.2			Faulty temperature controller for AR filter trace heating	Low	1	Increased temperature in AR filter. Risk of hot spot formation. Damage to filter/filter candles	medium	2	· Temperature limiter in trace heating switches off trace heating at T++	2	
'13.7.1		HIGH LEVEL	Too high dust level in AR filter (e.g. bridge building in downpipe, faulty rotary valve)	Low	1	see 1.7.2	medium	2		2	

'1.8.1	Producer Gas FR	NO FLOW	No flow of syngas from FR	Low	1	Induced draft fan reduces motor speed to minimum. At minimum motor speed, Pressure in FR drops. Risk of oxygen influx into syngas line	Medium	2	· Mapping of pressure in FR. Alarm at P- · Safety Shut down at P--	2	
'1.8.2			No flow of dust through rotary valve below FR filter.	Low	1	No extraction of dust from filter possible. Level in FR filter increases. Risk of damage of filter candles	Medium	2	· Mapping of motor speed of rotary valve · Mapping of solid level in FR filter. · Warning at L+, Alarm at L++	2	
'1.8.3			Failure of induced raw gas compressor.	Low	1	No flow of flue gas. Increased pressure in reactor system (-> see 8.4.1). Risk of damage to filter candles.	Low	1	· Mapping of raw gas compressor of induced draft fan · Mapping of pressure in FR. Alarm at P- · Safety Shut down at P--	1	
'2.8.1		LOW FLOW	Low flow of gas (CO2) to FR filter cleaning system.	Low	1	Increased pressure drop over FR filter. Decreased flow of raw gas. Risk of damage of filter candles. Risk of damage of FR filter due to low pressure.	medium	2	· Mapping of pressure drop over FR filter. · Alarm at P++ · Mapping of pressure upstream of FR filter · Alarm at P--	2	
'2.8.2			Faulty pressure controller reduces motor speed of raw gas compressor.	Low	1	Increased pressure in reactor system (see 8.4.1). Risk of damage to filter candles.	medium	2	· Mapping of motor speed of raw gas compressor. Alarm at speed— · Mapping of pressure in reactor system, Alarm at P++	2	
'3.8.1		HIGH FLOW	Faulty pressure controller increases motor speed of raw gas compressor	Low	1	Decreased pressure in reactor system (-> see 8.5.1). Risk of damage to filter/ filter candles.	Medium	2	· Mapping of motor speed of induced draft fan. Alarm at speed++ · Mapping of pressure in reactor system, Alarm at P--	2	
'3.8.2			Flow from reactor system is larger than capacity of raw gas compressor	Low	1	Increased pressure in reactor system (-> see 8.4.1). Risk of damage to filter/ filter candles.	Medium	2	· Mapping of pressure in reactor system, Alarm at P--	2	27
'3.8.3			Too much flow of dust through rotary valve of FR filter.	Low	1	Complete emptying of FR filter. Increased risk of backflow of air (O2) into filter -> risk of explosion.	High	3	· Level in FR filter is mapped by independent level switches. Rotary valve is switched off at L--	3	
'6.8.1		LEAKAGE	Damage to FR filter candles.	Low	1	Dust reaches raw gas compressor (-> erosion, increased risk of damage) and gas cleaning system.	medium	2	· Dust detection downstream of FR filter. · Water scrubber downstream of FR filter	2	
'11.8.1		HIGH TEMPERATURE	Problem in FR heat exchanger (e.g. dust deposition, low cooling medium flow)	Low	1	Raw Syngas temperature increases. Risk of damage to piping, filter or filter candles.	medium	2	· Mapping of temperature in FR flue gas tract · Alarm at T+	2	
'11.8.2			Faulty temperature controller for FR filter trace heating	Low	1	Increased temperature in FR filter. Risk of hot spot formation. Damage to filter/filter candles	medium	2	· Temperature limiter in trace heating switches off trace heating at T++	2	
'12.8.1		LOW LEVEL	Rotary valve below FR filter does not switch off	Low	1	FR filter is emptied completely. Risk of backflow of O2-containing gases into filter. -> Risk of explosion	High	3	· Level switch turns rotary valve off at L-- · O2 Sensor detects O2 in system and turns of raw gas compressor at Q++	3	
'13.8.1		HIGH LEVEL	Too high dust level in FR filter (e.g. bridge building in downpipe, faulty rotary valve)	Low	1	see 1.8.2	medium	2		2	

'15.x.1	Overall system	NO UTILITIES	No pressurized air	low	1	No more control over pneumatic actuators	Very high	4	· Redundant pres. Air supply (e.g. two compressors) · Mapping of pressure in pres. Air system incl. alarm at P- · Safe position for all pneumatic actuators transfer plant into safe state	4	28
'15.x.2			No 24 V DC supply	low	1	No more control over actuators.	Very high	4	· Emergency power supply · All actuators go to safe position (which transfers gasifier into safe state)	4	
'15.x.3			No 230 V DC supply	low	1	Failure of all power units.	Very high	4	· Emergency power supply · All actuators go to safe position (which transfers gasifier into safe state)	4	
'15.x.4			No N2	low	1	· Inerting no longer possible. · Fluidization no longer possible.	Very high	4	· Redundant supply (e.g. two tanks). · Mapping of pressure in N2 system incl. alarm at P-	4	
'15.x.5			No CO2	low	1	· Inerting no longer possible. · Fluidization no longer possible.	Very high	4	· Redundant supply (e.g. two tanks). · Mapping of pressure in CO2 system incl. alarm at P-	4	
'15.x.6			No Cooling media (see also x.3.x)	low	1	· Damage to reactor parts. · Exceeding of max. permissible temperatures in different plant sections (e.g. flue gas tract)	Very high	4	· Redundant equipment in each cooling cycles (esp. pumps). · Mapping of all flows/temperatures	4	
'15.x.7			Failure of PCS	low	1	Process cannot be controlled anymore. "Blind flight".	Very high	4	· Redundant operating servers · Emergency power supply for PCS	4	