Pressurized pilot-scale fluidized bed gasifier: A risk analysis

KE2351 Risk analysis and management for chemical engineers

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Abstract

This comprehensive report explores the gasification process at the KTH plant in Sweden, focusing on biomass conversion and associated risks. The study employs methodologies such as Preliminary Hazard Analysis (PHA) and What-if analysis to identify, assess, and propose mitigation strategies for potential hazards. Specific hazards, including if the cooling of the reactor fails or if the control valves malfunction, are meticulously analyzed, and protective measures are recommended. The risk rating system clarifies risk levels, categorizing them as marginal, considerable, or important. The report concludes by summarizing key findings, emphasizing the need for continuous monitoring and personnel alertness, and acknowledging the report's limitations. This work serves as a valuable resource for understanding gasification processes, offering detailed risk assessments and mitigation strategies for researchers and industry professionals in the field.

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1. Introduction

The escalating reliance of modern society on fossil feedstocks for the production of fuels, chemicals, energy, and everyday items is a significant contributor to the environmental and societal challenges we face today. These challenges include global warming, climate change, energy scarcity, and geopolitical tensions. The urgency of these issues has led to an increasing demand for sustainable alternatives to fossil feedstocks. Biomass, an abundant, versatile, and sustainable resource, holds immense potential to replace many of the fossil feedstocks currently in use today. However, to transform biomass into valuable products, we need effective conversion technologies, one of which is the gasification of biomass.

Gasification is a flexible method for producing a wide variety of products from biomass. However, due to the diverse sources of biomass and the varying product gas composition requirements from industry, the gasification process must be tailored for each feedstock in order to safely and effectively utilise this resource to its full potential.

To achieve this, it is crucial to research, test, and develop the gasification process for different types of biomass and bed technologies to find optimal combinations. The gasification plant at KTH in Sweden, which is the focus of this report, is a pressurized pilot-scale fluidized bed gasifier used for such research.

This plant's main area of research is the different combinations of various bed materials and fuels, and the resulting composition and yield of the produced production gas. The aim of the research is to find good combinations of fuels and materials in order to produce a desired production gas. Some of the challenges the research focuses on are the formation and breakdown of tars in the process, the effects of different catalysts and the interaction between bed materials and the intermediate products and feedstock. Some examples of fuels used include birch-, pine- and spruce chips, straw pellets, and various energy crops.

However, like any other technology, it also presents certain risks that need to be thoroughly evaluated to ensure safe and reliable operation. This risk analysis aims to identify, assess, and propose mitigation strategies for potential hazards associated with the operation and to protect the surrounding environment. This is achieved by performing a what-if analysis on the pressurized pilot-scale fluidized bed gasifier and a PHA analysis of the immediate environment around the gasifier.

In the following sections, we will delve into the specifics of the gasifier’s operation, the characteristics of the biomass feedstock, and the potential risks associated with each. We will also discuss the methodologies used for risk identification and assessment, and present our findings and recommendations.

2. Description of Process

In this project, the entire process is divided into three main areas to simplify the risk analysis process and draw clear lines between the main parts of the gasifying operation. The three parts are the gasifier, filter, and reformer as seen in Fig. 1.

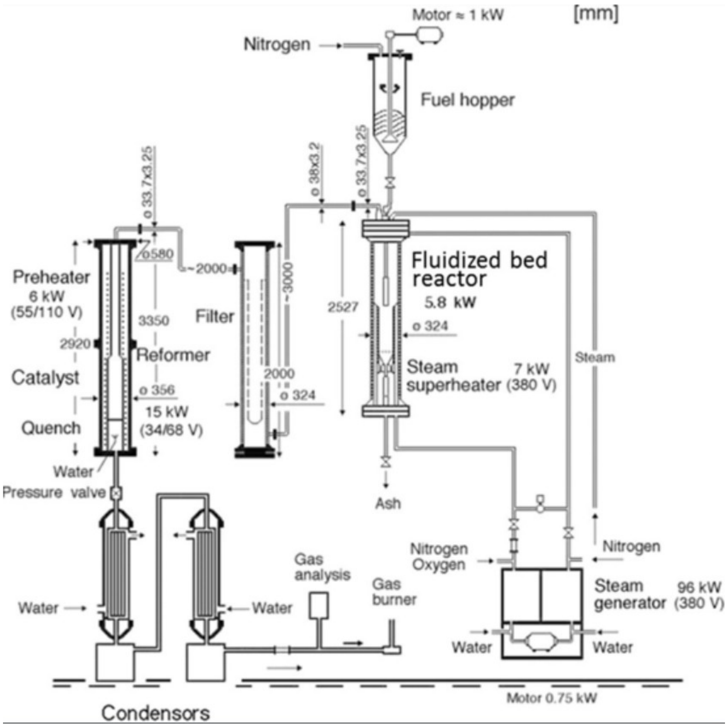

Figure 1. Schematic over the process including a pressurized gasifier, filter, and reformer setup.

2.1. Fluidised bed gasifier

In the gasifier, solid biomass material is thermo-chemically converted to gas. The fuel used in the process can be wood pellets or chips, forest residues, and dried organic waste. The products formed during the gasification are CO, CO_2, H_2, H_2O, CH_4, tars, heavier hydrocarbons, inorganics, as well as ashes [1]. The conversion from biomass to said products consists of several reactions such as pyrolysis, partial oxidation, gasification, etc. In this particular process, a pressurized bubbling fluidized bed (PBFB) is used for the gasification at a pressure of 30 bar, with the possibility of 50 bar. See Fig. 1 for a schematic of the process. Fluidized beds are characterized by a fluid-like behavior of the solid bed material as a result of gas moving through the bed, which yields good heat transfer. The maximum temperature allowed in the gasifier during operation is limited by the melting point of the bed material, and is usually in a range between 800–900 °C for the regular sand and rock materials used [2].

In this process, the fuel is fed into the fluidized bed reactor with a fuel hopper at the top of the reactor. The reactor is heated partly with process steam which is fed from a steam generator and a steam superheater. The rest of the heating in the process is delivered by the combustion of hydrogen with oxygen to reach the top temperature. Ash generated in the gasification process is removed from the bottom of the fluidized bed reactor, and the product gas leaves at the top of the reactor. The process in total is situated over three different floors in the building, where the fluidized bed reactor is located between the middle and top floor together with the consequent filter and reformer downstream. The reactor is accessed physically to personnel by walking on metal walkways between the process equipment, which may be done for sampling and maintenance.

2.2. Filtration

As previously mentioned the products leaving the fluidized bed reactor are many, and before the gas can be used it needs to be cleaned from contaminants. Firstly, particulates in the gas are removed with filtration. The particulate material in the gas leaving the reactor originates from unconverted biomass, char, and bed material. Particulate material can cause erosion and plugging of equipment downstream which damages the process over time [1]. In this process barrier filters are used to separate the particulate contaminants from the product gas. The gas is kept at a fairly high temperature through the filtration step to avoid tar condensation which would lead to the need for cleanup and possible clogging of the pipes and equipment.

2.3. Catalytic reformer

Post particulate removal, the product gas is still rich in tars and lighter hydrocarbons which can be problematic if tar condensation is unavoidable in downstream applications. For this reason, catalytic tar reduction has become a relevant substep in some gasification processes as this converts the tar into permanent gasses through thermal conversion, catalytic steam reforming and catalytic dry reforming. The catalyst can either be added to the fuel before gasification (Primary catalyst) or in a reactor downstream from the fluidized bed gasifier (Secondary catalyst). The reactor considered in this report utilizes a secondary catalyst in a catalytic reformer downstream from the filter. The catalysts predominantly used in the reformer are nickel-type catalysts [2].

3. Methodology Description

Several methods are available to identify and assess the hazards in a specific system, but the selection of methodologies depends on the size and complexity of the system. In this context, the risk analysis is confined to the 'Preliminary hazard analysis' and 'what if' for the concerned Pilot scale biomass gasifier system.

3.1. Preliminary hazard analysis (PHA)

PHA is an analysis of the generic hazards associated with the system along with their evaluation and mitigations to overcome the consequences of the hazards. It involves multiple steps, and it will take a few weeks to complete, additionally, this needs to be done by a group involving members from all domains [3]. Simply the following schematic describes how PHA is being carried out.

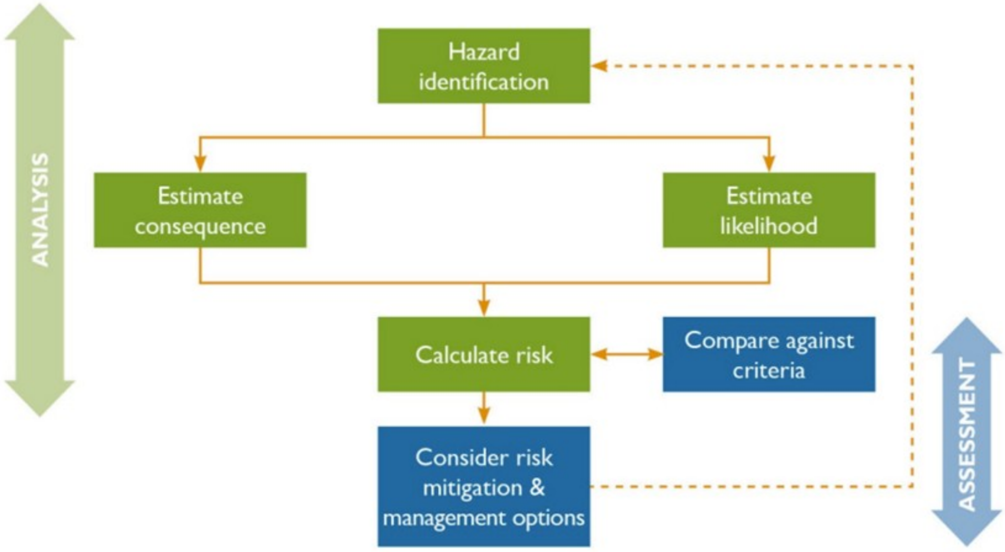

Figure 2. Preliminary hazard analysis methodology [5]

Step 1. Planning and preparing:

It involves the decision clarification & criteria, defining outputs from the analysis, and defining objectives and scope for the study. Further, establishing the study team and organization work to perform the assessment and collect relevant data for the study. The last sub-step in planning is to schedule the project flow and meetings with the group.

Step 2. Identifying hazards and hazardous events:

The motive of this step is to formulate a list of hazards that can be further investigated in the following steps. Possible hazards will be identified such as sources of harm, starting events for accidents/near-miss, center events in the bow-tie diagram, and potential accident-causing events, which can also be called unsafe conditions and unsafe events. Hazard identification can be done in reference to the generic list of checklists to avoid conflicts and confusion with too many events. Additionally, this will allow us to filter out the low-risk hazardous events which have negligible probability and consequence. Data from past incidents, accident statistics, plant operational data, existing safety studies, and standards may be considered for the same.

Step 3. Identifying causes and estimating frequency:

The next step to hazard identification is to find out the causes leading to the hazardous events and to estimate their frequency (no. of repetitive happenings). This causal analysis shall be brief and coarse and shall consider only the direct causes of the identified hazards. The frequency of the causes can be determined by using historical data and references, experts' recommendations, standards, and the assumptions made by the study team. While assessing, existing safeguards to reduce the potential hazardous events shall be considered to determine the frequency.

Step 4. Identifying consequences and assessing:

In this step, possible consequences resulting from the hazards listed in the previous step are identified and assessed. It consists of both immediate and after-effects of the hazardous events. Identified consequences are assessed by either of the following approaches: i) the most probable case ii) the worst conceivable case iii) the worst credible case. Identified consequences shall be listed in the table to have risk ratings and recommendations eventually.

Step 5. Identifying relevant risk reduction and assessing:

To reduce and mitigate the identified risks, some of the safeguards might be already available in the system design. Further, the study team suggests recommendations to reduce the severity and frequency of the event. The overall risk rating will be brought down with the recommendations. While doing this step, recommendations can be matched with reality, and at the same time, the study team can offer a simple cost/benefit assessment for each proposal. Assessing the risk is often coupled with the risk rating, the risks are ranked according to their severity and frequency based on the risk matrix made by the team. The risk matrix and rating will be discussed below.

Step 6. Compile the study results and prepare the report:

After evaluating all the data and risks assessed will be reported in the standardized format. This report shall be preserved and can be used for implementation, further safety studies, for safety auditing. It is important that the recommendations must be included. Any other checklists, FMEA, and matrices shall be included and added to the appendix of the report. This document to be reviewed and approved by the responsible authorized team leaders and plant head.

3.2. What-if analysis

This method is similar to PHA but the process methodology is different and the formatting also differs. What-if analysis is a systematic brainstorming approach for identifying potential pitfalls and assessing the probability and impact of such scenarios. The insights gained from addressing these inquiries serve as the foundation for evaluating the tolerability of associated risks and devising a suggested course of action for risks deemed unacceptable. A proficient review team, guided by a dynamic and concentrated facilitator, can adeptly identify significant concerns related to a process or system. Each team member actively contributes to the assessment of potential issues, drawing on their historical experiences and understanding of analogous situations [6]. It involves the following steps.

- Developing questions
- Determining answers
- Assessing the risks and Determining the consequences category, probability, and resulting risk levels
- Making recommendations

- Reporting the work

Instead of the typical hazard identification steps, in this method, what-if situation questions will be developed and the consequences will be raised based on the questions and entered in the determining answers step. Next to that the risks will be assessed and fit into the suitable category. Further probability and risk rating will be done.

3.3. Risk rating

This is often coupled with the assessment of risks and a matrix can be formulated to rate the hazards. The Risk Prioritization Matrix/Risk rating serves as a tool to enhance uniformity in qualitatively evaluating risks associated with workforce safety and health, public health and safety, environmental impact, as well as risks to assets, business, and reputation. The matrix is intended to offer a singular instrument for the qualitative appraisal of risks. Its design is aimed at assisting asset management teams and project development teams in systematically and consistently identifying, prioritizing, and managing risks pertaining to current facilities, ongoing activities, and projects [4,6].

The risk matrix shall be customized to the specific system/plant without neglecting the generic causes and consequences and it has been shown in the table below.

Likelihood Qualitative Descriptions	# of Barriers			Risk Level (Likelihood with confirmed Barriers and Consequence without Barriers)				
Expect to occur - Likely	0	5	Decreasing Likelihood	6	7	8	9	10
Conditions may allow to occur - Occasional	1	4		5	6	7	8	9
Exceptional conditions may allow to occur - Seldom	2	3		5	5	6	7	8
Reasonable to expect will not occur - Unlikely	3	2		3	4	5	6	7
Has occurred once in the industry - Remote	≥4	1		2	3	4	5	6
	Consequence Descriptions and Index (without Barriers)			Decreasing Consequence				
			Consequence Category	1 Incidental	2 Minor	3 Moderate	4 Major	5 Severe
			Health and Safety	One injury or illness requiring treatment but not life altering	More and than one injury or illness requiring treatment but not life altering	One or more injuries or illnesses with potential life altering effects	One or more life altering injuries or illnesses	One or more fatalities
			Environment	Limited on pad spill, temporary impact, remediation efforts require less than 1 week cleanup	Localized spill on pad or immediate surrounding areas, remediation efforts require between 1 week to 6 months to cleanup	Localized spill on pad and or surrounding areas, remediation efforts take between 6 months to 1 year to cleanup	Long -term, widespread impact, remediation requires 1 to 5 years to cleanup	Long-term, widespread impact, restoration is greater than 5 years

Figure 3. The figure shows a typical risk matrix

4. Preliminary Hazard Analysis

PHA has been done on all detected general hazards for the pilot plant and can be found in Appendix 1. In this section, two issues have been selected for a more detailed analysis with recommendations on how to mitigate the risks. The first hazard identified is if someone accidentally pushed the emergency shutdown button which does not have any protective cover. The main consequence would be that the experiments would need to be redone which requires time, energy and new materials. Our recommendation is to put a cover on the button to mitigate the risk of an accident.

The second hazard identified are the jet fuel and diesel fuel pipes that are right next to the pilot plant. If something happened to the pilot plant and there would be some sort of leakage or explosion there is a high risk that these pipes could blow as well, increasing the damages. Our proposal is to put a protective cover around these pipes as well to mitigate the risks.

5. What-if analysis

What if analysis has been done on all detected hazards and can be found in appendix 2. In this section some issues have been selected for a more detailed analysis with recommendations on how to mitigate the risks.

5.1. Reactor

A potential risk is if the cooling of the reactor fails. A potential error for this could lead to two possible scenarios. Either will it lead to increased temperature and pressure or vice versa. However, there will only be consequences from higher temperature and pressure which could lead to explosion or release of vapor. To avoid this a safety lifeguard could be thermocouples for temperature measurements. Proposal and recommendations to avoid this is to have a Temperature safety indicating transmitter in the reactor to cause PSD.

An identified risk is improper removal of ash from the reactor. In this pilot plant the ash from the rector is removed manually. This ash has high temperatures which can lead to spontaneous ignition which can lead to fire and personnel injury. The existing safeguard for this risk is that the removal is performed 12 hours after reactor shut-off. N_2 gas is also blown on the ash during removal to reduce the risk of spontaneous combustion. After 12 hours the ash still has a high temperature of around 200–250°C. Lowering the temperature is not an option since this could introduce water into the system which leads to corrosion. Our proposal is to implement a Permit to Work system and proper safety training for all personnel involved. We also suggest a proper Standard Operating Procedure to be made that all personnel must follow to reduce the risk of ignition and personal injury.

5.2. Steam generator

A potential risk in the steam generator is control valve malfunction. A potential error in this part could lead to two plausible scenarios. Either there will be more flow in the downstream or less flow in the downstream. More flow downstream could lead to pressurization in the reactor and loss of steam. Less flow downstream could lead to Pressurization in the upstream of the valve and choking of the reactor. This hazard will also lead to an incomplete reaction in the reactor. There are no existing safeguards to these potential hazards, however, three proposals have been made. First of all installing Pressure Safety Indicating Transmitters (PSIT) or Flow Safety Indicating transmitters to cause alarms at set points and Process Shut Down (PSD) in case of more steam flow. Bypass valves shall be installed for safe stream release into the system. Lastly, proper implementation of Standard Maintenance Procedure (SMP) and recording of it shall be done.

A potential risk in the steam generator is malfunctioning sensors, mainly temperature, pressure and fluid velocity sensors. Sensors showing either too high values or too low values can lead to a multitude of unwanted consequences. A temperature sensor showing lower values can lead to higher than anticipated temperature in the reactor, with this the pressure increases which can lead to a reactor explosion. This can be prevented if the pressure sensors are working properly which will then send a signal to the control room if the pressure is increasing. If the fluid velocity sensors show misleading values we can either have less or more than the anticipated fluid pumped into the reactor. With lower fluid flow the temperature of the fluid will increase leading to higher pressure and consequences as mentioned above. With higher fluid flow it is also possible that the pressure in the reactor would start to build up. There are existing safeguards for these hazards which are mainly the pressure safety valve after the steam generator. If the pressure builds up the pressure valve can be opened and excess steam can vent out. External safety controls are also performed every year.

5.3. Reformer

From the reformer, tar samples are collected by directly using a syringe that is used on a plastic like membrane, to manually poke a hole while applying enough pressure onto it against 30 bar to control the collection rate at approximately 100 ml per 1 min. Because of the high internal pressure, potential mishandling of the sampling instrument or lack of alertness of the personnel collecting the sample imposes a great risk of explosive leakage of the sample. In addition, repeated sample collections might result in a failure of the material, which would eventually cause leakage of vapor. The temperature of this gas would be roughly 350 °C, as well as containing toxic CO-gas, posing a risk to any personnel standing in the proximity of the plant. Currently, a suction pipe is placed by the tar sampling extraction to prevent the workers from being exposed to the gas. However, since a total failure of the tar extracting membrane is possible since multiple uses can cause the membrane to leak, we suggest installing a pressure-controlled chamber/vessel for sample collection, the pressure in which can be already reduced to a pressure just slightly above the atmospheric pressure, so the risk of exposure to high pressure is eliminated. Furthermore, this would add additional protection as the extracting membrane would not be exposed to the same high pressures decreasing the risk of total failure. The primary solution to mitigate the potential risk that is present during tar sampling would be to overhaul the collection process. Being able to fully separate the collection system and operating system mechanically with for example valves or shut offs or even automating the whole collection would drastically reduce the risks during sampling.

The water quench process occurs at the outlet of the reformer. Cold water is continuously sprayed, thereby taking up much of the produced heat from upstream. The gas has to be cooled to a temperature range of roughly 400–500 °C before entering the pressure valve downstream, due to structural limitations in the pipes and risk of corrosion. If the quenching process somehow fails completely, the temperature of the gas entering the pressure valve would be too high, leading to an increased risk of leakage of the pipes since they might be unable to contain the gas. Reactor material might also be damaged simultaneously, especially at the reformer outlet. The main safeguard against a malfunction of the water quenching process is to monitor the temperature in the reformer by continuously reading data from thermocouples in proximity to the outlet.

Following the water quench process, the steam is heated before entering the pressure valve in order to avoid the dew point which may otherwise be reached at the present pressure of 30 bar. Condensation of water onto the pipe surface could potentially corrode the material and cause structural damage and loss of capacity. Excess heating is not desired either, however, since the pipes as previously mentioned are only able to contain steam and gas at an appropriate temperature range between (400–500 °C). Additionally, if the superheated steam is too hot at the condenser inlet, the condenser might not be able to operate properly. These two risks are mainly preventable through continual maintenance of the pressure valve pipes. The monitoring of temperature and pressure, through thermocouples and pressure-gauges, respectively, also ensures that in case of failure of the heating process, the process can be shut-down to reduce further damage to equipment and material.

The reaction which occurs in the top half of the reformer is an exothermic reaction and can cause degradation of the physical properties in the reformer if the temperatures reach a certain level. As reactions can cause the reformer to reach upwards of 900 °C, cooling fans are used at the center point on the outer wall, contained within a metal jacket around the pre-heater. If the two cooling fans were to fail, it would cause degradation in the reformer's structural properties. As the system operates at high pressures, up to 30 bar, weakness in the reformer due to these elevated temperatures can cause cracks and in a worst case scenario may also result in an explosion. As two fans are used the risk for both fans malfunctioning or failing is lower but as there are no other safeguards installed if such a scenario was to occur the risk is still relatively high. Furthermore, degradation caused by the high temperatures during short term malfunction of the fans could be missed as notable physical damages may not appear. At the moment a yearly inspection is done on the whole system to test the system. These latent issues can build on top of another which eventually causes the reformer to fail. Such changes in structural properties are harder to evaluate as they may on the surface or during normal operating pressure not be noticeable. For example if there is a pressure build up due to another issue in the system this degradation could cause an explosion before the pressure release system is activated.

Multiple thermocouples are installed along the reformer to monitor the temperatures inside at different levels. A potential malfunction of the thermocouples can cause incorrect temperature reading, leading to incorrectly operating the process instruments related to temperature control (cooling fans, water quench, etc.), causing either too hot or too low temperatures inside the reactor. Too low temperatures inside the reformer does not directly involve any hazards, however, too high temperatures can cause degradation of the reactor material as well as possible explosion due to pressure build-up inside. We suggest having the thermocouples in parallel, i.e., in such a way that even if one of them malfunctions, other thermocouples would not be affected.

5.4. Risk rating

For each identified hazard a risk rating (RR) was determined from the occurrence and consequence value (OV and CV). The risk rating for the selected issues in the pilot plant discussed above can be found in table 1. The risk rating for the rest of the hazards can be found in appendix 2.

Table 1: Risk rating (RR) for the selected issues with their corresponding occurrence value (OV) and consequence value (CV).

Part of plant	RISK	OV	CV	RR	Level of risk
Reactor	Cooling of reactor fails	1	4	4	Considerable
	Improper removal of ash	2	4	8	Important
Steam generator	Control valve malfunction	1	3	3	Considerable
	Malfunctioning sensors	2	4	8	Important
Reformer	Issues with tar sample extraction	2	4	8	Important
	Water quench process malfunctions	1	2	2	Marginal
	Heating post-quenching (at pressure valve inlet) malfunctions	1	2	2	Marginal
	Cooling fans malfunction	2	4	8	Important
	Thermocouples along the reformer malfunction	2	4	8	Important

6. Conclusion

In summary, this report highlights the importance and principles of biomass gasification processes, and presents a detailed process description and results of a systematic risk analysis for a pressurized pilot-scale fluidized bed gasifier in KTH. A preliminary hazard analysis for the overall process as well as a what-if analysis for three main segments of the process (the reactor, the steam generator, and the reformer) were carried out.

Several hazards were identified and assessed by our PHA, two of which were selected for more detailed analysis: accidental activation of the uncovered shutdown button, and the process's proximity to jet fuel and diesel fuel pipes which would worsen the damages in case of an accident. Introducing protective covers on the button and around the pipes was suggested as an additional safety measure for the hazards. Other hazards detected by the PHA include emissions to the environment, failure to locate a fire extinguisher, fall of loose objects, and gas leak.

Our what-if analysis revealed that the highest risk rating reported in this project is 8, which corresponds to the risk level "important". The only important risk found in the reactor part of the process is improper removal of ash. Malfunction of sensors was identified as an important risk for the steam generator. And for the reformer, issues with tar sample extraction, malfunction of the cooling fans, failure of the thermocouples along the reformer were identified as important risks. Our suggestions/proposals to lower the risk level were provided for each of the hazards.

Although this report gives a good overview of the overall safety hazards of the process, it is by no means a complete assessment of all possible risks of the entire process, especially because the scope of the what-if analysis is limited to only the three main components of the process. Critical decision-making in case of an emergency and alertness of the working personnel are mandated in addition to what is presented in this report to ensure safe operation of the process.

7. References

[1] Engvall, H. Kusar, K. Sjöström, and L. J. Pettersson, “Upgrading of Raw Gas from Biomass and Waste Gasification: Challenges and Opportunities,” *Topics in Catalysis*, vol. 54, no. 13–15, pp. 949–959, Aug. 2011, doi: https://doi.org/10.1007/s11244-011-9714-x.

[2] E. Dahlquist, *Technologies for converting biomass to useful energy*. Boca Raton: Crc Press, 2013.

[3] M. Rausand, “Preliminary Hazard Analysis,” Wiley, 2005. Available: https://ab-div-bdi-bl-blm.web.cern.ch/Literature/fmcea/pha.pdf (visited 24.11.2023 16:45)

[4] “Hazard Identification,” pp. 259–337, Mar. 2020, doi: https://doi.org/10.1002/9781119377351.ch10.

[5] Jeffrey W. Vincoli, “Preliminary Hazard Analysis,” *Basic Guide to System Safety*, pp. 71–90, Jun. 2014, doi: https://doi.org/10.1002/9781118904589.ch6.

[6] “ONSHORE SAFETY ALLIANCE (OSA) onshoresafetyalliance.org How to Conduct a Risk Assessment Using the What-If Methodology Risk Assessment User Guide.” Available: https://www.onshoresafetyalliance.org/-/media/BrightfindOSA/Resource-Library/What-If%20Methodology.pdf (visited 25.11.2023 17:00)

8. Appendix

Appendix 1. Table of all identified hazards for the PHA with corresponding risk rating.

Hazard	Possible causes	Consequences	Recommended actions/Actions taken	Risk rating		
				OV	CV	RR
Emissions to environment	System was built this way	Air pollution	Outgoing gas is heavily diluted	4	0	0
Accidental push on emergency shutdown button	No cover on emergency shutdown button	Experiment needs to be redone	Put a cover on the emergency button	2	3	6
Jet fuel and diesel fuel pipes ignition	Pilotplant malfunction, leakage or explosion	Increased damages, jet fuel and diesel can ignite	Put a protective cover on the pipes	1	4	4
Failure to locate fire extinguishers	No dedicated places, no signs	Failure to extinguish potential fire	Dedicated places with signs	2	3	6
Fall of loose objects	Routine	Damage of personnel and/or equipment	Better practice of putting back tools	2	2	4
Gas leak	Poor flange joints/sampling points	Damage to personnel/insulation/instruments	Install CO sensor	1	3	3

Appendix 2. What-if analysis of all identified risks in the process with corresponding risk rating.

Part of system	What if?	Hazard(s)	Consequence(s)	Existing safeguard(s)	Proposals/Recommendations	Risk rating		
						OV	CV	RR
Reactor	Cooling of reactor fails	Decreased temperature and pressure	None	None	Temperature safety indicating transmitter in reactor to cause PSD	1	1	1
		Increased temperature and pressure	Risk of explosion and release of vapors	Thermocouples for measurement of temperature	-	1	4	4
	Nitrogen gas system fails	None	Less yield for reaction	None	-	1	2	2
	Accidental emergency shut-off	None	Ruined experiment results	None	Protective cover on emergency shut-off buttons.	1	3	3
	Pressure safety valve (30 bar) fail closes	Pressure low (PLL) in lines	More steam venting out	Emergency shutdown	-	1	2	2
			Less steam available for process		-	1	2	2
	Pressure safety valve (30 bar) fail opens	Pressure high (PHH) in lines	Line rupture	Alternative pathways	-	1	3	3
			Explosion of steam generator			1	4	4
	Thermocouples malfunction/show misleading values	Sensors show higher values	Less yield for reaction	None	internal safety controls one every 3-6 months to make sure all sensors work as intended	2	2	4
		Sensors show lower values	Higher pressure and temperature, risk for explosion if PSV is not working correctly	PSV		2	4	8
	Ash outlet fail / Improper removal of ash	Ignition of ash	Risk of fire and personal interjury	Waiting 24h after reactor shut-off before ash is removed. While ash is removed N2 gas is blown on the ash to prevent spontaneous combustion.	1. Implementing Permit to Work system (PTW) and proper safety training to be given for the personnel involved. 2. Proper Standard Operating Procedure shall be made and in place.	2	4	8
Steam generator	Sensors malfunction/show misleading values	T sensor showing too high values	No apparent risk	Pressure safety valve, Continuous maintenance of sensors (external safety control once a year) to make sure they show correct measurements	Internal safety controls more often, perhaps once every 3-6 months	2	1	2
		T sensor showing too low values	Higher than anticipated T can lead to ignition inside the reactor			2	3	6
		P sensor showing too high values	No apparent risk			2	1	2
		P sensor showing too low values	P rising can lead to explosion in pipes or reactor			2	4	8
		Fluid velocity sensor showing too high values	Less than anticipated fluid pumped into reactor, temperature of steam will be higher, pressure rising, explosion			2	4	8
		Fluid velocity sensor showing too low values	Higher than anticipated fluid pumped into reactor, lower temperature, pressure in reactor could build up			2	3	6
	Pressure safety valve (50 bar) fails to close	Pressure low low (PLL) in lines	More steam venting out	Periodical maintenance of PSV and recording them.	1. One more PSV shall be installed after considering the PSV study. 2. Proper implementation of Standard Maintenance Procedure (SMP) and record of it.	1	2	2
			Less steam available for process			1	2	2
	Pressure safety valve fails to open	Pressure high high (PHH) in lines	Line rupture	Pressure control valve and Pressure Indicators available to monitor the pressure of the steam		1	3	3
			Explosion of steam generator			1	4	4
	Control valves malfunction	More steam flow in downstream	Pressurization in the reactor		1. Installing Pressure Safety Indicating Transmitters (PSIT)/Flow Safety Indicating Transmitters (FSIT) to cause alarms at set points	1	2	2
			Loss of steam			1	2	2

Part of system	What if?	Hazard(s)	Consequence(s)	Existing safeguard(s)	Proposals/Recommendations	Risk rating		
						OV	CV	RR
		Less steam flow in downstream	Pressurization in upstream of valve	Pressure safety valve (calibrated at 50 bar) is available in the steam generator	and Process Shut Down (PSD) in case of more steam flow.	1	2	2
			Choking of the reactor	Pressure and Temperature transmitters are available in the reactor to monitor any process change (?)	2. Bypass valves for control valves shall be installed for safe steam release into the system. 3. Proper implementation of Standard Maintenance Procedure (SMP) and record of it.	1	3	3
			Incomplete reactions in the reactor			1	2	2
Reformer	Jacket breaks/insufficient	Loss of cooling effect, leading to the outer wall of the reactor getting too hot	The reactor wall gets damaged, structural integrity of the reformer is compromised.	Temperature monitor	Regular testing of existing safeguard	1	2	2
	H2/O2 inlet malfunctions	Too much flow	A rapid temperature increase leading risk of fire	Pressure gauge(s), temperature monitor	Regular testing of existing safeguard	1	3	3
		Too little flow	None			1	1	1
	Reformer insulation insufficient	Bad insulation, loss of heat	Damage to working personnel	None	1. Regular testing of existing safeguard 2. Temperature monitoring of outer jacket	1	2	2
	Cooling fans malfunction	Loss of cooling effect, leading to the wall of the reactor getting too hot	The reactor wall gets damaged, structural integrity of the reformer is compromised.	Temperature monitor	1. Connect to emergency shutdown system 2. Internal safety controls perhaps once every 3-6 months	2	4	8
	Thermocouples along the reactor malfunction	Inaccurate temperature reading, leading to too high T in the reactor	Explosion, material degradation	Personnel on site during use	Internal safety controls one every 3-6 months to make sure all sensors work as intended	2	4	8
		Inaccurate temperature reading, leading to too low T in the reactor	Reduction of yield	None	-	2	1	2
	Catalytic rod is mishandled	Human exposure to toxic chemicals	Irreversible health damages	Adequate safety equipment and routines	-	1	2	2
	Catalytic rod is clogged	Pressure build-up in the reactor	Risk of explosion	Pressure release valve	-	1	4	4
	Water quench process malfunctions	Too much water	None	None	Monitoring of water flow	1	1	1
		Not enough water, causing too high T	Damage to reactor materials	System shutdown in case of pump malfunction	Monitoring of water flow	1	2	2
Pressure valve	Heating rods in the reformer malfunctions	Temperature too high	Risk of explosion, material degradation	maintenance and temperature monitor	-	1	4	4
		Temperature too low	Reduction of yield		-	1	1	1
	Issues with tar sample extraction	Multiple uses can cause leaks, even the membrane breaking	An explosive leakage of the sample	A suction pipe by the tar sampling extraction	1. A pressure-controlled chamber 2. Automated sample collection that can be disconnected fully from the system	2	4	8

Part of system	What if?	Hazard(s)	Consequence(s)	Existing safeguard(s)	Proposals/Recommendations	Risk rating		
						OV	CV	RR
	Top pressure safety valve malfunction	Does not release pressure even when it's too high	Risk of explosion	Automatic response	-	1	4	4
		Unwanted release of pressure: release of flammable and toxic gas	Damage to personnel, increased risk of fire	Maintenance and pressure gauge(s)	-	1	3	3
	None/Both of bypass switches are removed before operation	-	Minor delay in the operation	Automatically opened. Also detectable during the starting of the process with nitrogen. Another safety pressure valve installed at the bottom of the reformer	-	1	1	1
	Pressure valve/regulator malfunctions	Closed position, leading to pressure build-up	Risk of explosion	Maintenance	-	1	4	4
		Open position, leading to higher P in downstream and failure to control T	Potential damage to pressure valve and condenser unit	Maintenance	-	1	2	2
	Bottom pressure safety valve malfunctions	Failure to flush out flammable and toxic gas (Always in closed position unless activated), leading to pressure build up when system is flushed with nitrogen gas	Risk of explosion, potential damage to personnel	Maintenance, regular testing. Another safety pressure valve installed at the top of the reformer	Regular testing of existing safeguards	1	3	3
	Heating post-quenching (at pressure valve inlet) malfunctions	Too little heating: Steam in pressure valve might condense due to T below dew point	Loss of capacity, potential rust-build up on inner pipe-surface	Controlled automatically by temperature monitor and P-gauge(s), maintenance	Regular testing of existing safeguards	1	1	1
		Too much heating: Superheated steam at too high/elevated T	Too high T of superheated steam at condenser inlet	Controlled automatically by temperature monitor and P-gauge(s), maintenance		1	2	2