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3 SCADA System Manual - Introduction

C1000 System Overview

The C1000 is a high-efficiency pyrolysis system designed for controlled biomass combustion and thermal energy recovery. The system consists of several key components, each optimized to ensure stable operation, consistent Biochar quality and maximum energy conversion.

Active Grate & Pyrolysis: The primary furnace features a mechanically agitated active grate, where feedstock is processed through staged pyrolysis. The grate is surrounded by ceramic insulation to maintain high thermal efficiency.

Choke Ring & Airflow Control: A choke ring with a water-cooled jacket and controlled secondary air injection ensures complete combustion and optimized gas flow.

Temperature Monitoring & Process Optimization: Primary furnace with two thermocouples and an infrared sensor. The Infrared sensor regulate combustion temperature using PID (Proportional-Integral-Derivative) control to achieve a stable operation temperature. The thermocouples are used for primary furnace temperature monitoring.

PID Control in the C1000 Furnace

The PID (Proportional-Integral-Derivative) Control System is the foundation of the C1000’s automated temperature and airflow regulation. It ensures precise process control by continuously adjusting system parameters based on sensor feedback.

Primary Furnace Temperature Control: The PID controller adjusts primary air fan speed and fuel feed rate (FFR) to maintain optimal combustion temperatures.

Secondary Furnace & Oxygen Regulation: The secondary air fan is controlled using a PID loop, which monitors oxygen levels to ensure complete gas combustion.

Exhaust Fan Negative Pressure Control: The PID controller regulates the exhaust fan speed to maintain the system’s negative pressure balance, preventing flue gas leaks.

SCADA System Overview

The SCADA (Supervisory Control and Data Acquisition) System is responsible for monitoring, controlling, and analyzing all critical operational parameters of the C1000 pyrolysis process. It allows for real-time data collection, automated process adjustments, and failure detection.

SCADA & PLC Integration: The SCADA system interfaces with Programmable Logic Controllers (PLCs) to execute process automation and control machine functions.

Human Machine Interface (HMI): Operators interact with the SCADA system through an HMI display, which provides visual process monitoring, alarms, and operational controls.

Key SCADA Sensors & Monitoring Devices

The SCADA system continuously monitors the C1000 using a network of sensors, including:

Primary Furnace Temperature Sensors: Infrared and thermocouple sensors for combustion monitoring.

Oxygen Sensor: Regulates secondary air for optimized gas combustion.

Negative Pressure Sensor: Ensures controlled draft and prevents gas leakage.

Fuel Feed Rate Auger & Rotary Valve rotation: Regulate feedstock delivery and fuel consistency.

Heat Exchanger Flow & Return Sensors: Monitor thermal transfer efficiency.

Valve & Conveyor Operation Sensors: Ensure proper mechanical function.

Fan Speed: Maintain airflows.

The SCADA system enables automatic process control, failure detection, and real-time data analysis, ensuring safe and efficient operation of the C1000.

3.1 SCADA Start-up & Shutdown Procedures

3.1.1 Start-up Process

The C1000 system start-up sequence ensures controlled ignition and gradual temperature buildup before transitioning into normal operation.

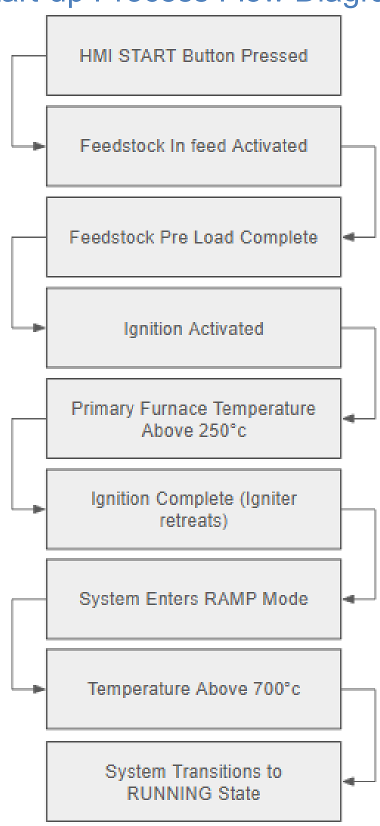
System Start: The HMI screen 'START' button is pressed to initiate the start-up sequence.

Feedstock Pre-loading: The Feedstock Infeed system operates continuously for a set time (determined during commissioning) to ensure sufficient material is inside the primary furnace.

Ignition Activation: The electronic igniter is engaged, and a motorized ram pushes it into the Primary Furnace to ignite the feedstock.

Ignition Completion: The Primary Furnace thermocouples (PFT1 & PFT2) measure the furnace temperature. Once it reaches 250°C, the igniter is automatically retracted, and the system enters RAMP Mode.

Start-up Process Flow Diagram



RAMP Mode - Stabilization Mechanism

RAMP Mode is a stabilization mechanism that ensures a controlled increase in temperature before allowing normal operation. This prevents ignition issues and ensures efficient pyrolysis under fluctuating combustion conditions.

RAMP Level	Temperature Threshold	Fuel Feed Rate (FFR) & Grate Movement
RAMP 4	Below 700°C	FFR = 60%, No Active Grate Movement
RAMP 3	Below 550°C	FFR = 40%, No Active Grate Movement
RAMP 2	Below 400°C	FFR = 20%, No Active Grate Movement
RAMP 1	Below 250°C	FFR = 2%, No Active Grate Movement
System transitions to RUNNING state once the temperature exceeds 700°C		

3.1.2 Shutdown Procedures

Safety Circuit E-Stop Shutdown

A Safety Circuit Stop (E-Stop) is triggered in response to critical system failures. The system will transition to the Emergency Stop state when any of the following conditions occur:

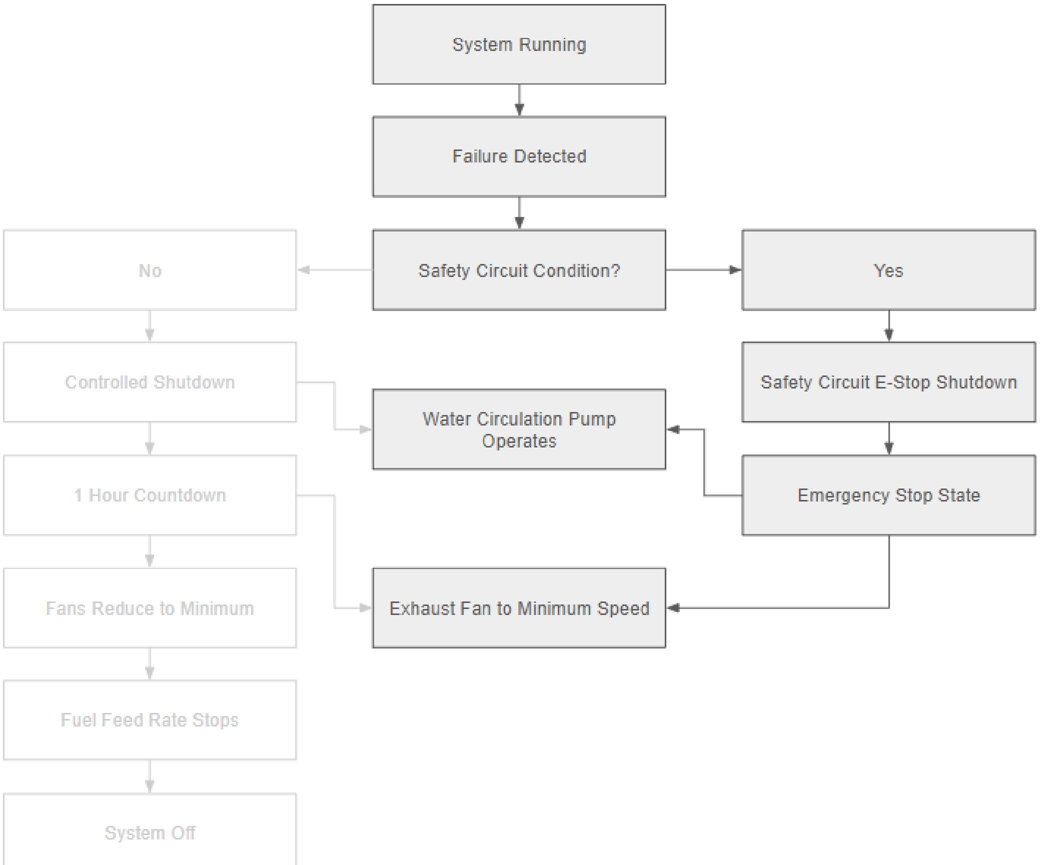
- High water pressure
- Low water pressure
- High water temperature
- Exhaust fan failure
- Emergency stop button activation

System Response:

- Water circulation pump, back-end protection/3-port valve, exhaust fan, FFR auger and the stoker auger continue to operate for 1 hour.
- Exhaust fan speed is reduced to 10 Hz (minimum speed setting).
- If the shutdown is triggered due to Exhaust Fan Failure, only the circulation pump, back-end protection/3-port valve, FFR and stoker auger continue to operate.
- Natural negative draft ensures safe gas flow and prevents backflow of combustion gases.

Displayed System State:
Emergency Stop displayed on SCADA interface.

Safety Circuit E-Stop Shutdown Flow Diagram



Controlled Shutdown

A Controlled Shutdown occurs for all other failure scenarios or trip conditions that do not require an immediate E-Stop. The system transitions into Shutdown Mode while maintaining controlled operation.

System Response:

• Water circulation pump and back-end protection/3-port valve remain active.
• Primary and secondary air fans reduce to 10 Hz minimum speed.
• Exhaust fan continues to operate at the set negative pressure level as per normal operation.
• Fuel Feed Rate (FFR) and stoker augers remain operational.

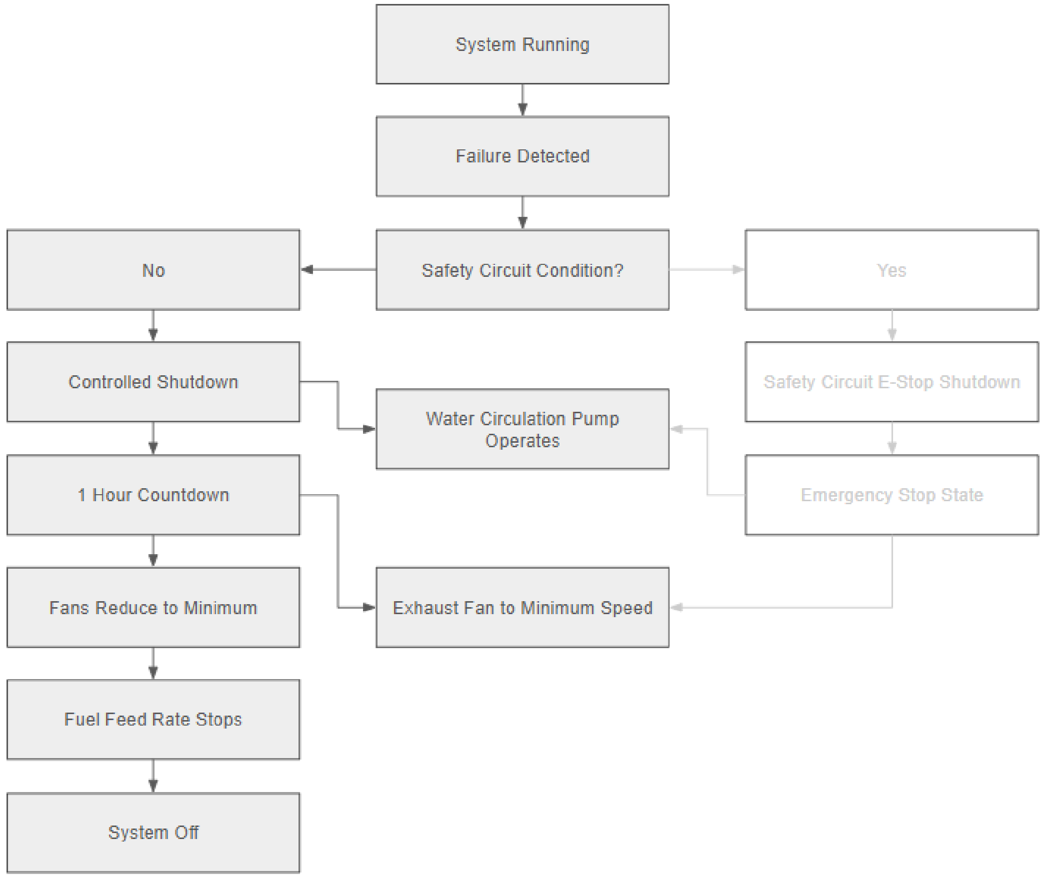
Shutdown Duration:

• The controlled shutdown sequence operates for 1 hour, ensuring safe cooling and complete burnout of residual fuel.

Displayed System State:

-Shutdown Mode for the first hour.
-After 1 hour, system transitions to System Off state.

Controlled Shutdown Flow Diagram



3.2 SCADA System Manual - Feedstock Infeed

SCADA Process Description: Feedstock Infeed (Rotary Valve & Auger System)

3.2.1 Process Overview

The Feedstock Infeed System starts with the Rotary Valve, which meters prepared feedstock from storage into the pyrolysis system while also acting as a fire break between the pyrolysis process and the feedstock supply. The process is controlled by a Bindicator, which monitors the level of feedstock in the vertical drop hopper above the rotary valve.

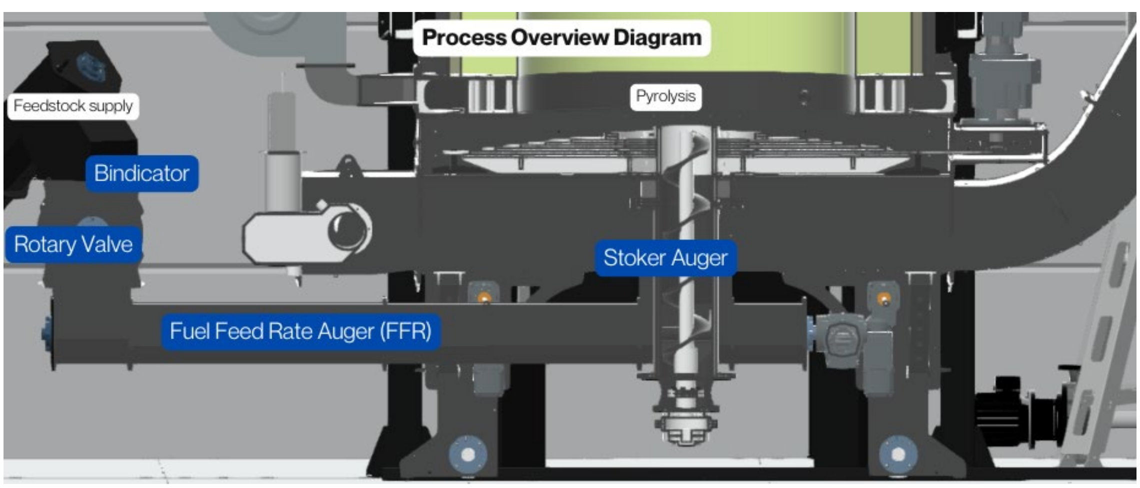
When the Bindicator detects low feedstock, it calls for more feedstock until the hopper reaches the set level, at which point the feedstock supply automatically stops.

The Rotary Valve remains closed when inactive. When activated, it completes one full rotation, exposing the barrel opening to load feedstock into the system.

After passing through the Rotary Valve, the feedstock is transferred by:

1. Fuel Feed Rate (FFR) Auger – The primary SCADA-controlled auger that determines the power level of the C1000 by fuel flow.
2. Stoker Auger – A vertical auger that transports the feedstock into the combustion system.

The Rotary Valve cannot activate unless both the FFR Auger and the Stoker Auger are running.



3.2.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Bindicator	Detects hopper feedstock level	Within range	Out of range	Yes, stops feedstock supply	Ensure feedstock is available
Rotary Valve Motor Load **RV**	Measures rotary valve motor torque	Normal operating range	High load detected	Yes, triggers unblock routine	Auto-reverse, if unresolved, alarm for manual check
FFR Auger Load **FFR**	Measures auger motor torque	Normal operating range	High load detected	Yes, triggers unblock routine	Auto-reverse, if unresolved, alarm for manual check
Stoker Auger Load	Measures auger motor torque	Normal operating range	High load detected	Yes, triggers unblock routine	Auto-reverse, if unresolved, alarm for manual check
Fuel Feed Rate Speed **FFR**	Sets power level of the system	20-100%	Out of range	No	Adjust fuel rate, check motor

3.2.3 Automated System Actions & Operator Requirements

Automated System Actions:

- Bindicator Activated (Low Feedstock): Calls for more feedstock.
- Bindicator Full: Stops feedstock supply.
- Rotary Valve Start Condition:

- FFR Auger & Stoker Auger must be running for activation.

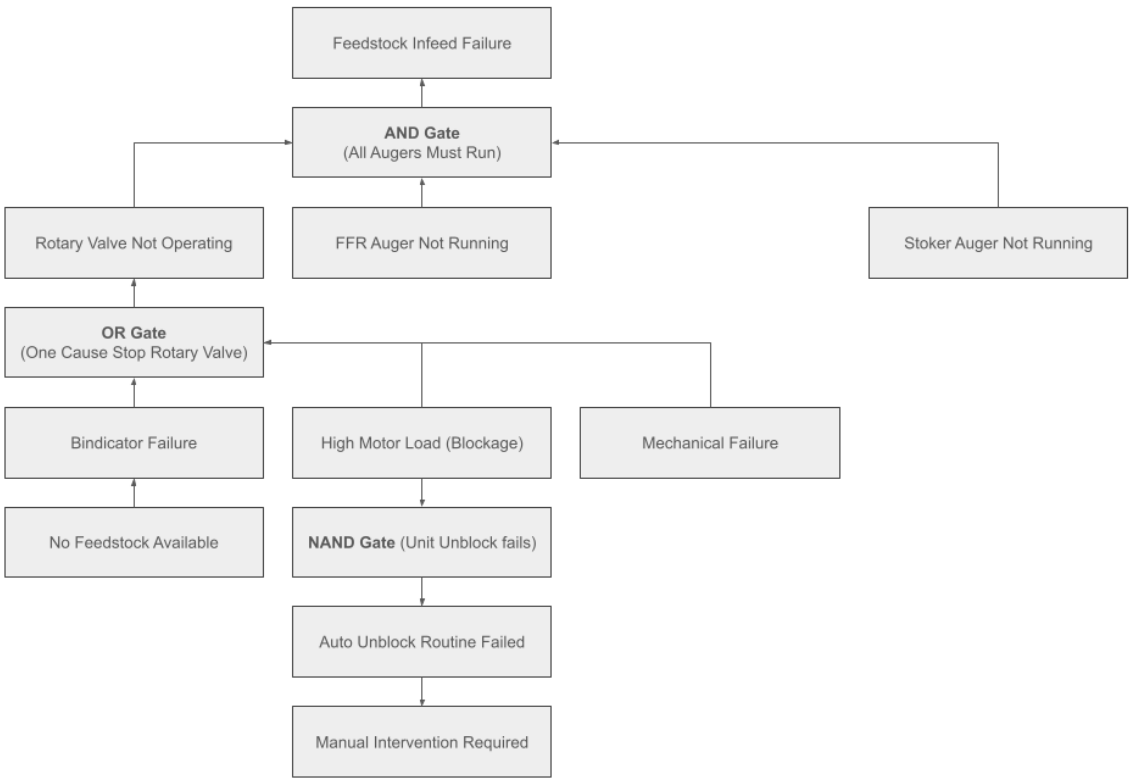
- High Load Alarm on Any Auger:

- Step 1: Attempt Auto Unblock Routine (Reverses auger to clear block).
- Step 2: If unresolved, trigger alarm for manual inspection.

- FFR Auger Determines Fuel Input Rate → Adjusts power of the C1000.

3.2.4 Fault Tree Analysis (FTA) - Feedstock Infeed System Failure

The following FTA diagram illustrates the failure pathways in the Feedstock Infeed system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.2.5 Failure Response Guide

Failure: Feedstock Infeed System Not Operating

Possible Causes:

- Rotary Valve Not Operating (System not metering feedstock)
- FFR Auger Not Running (Fuel feed rate failure)
- Stoker Auger Not Running (Vertical auger failure)

SCADA System Actions:

- Check if all augers are running (AND Logic)
- If any auger is down, trigger alarm
- If rotary valve fails, inspect Bindicator, Blockage, or Mechanical Issue

Failure: Rotary Valve Not Operating

Possible Causes (OR Logic):

- Bindicator Failure (No feedstock detected)
- Blockage Detected (High Motor Load)
- Mechanical Failure (Motor or gearbox issue)

SCADA System Actions:

- Attempt Auto Unblock Routine (NAND Logic)
- If unblock fails, trigger manual intervention alarm
- If mechanical failure is detected, initiate emergency shutdown

Failure: Blockage Detected (High Load Alarm)

Possible Causes:

- Foreign object obstructing auger
- Excess fuel causing jam
- Mechanical issue (broken gearbox, bearing failure)

SCADA System Actions:

- Attempt Auto Unblock Routine
- Reverse auger to clear blockage
- If blockage persists, manual intervention is required

3.3 SCADA System Manual - Pyrolysis of Feedstock

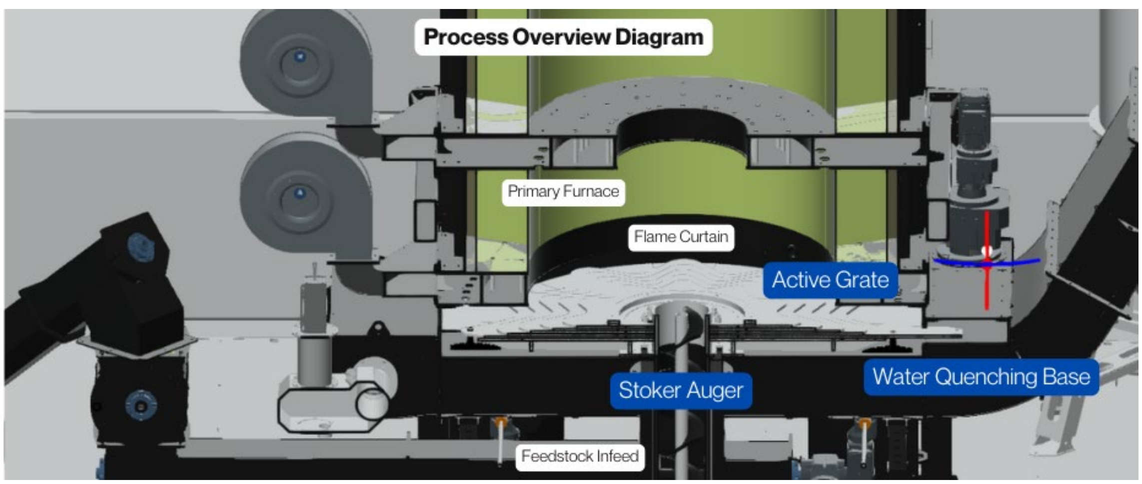
SCADA Process Description: Pyrolysis of Feedstock

3.3.1 Process Overview

The pyrolysis process begins when feedstock from the Feedstock Infeed is transported into the Primary Furnace via the vertical stoker auger. At the end of the stoker auger, feedstock cascades evenly onto the circular active grate.

During the pyrolysis process, feedstock agitates through and under a flame curtain, where it is converted into biochar over a 10-15 minute process. The active grate moves the biochar outward towards the perimeter, where it is vertically fed into the water quenching base to complete the pyrolysis process.

Above the active grate is the air ring, which provides a controlled flow of air to maintain the target pyrolysis temperature. Beneath the air ring, the pyrolysis gases act as a barrier between the feedstock and air, ensuring an oxygen-restricted environment. Above the air ring, syngas, wood tars, and volatiles combust in the Secondary Furnace.



3.3.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Fuel Feed Rate Speed **FFR**	Sets power level of the system	20-100%	Out of range	No	Adjust fuel rate, check motor
Primary Air Fan **PRI**	Controls airflow via PID	PID Setpoint	Fan failure	Yes, enters RAMP mode	Inspect fan operation, check motor
Infrared Sensor **IFRS**	Measures biochar temperature	Target range	Below min or above max	Yes, triggers shutdown	Check calibration, inspect sensor
Thermocouples **PFT1 & PFT2**	Monitor furnace temperature	Above 700°C	Below 700°C	Yes, enters RAMP mode	Replace failed thermocouple
Active Grate **GRATE**	Moves biochar outward	Synchronized with FFR	Movement failure	Yes, triggers shutdown	Inspect position sensor, check for blockage

3.3.3 Interlocks & Safety Controls

The system includes multiple interlocks and safety mechanisms to ensure stable operation and prevent damage due to abnormal conditions.

Infeed Feedstock System Interlock
Any failure in the infeed system will lower the Primary Furnace temperature, causing the system to enter RAMP Mode. If the system remains in RAMP1 for longer than 10 minutes without a temperature increase, it will perform a controlled shutdown.

Active Grate Interlock
The Active Grate cannot operate or enter normal operation mode until the Primary Furnace reaches 700°C. If the Active Grate motor is running but the position sensor is out of range, a controlled shutdown is triggered with an Active Grate Movement Alarm.

Fuel Feed Rate & Airflow Interlock
If there is a fuel feed rate interruption or Primary Air Fan failure, the pyrolysis temperature will drop, affecting the Primary Furnace temperature. If the system continues to drop to RAMP1 and remains there, a controlled shutdown is initiated.

Infrared Sensor Monitoring
In RAMP Mode, the Infrared Temperature Sensor does not control any settings.
In Normal Operation Mode, if the temperature reading is consistently below or above the set range, a controlled shutdown is triggered.

Primary Furnace Temperature Sensors (Thermocouples)
The system uses two thermocouples to provide an average temperature reading.
A failed thermocouple typically displays 0°C or 3168°C, which will push the average temperature outside of range and trigger a Primary Furnace Temperature Alarm, leading to a controlled shutdown.

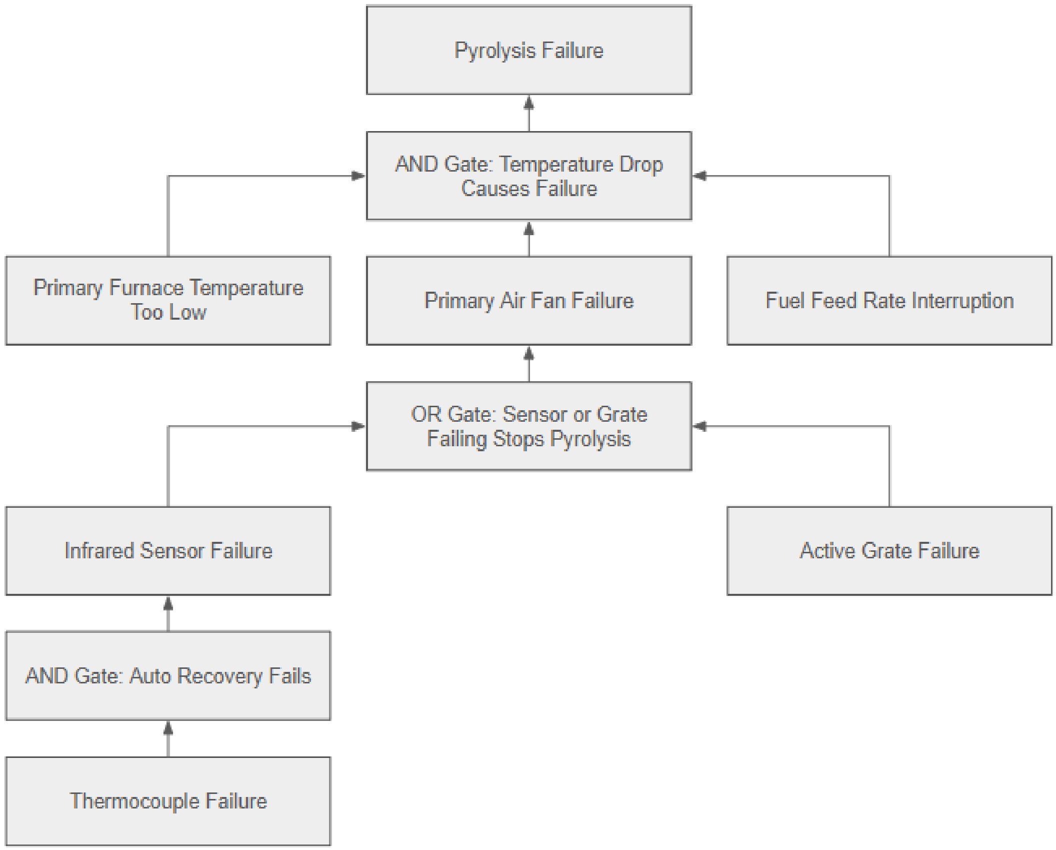
Operator Actions

The operator cannot manually override RAMP mode. The following steps should be taken based on failure conditions:

• Feedstock Feed Interruption: Refer to 'SCADA Process Description: Feedstock Infeed (Rotary Valve & Auger System)'.
• Active Grate Failure: Inspect the position sensor and motor. If operational, check the mechanical agitating grate for blockages.
• Infrared Sensor Failure: Remove and check calibration.
• Primary Furnace Temperature Sensor Failure: Inspect thermocouple, replace if failed.
• Primary Air Fan Failure: Perform the following troubleshooting steps:
  - Check for power supply to the fan motor.
  - Inspect for any blockages in the airflow path.
  - Verify fan motor operation and check for excessive vibrations or overheating.
  - Examine control wiring and signal feedback to SCADA.
• General Pyrolysis Temperature Control Issues: If all critical controls are functioning but temperature issues persist:
  - Investigate feedstock quality to ensure it matches commissioning specifications.
  - Contact an engineer for additional support if required.

3.3.4 Fault Tree Analysis (FTA) - Pyrolysis of Feedstock Failure

The following FTA diagram illustrates the failure pathways in the Pyrolysis of Feedstock system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.3.5 Failure Response Guide

Failure: Pyrolysis Process Not Operating

Possible Causes:
• Primary Furnace Temperature Too Low
• Primary Air Fan Failure
• Fuel Feed Rate Interruption

SCADA System Actions:
• Check fuel feed rate and adjust if necessary.
• Verify primary air fan operation and restart if required.
• If temperature continues to drop, system enters RAMP Mode and may initiate shutdown.

Failure: Primary Furnace Temperature Too Low

Possible Causes:

- Fuel Feed Rate Below Required Level
- Airflow Imbalance (Primary Fan Malfunction)

SCADA System Actions:

- Increase fuel feed rate within safe limits.
- Adjust airflow to balance combustion.
- If sustained temperature drop below 700°C, system enters RAMP mode.

Failure: Infrared Sensor Failure

Possible Causes:

- Sensor out of calibration
- Wiring or communication failure

SCADA System Actions:

- Remove and check sensor calibration.
- Inspect wiring connections and verify data signal.
- If failure persists, system will alarm and enter controlled shutdown.

Failure: Primary Air Fan Failure

Possible Causes:

- Motor failure
- Obstruction in airflow path
- Power supply issue

SCADA System Actions:

- Check power supply and restart fan if safe.
- Inspect for mechanical blockage and clear if necessary.
- If failure persists, system will enter RAMP mode and adjust operations.

Failure: Active Grate Not Moving

Possible Causes:

- Position sensor failure
- Mechanical blockage or jam

SCADA System Actions:

- Inspect position sensor and verify movement data.
- Check for mechanical blockages and clear debris if needed.
- If movement failure persists, system enters shutdown mode.

3.4 SCADA System Manual - Agitation of Biochar into the Water Quenching Base

SCADA Process Description: Agitation of Biochar into the Water Quenching Base

3.4.1 Process Overview

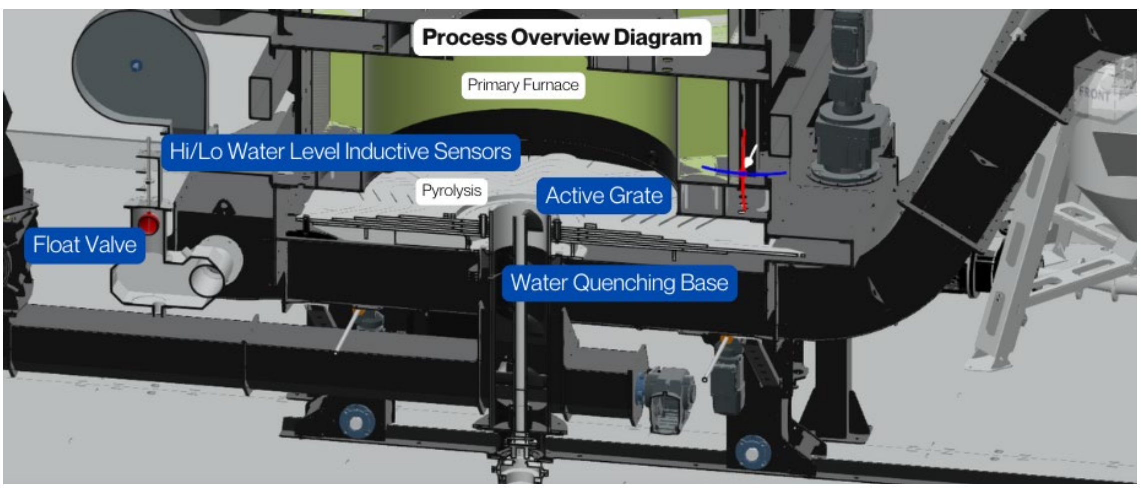
The process of biochar agitation into the water quenching base begins once the biochar has completed its pyrolysis cycle on the active grate. The active grate agitates the biochar outward towards the edge, where it falls off into the water quenching base.

The water quenching base has a dual function:

1. Quenches the biochar to stop the pyrolysis process.

2. Acts as an airlock, maintaining the negative pressure seal in the C1000 Furnace.

The water level in the quenching base is controlled by a float level system, which consists of high and low set inductive sensors to regulate water levels and maintain safe operation.



3.4.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Float Level - Low	Detects if water level is below safe range	Normal level	Low for >60s	Yes, triggers shutdown	Activate water infeed valve, if unresolved, initiate shutdown
Float Level - High	Detects if water level is above safe range	Normal level	High for >60s	No, visual alarm only	Continue monitoring, overflow protection active
Water Infeed Valve	Controls water replenishment	Auto on/off	Fails to open	Yes, triggers shutdown	Check valve operation and supply

3.4.3 Interlocks & Safety Controls

The water quenching system is critical to ensuring safe furnace operation and maintaining the negative pressure seal. The following interlocks and controls are in place:

Low Water Level Interlock
If the low set sensor reads low for 60 seconds, the system will:
Trigger a visual alarm.
Open the water infeed valve for 60 seconds or until the high set is reached.
If the low set reading persists, a **controlled shutdown is initiated**.

High Water Level Alarm
If the high set sensor reads high for 60 seconds, the system will:
Trigger a visual alarm on the HMI.
Not cause a shutdown (overflow protection is in place).

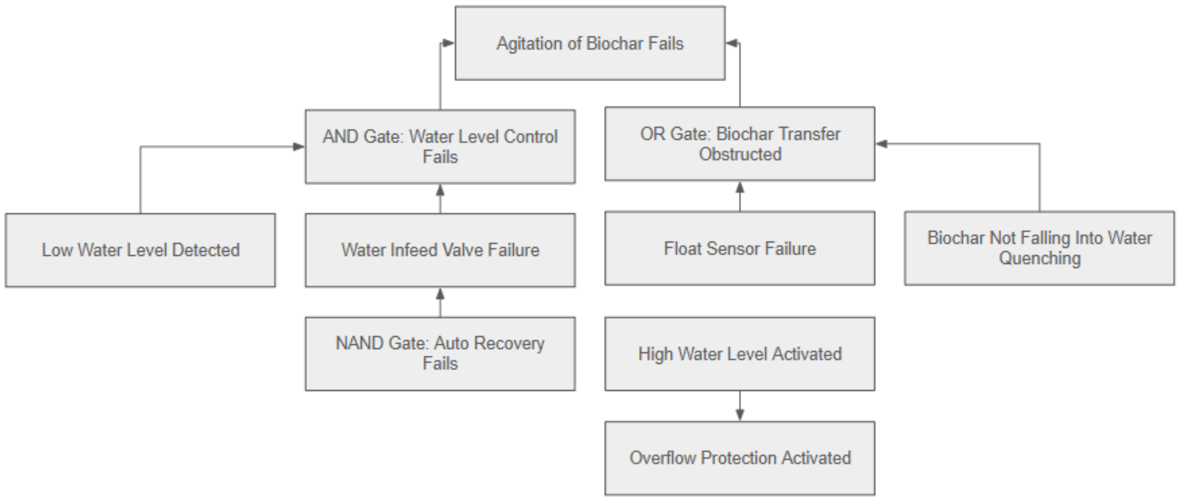
Operator Actions

The following steps should be taken based on failure conditions:

- Low Water Level Alarm: Check water supply, inspect float sensor functionality.
- High Water Level Alarm: Monitor system; overflow protection is active.
- Water Infeed Valve Failure: Verify valve operation and check for blockages.
- General Quenching System Issues: Ensure float sensors are calibrated and functional.

3.4.4 Fault Tree Analysis (FTA) - Agitation of Biochar into Water Quenching Base Failure

The following FTA diagram illustrates the failure pathways in the Agitation of Biochar into the Water Quenching Base system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.4.5 Failure Response Guide

Failure: Biochar Not Falling into Water Quenching Base

Possible Causes:
• Active grate failure (mechanical issue or motor failure)
• Blockage or obstruction at grate outlet

SCADA System Actions:
• Check active grate motor and position sensor readings.
• If grate is jammed, trigger visual alarm and controlled shutdown if unresolved.

Failure: Low Water Level in Quenching Base

Possible Causes:
• Water infeed valve failure or supply issue
• Float sensor malfunction

SCADA System Actions:
• Trigger visual alarm and attempt automatic refill for 60 seconds.
• If water level does not return to normal, system enters controlled shutdown.

Failure: High Water Level in Quenching Base

Possible Causes:
• Float level sensor failure
• Water infeed valve remains open

SCADA System Actions:
• Trigger visual alarm but continue operation (overflow protection active).
• Monitor system for excessive water accumulation.

Failure: Water Infeed Valve Failure

Possible Causes:
• Valve stuck closed (no water replenishment)
• Valve stuck open (excessive water inflow)

SCADA System Actions:
• If valve fails to open, trigger alarm and attempt override.
• If valve fails to close, monitor water level and rely on overflow protection.

Failure: Float Sensor Failure

Possible Causes:
• Sensor reading out of range
• Wiring issue or mechanical damage

SCADA System Actions:
• Trigger alarm and use redundancy measures (manual water level check).
• If sensor failure persists, controlled shutdown is initiated.

3.5 SCADA System Manual - Transfer of Biochar

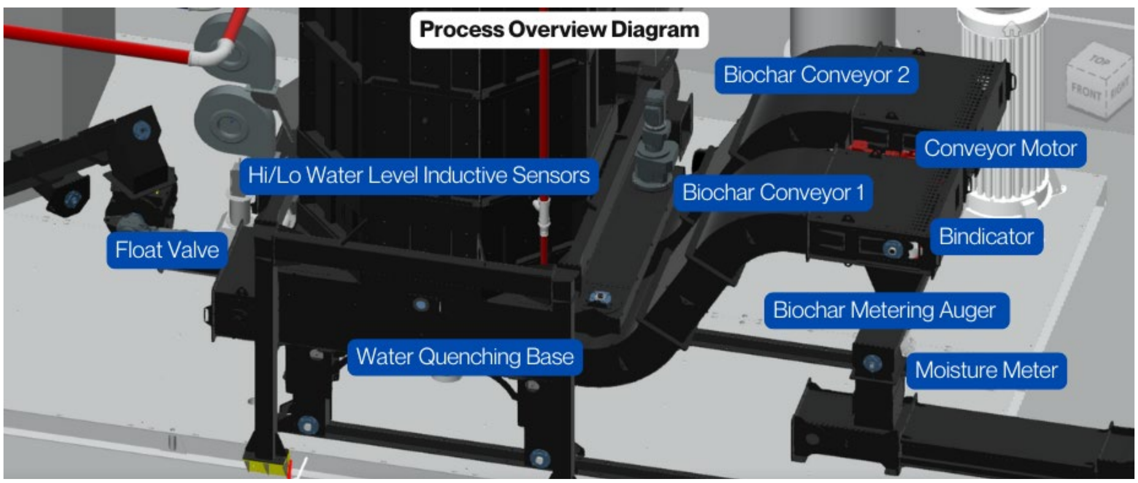
SCADA Process Description: Transfer of Biochar

3.5.1 Process Overview

The biochar transfer process begins in the Water Quenching Base, where the Dual Scraper Chain Biochar Conveyors transport the biochar to the Biochar Metering Auger.

As the biochar is conveyed out of the base at an upward angle, excess water flows back into the Water Quenching Base, ensuring optimal moisture retention. The conveyors are powered by a single motor with dual chain-linked sprockets. In the event of a failure on one conveyor, the chain can be removed to allow the other conveyor to continue operating, keeping the system functional.

At the end of the conveyor system, the biochar is fed vertically into the Biochar Metering Auger, which is essential for monitoring production output. The auger's rotation count is used to calculate the Feedstock to Biochar ratio, allowing the system to make real-time adjustments to maintain efficiency.



3.5.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Biochar Conveyor Motor Load	Monitors load on conveyor motor	Normal range	High load detected	Yes, auto unblock routine	Attempt unblock, if unresolved trigger alarm
Biochar Metering Auger Rotation	Tracks biochar production rate	Steady operation	Inconsistent or no rotation	Yes, prevents operation	Inspect auger feed and bindicator
Bindicator (Hopper Level)	Ensures auger is properly filled	Rotating freely	Continuously obstructed or free	Yes, prevents auger operation	Check biochar levels in hopper
Biochar Moisture Sensor	Measures biochar moisture content	35-75%	<45% triggers shutdown	Yes, critical shutdown	Check water quenching base levels

3.5.3 Interlocks & Safety Controls

The biochar transfer system is equipped with multiple interlocks and automated safety mechanisms to prevent system malfunctions and maintain continuous operation.

Biochar Conveyor Motor Interlock

If the conveyor motor detects high load, the system initiates an auto-unblock routine.

If the blockage persists, an alarm is triggered, and a controlled shutdown is performed.

Biochar Metering Auger Interlock

The auger will not operate unless the Bindicator detects sufficient biochar levels in the hopper.

If the auger rotation deviates from expected values, an alarm is triggered.

Biochar Moisture Sensor Interlock

If moisture drops below 45%, a controlled shutdown is triggered.

If moisture exceeds 75%, a warning alarm is displayed to check for excessive water levels.

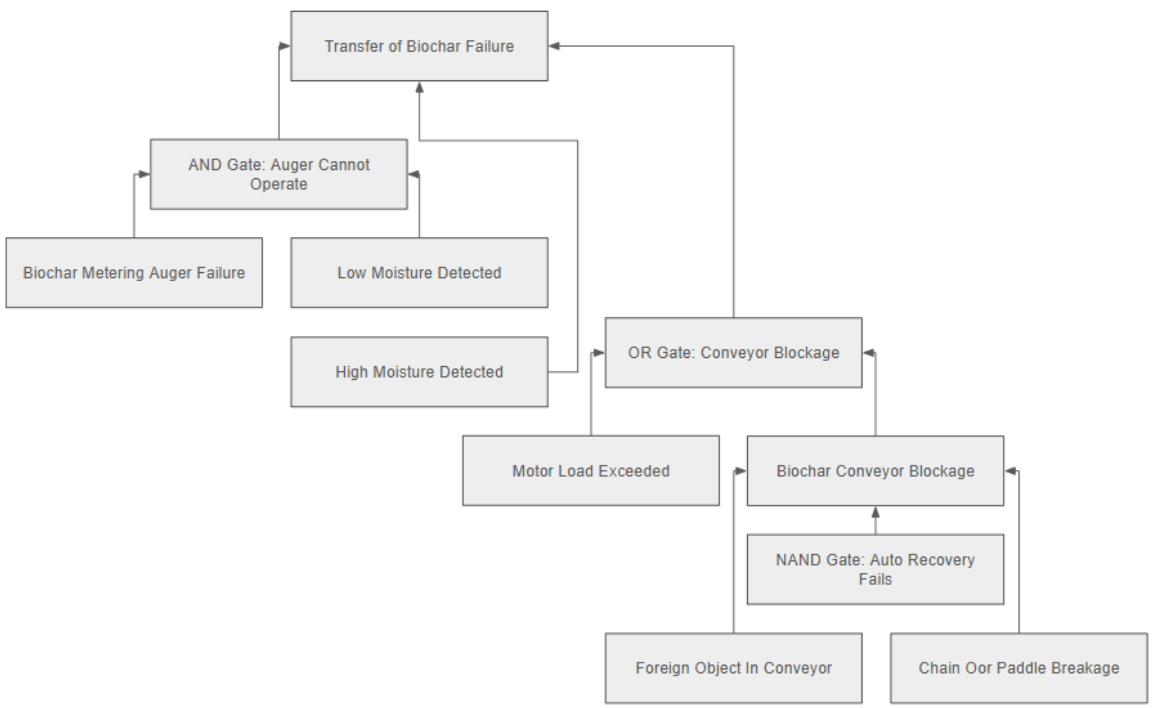
Operator Actions

The following operator actions should be taken based on specific failure conditions:

- Biochar Conveyor Blockage: Manually inspect conveyor chains and paddles for material blockage.
- Auger Rotation Failure: Verify auger feed levels and Bindicator functionality.
- Low Biochar Moisture Alarm: Check quenching base water levels and sensor calibration.
- High Biochar Moisture Alarm: Inspect the quenching system for overflow or excessive moisture.

3.5.4 Fault Tree Analysis (FTA) - Transfer of Biochar Failure

The following FTA diagram illustrates the failure pathways in the Transfer of Biochar system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.5.5 Failure Response Guide

Failure: Biochar Conveyor Blockage

Possible Causes:

• Foreign object obstructing conveyor movement
• Chain or paddle breakage
• Excessive material accumulation

SCADA System Actions:

• Detects high load and initiates auto-unblock routine.
• If unsuccessful, system triggers alarm and controlled shutdown.

Failure: Biochar Metering Auger Failure

Possible Causes:

• Auger not receiving sufficient biochar from conveyor
• Bindicator not activating auger rotation

SCADA System Actions:

• Prevents auger operation if bindicator does not detect biochar.
• System alarms and prompts operator to inspect blockage.

Failure: Low Moisture Content in Biochar

Possible Causes:

• Low water level in quenching base
• Incomplete auger filling causing false readings

SCADA System Actions:

• If moisture drops below 45%, system triggers controlled shutdown.
• Operator instructed to check quenching base water level.

Failure: High Moisture Content in Biochar

Possible Causes:

• High water level in quenching base
• Biochar not properly draining before entering metering auger

SCADA System Actions:

• If moisture exceeds 75%, system triggers warning alarm.
• Operator instructed to inspect quenching base and drain excess water.

3.6 SCADA System Manual - Post-Pyrolysis Gas to Heat Exchanger

SCADA Process Description: Post-Pyrolysis Gas to Heat Exchanger

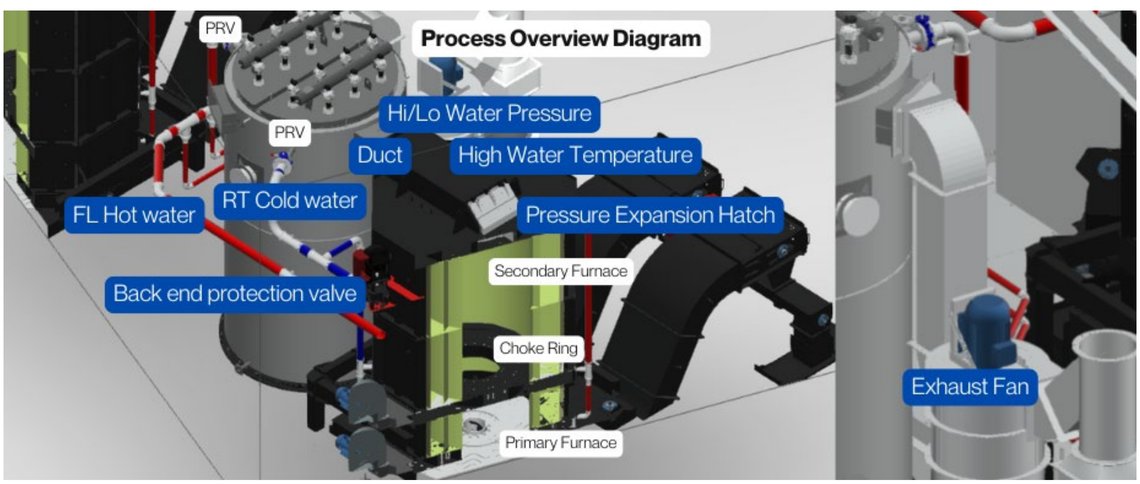
3.6.1 Process Overview

The post-pyrolysis gas flow travels through the Primary Furnace and Secondary Furnace, passing through key components such as the Choke Ring, Secondary Air Fan, and Heat Exchanger.

The Choke Ring is a circular separator that allows post-pyrolysis gases to travel cyclonically through a small central opening. This design forces particulates to drop back into the pyrolysis zone, reducing fouling and improving gas quality.

To prevent clinker buildup and potential obstruction in the choke ring, a small amount of air is fed at high pressure onto its surface. This maintains clean air pathways, prevents blockages, and prolongs the furnace refractory's lifespan.

After passing through the choke ring, gases are directed through the heat exchanger ducting, which transfers thermal energy from the post-pyrolysis gases into a hot water circuit. The system is water-cooled, with heat exchanger flow and return pipes connected to the C1000's water cooling circuit.



3.6.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Flue Gas Exit Temperature	Temperature of gases leaving heat exchanger	130-180°C	<120°C or >190°C warning	Yes, critical shutdown at <90°C or >250°C	Adjust FFR, check system for issues
Flow Temperature (FL)	Hot water temperature out of heat exchanger	Commissioned setpoint	4°C above setpoint	Yes, controlled shutdown	Adjust FFR or investigate system imbalance
Return Temperature (RT)	Cold water return to heat exchanger	Above 85°C	<85°C triggers valve modulation	No	Monitor system to prevent condensation
Negative Pressure	Measures furnace pressure stability	Target 50 Pa (Range 20-80 Pa)	<20 Pa for 20s or 0 Pa for 3s triggers shutdown	Yes, controlled shutdown	Adjust exhaust fan speed, check for blockages
Exhaust Fan Speed	Regulates negative pressure	PID-controlled	Out of PID range	No	Inspect fouling or sensor failure
Water Pressure	System hydraulic pressure	1.0-4.5 bar	Outside range	Yes, safety circuit shutdown	Check system pressure, inspect leaks or PRVs

3.6.3 Interlocks & Safety Controls

To ensure operational safety, the system includes several critical interlocks:

High Flue Gas Temperature Interlock
If flue gas temperature exceeds 190°C, a warning alarm is triggered.
If temperature exceeds 250°C, the system enters a controlled shutdown.

Low Flue Gas Temperature Interlock
If flue gas temperature drops below 120°C, a warning alarm is displayed.
If it drops below 90°C, a controlled shutdown is triggered.

Negative Pressure Interlock
If negative pressure drops below 20Pa for more than 3 seconds, a warning alarm is displayed.
If negative pressure stays below 20Pa for more than 20 seconds or reaches 0Pa for 3 seconds, a controlled shutdown is initiated.
In the event of excessive positive pressure there is a spring loaded expansion hatch at the beginning of the flue gas ducting on the C1000 roof.

Water Pressure Interlock
If water pressure falls below 1.0 bar or exceeds 4.5 bar, a safety circuit shutdown is triggered.

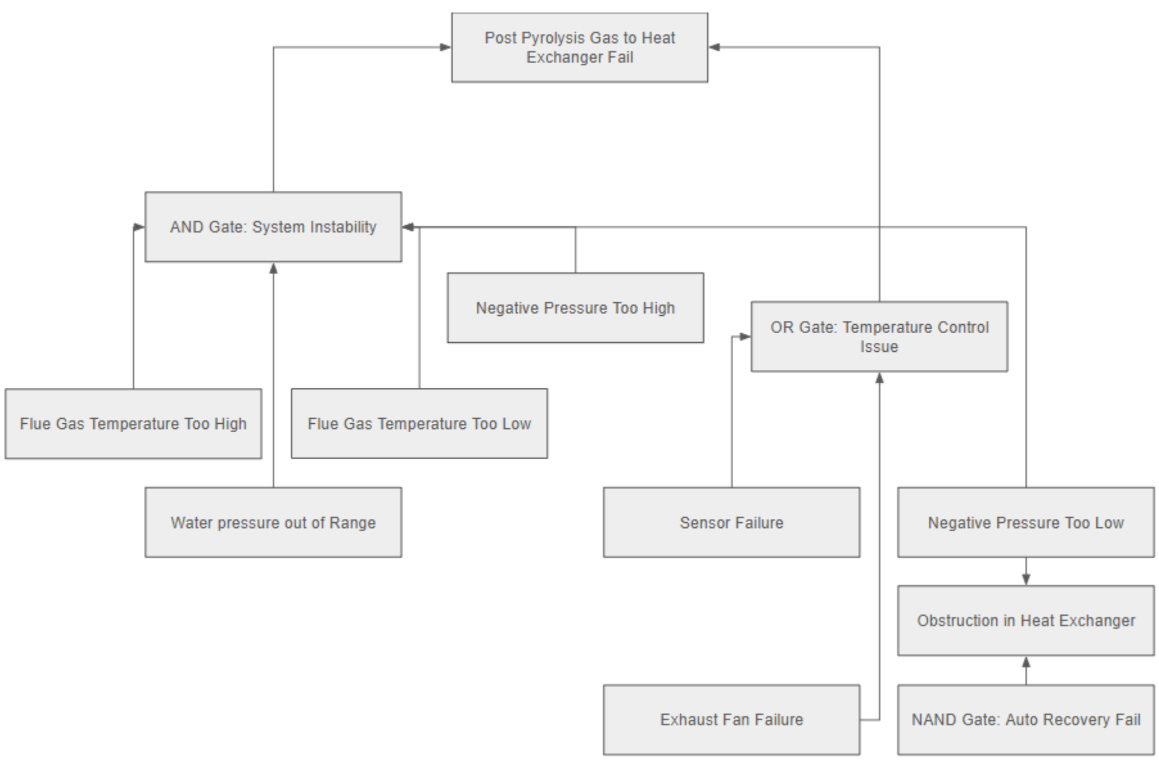
Operator Actions

The following operator actions should be taken based on specific failure conditions:

• Flue Gas Temperature Alarm: Inspect FFR settings and heat exchanger flow rates.
• Negative Pressure Alarm: Check exhaust fan operation and inspect system for fouling.
• Water Pressure Alarm: Verify system pressure settings, check for leaks or pressure release valve activation.
• High/Low Return Temperature Alarm: Inspect water flow balance and back-end protection valve modulation.

3.6.4 Fault Tree Analysis (FTA) - Post-Pyrolysis Gas to Heat Exchanger Failure

The following FTA diagram illustrates the failure pathways in the Post-Pyrolysis Gas to Heat Exchanger system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.6.5 Failure Response Guide

Failure: Flue Gas Temperature Too High

Possible Causes:
• Excessive fuel feed rate (FFR)
• Insufficient heat exchanger water flow
• Fouling in the heat exchanger

SCADA System Actions:
• If temperature exceeds 190°C, a warning alarm is triggered.
• If temperature exceeds 250°C, a controlled shutdown is initiated.

Failure: Flue Gas Temperature Too Low

Possible Causes:
• Low fuel feed rate (FFR)
• Heat exchanger extracting excessive heat
• Inadequate combustion due to airflow issues

SCADA System Actions:
• If temperature drops below 120°C, a warning alarm is displayed.
• If it drops below 90°C, a controlled shutdown is triggered.

Failure: Negative Pressure Too Low

Possible Causes:
• Exhaust fan not operating correctly
• Blockage in ducting or heat exchanger fouling
• Negative pressure sensor failure

SCADA System Actions:
• If negative pressure drops below 20 Pa for more than 3 seconds, a warning alarm is triggered.
• If it stays below 20 Pa for more than 20 seconds, a controlled shutdown is initiated.
• If it reaches 0 Pa for 3 seconds, a controlled shutdown occurs.

Failure: Negative Pressure Too High

Possible Causes:
• Over-speeding of exhaust fan
• Air leaks in the ducting or furnace system

SCADA System Actions:
• If negative pressure exceeds 80 Pa for more than 20 seconds, a warning alarm is triggered.
• Operator must inspect the exhaust system and check for leaks or excessive fan speed.

Failure: Water Pressure Out of Range

Possible Causes:
• Low pressure: Possible system leaks or pump failure
• High pressure: Expansion vessel failure or excessive heat buildup

SCADA System Actions:
• If pressure falls below 1.0 bar or exceeds 4.5 bar, a safety circuit shutdown is triggered.
• Operator must check pressure relief valves, water circuit integrity, and expansion vessels.

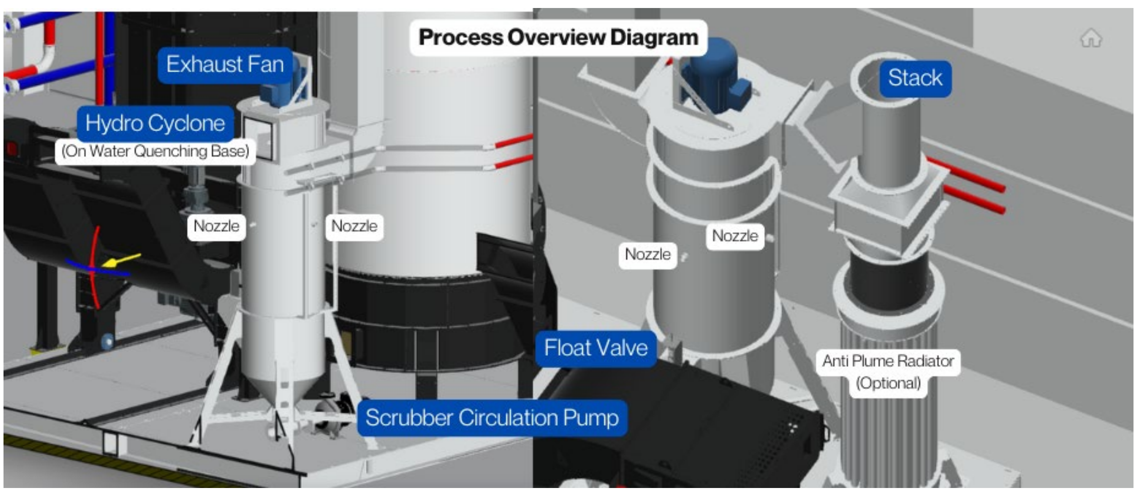
3.7 SCADA System Manual - Flue Gas Scrubbing

SCADA Process Description: Flue Gas Scrubbing

3.7.1 Process Overview

The Flue Gas Scrubber is a wet scrubbing system designed to remove particulates and regulate emissions before flue gases exit through the exhaust stack. Flue gases enter in a cyclonic flow, where they are atomized with water. The scrubbed gases exit through a central cyclone, passing through the exhaust fan before reaching the flue stack.

The scrubber operates with a continuous water circulation system, filtering and recirculating scrubber water. This ensures particulate removal and optimal scrubbing efficiency.



3.7.2 SCADA Parameters & Critical Operational Controls

Parameter	Description	Normal Range	Alarm Limit	Interlock Applied?	Action on Deviation
Scrubber Water Level	Inductive float sensor-controlled level	Between High and Low set	Low for 60s or high for 60s	Yes, controlled shutdown on low	Pump from quenching base or inspect hydro cyclone
Hydro Cyclone Function	Removes particulates before recirculation	Unrestricted flow	Blockage detected	Yes, warning alarm if high set remains for 60s	Inspect and clean hydro cyclone
Scrubber Flow Sensor	Ensures water flow in scrubbing circuit	Normal continuous flow	No flow detected for 60s	Yes, warning alarm	Inspect for pipe or spray nozzle blockage
Exhaust Fan Negative Pressure	Maintains furnace pressure balance	Target: 50 Pa (Range 20-80 Pa)	<20 Pa or failure to maintain pressure	Yes, controlled shutdown	Check scrubber water level and fan performance

3.7.3 Interlocks & Safety Controls

To ensure operational safety, the system includes multiple interlocks to prevent failures and protect furnace operation.

Scrubber Water Level Interlock
If the water level drops below the low set for 20 seconds, a warning alarm is triggered.
If the water level remains low for 60 seconds, a controlled shutdown occurs.

Hydro Cyclone Blockage Warning
If the high set sensor remains high for 60 seconds, a warning alarm is triggered, indicating a possible blockage.

Flow Blockage Warning
If there is no flow in the scrubber circuit for 60 seconds, an alarm is triggered to inspect possible pipe or spray nozzle blockages.

Exhaust Fan Negative Pressure Alarm
If the scrubber water level drops and the low level sensor fails, the exhaust fan will struggle to maintain furnace negative pressure.
A warning alarm is displayed, and if pressure remains outside the acceptable range, a controlled shutdown is initiated.

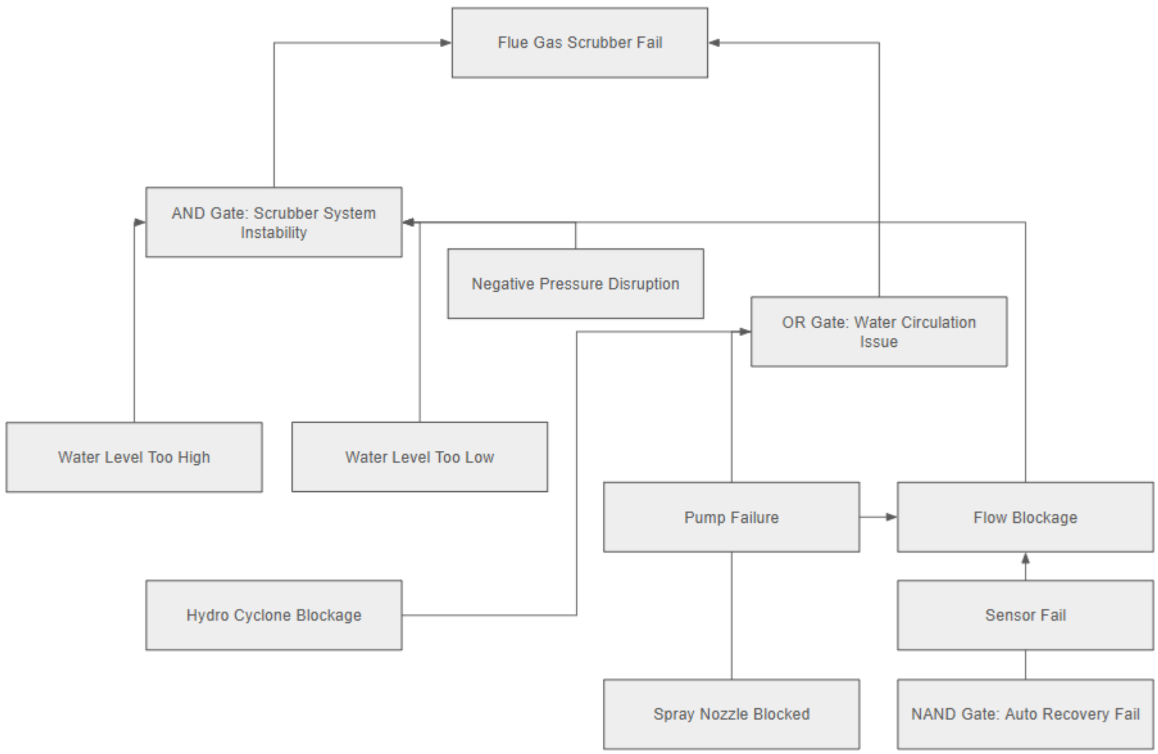
Operator Actions

The following operator actions should be taken based on specific failure conditions:

• Scrubber Water Level Alarm: Inspect water supply from quenching base, check for blockages.
• Hydro Cyclone Blockage Warning: Inspect and clean hydro cyclone if required.
• Scrubber Flow Alarm: Check spray nozzles, pipes, and flow sensor for blockages.
• Exhaust Fan Negative Pressure Alarm: Verify scrubber water level and inspect exhaust fan performance.

3.7.4 Fault Tree Analysis (FTA) - Flue Gas Scrubbing Failure

The following FTA diagram illustrates the failure pathways in the Flue Gas Scrubbing system, incorporating AND, OR, and NAND logic gates for critical decision points.



3.7.5 Failure Response Guide

Failure: Water Level Too High

Possible Causes:

• Water level control failure
• Hydro cyclone blockage causing overflow

SCADA System Actions:

• If the high set sensor remains high for 60 seconds, a warning alarm is triggered.
• Operator must inspect hydro cyclone and water level control.

Failure: Water Level Too Low

Possible Causes:
• Insufficient water supply from quenching base
• Pump failure or pipe blockage

SCADA System Actions:
• If water level drops below low set for 20 seconds, a warning alarm is displayed.
• If it remains low for 60 seconds, a controlled shutdown is triggered.

Failure: Scrubber Flow Blockage

Possible Causes:
• Spray nozzles clogged
• Pump failure or pipeline obstruction

SCADA System Actions:
• If no flow is detected for 60 seconds, a warning alarm is triggered.
• Operator must inspect and clean spray nozzles and check pump operation.

Failure: Negative Pressure Disruption

Possible Causes:
• Scrubber water level too low affecting gas flow
• Exhaust fan malfunction

SCADA System Actions:
• If furnace negative pressure falls outside the 20-80 Pa range, a warning alarm is triggered.
• If pressure remains critical, a controlled shutdown is performed.

Failure: Hydro Cyclone Blockage

Possible Causes:
• Accumulation of particulates in the hydro cyclone
• Water circulation restriction

SCADA System Actions:
• If blockage is detected and high set remains for 60 seconds, a warning alarm is displayed.
• Operator must inspect and clean the hydro cyclone.

4 SCADA Environmental Emissions Overview

The SCADA Environmental Emissions Monitoring System is responsible for detecting, analyzing, and mitigating emissions-related risks in the C1000 pyrolysis process. It ensures that **particulate matter (PM) and nitrogen oxides (NOx) emissions remain within regulatory limits** under both normal operation and failure conditions.

SCADA & PLC Integration

The SCADA system interfaces with Programmable Logic Controllers (PLCs) to continuously monitor emission-critical parameters, including:

-Flue Gas Scrubber Performance (flow rates, nozzle efficiency, circulation pump operation)
-Combustion Airflow and Gas Flow Rates (negative pressure, fan speeds)
-Process Temperature and Fuel Feed Rate (to prevent excessive combustion fluctuations)

When a deviation from acceptable emission levels occurs, the SCADA system responds automatically, adjusting combustion settings or initiating a controlled shutdown to minimize environmental impact.

Emission Control and Regulatory Compliance

The SCADA system ensures compliance with regulatory emission standards for NOx and PM emissions by:

-Real-time monitoring of scrubber efficiency and water flow
-Automated failure detection with alarm-triggered shutdowns
-Emission mitigation measures that reduce combustion power when faults occur

Failure Response and Environmental Impact Prevention

SCADA is programmed to respond to environmental risks proactively:

-Scrubber failure: Triggers a shutdown before PM levels exceed limits
-Exhaust fan failure: Ensures emissions remain stable by reducing overall combustion
-Circulation pump trip: Prevents PM emissions by limiting pyrolysis power

This system ensures continuous monitoring and protection, safeguarding both environmental compliance and system efficiency.

4.1 SCADA Environmental Emissions - Wet Flue Gas Scrubber Failure

4.1.1 Failure Scenario: Wet Flue Gas Scrubber Circulation Pump/Nozzle Blockage

In the event of a circulation pump blockage or a nozzle blockage, the system would experience a gradual increase in blockage, leading to reduced scrubbing efficiency. Without intervention, this could result in increased particulate matter (PM) emissions due to ineffective gas scrubbing.

SCADA Detection & Response

The SCADA system continuously monitors the scrubber circuit using a flow meter positioned between the main scrubber circulation pump and the scrubber nozzles.

-Low Flow Alarm: If the flow meter detects reduced circulation flow, an alarm is triggered, leading to a controlled shutdown before emissions exceed environmental limits.
-Hydro Cyclone Operation: Particulates and sludge are pumped from the scrubber base to a hydro cyclone, where they are removed and transferred into the water quenching base. The filtered water then flows back to the scrubber nozzles for continuous operation.

4.1.2 Failure Scenario: Scrubber Circulation Pump Failure

In the event of a mechanical or electrical failure of the scrubber circulation pump, the motor will trip, leading to a controlled shutdown to prevent further system damage and excessive emissions.

-Environmental Risk: The failure of the scrubber pump may cause a temporary increase in particulate emissions. However, due to the controlled shutdown sequence, combustion power will gradually decrease, reducing PM output.
-Feedstock Pyrolysis Limitation: The feedstock on the active grate undergoes pyrolysis for a maximum of 15 minutes. After this period, all combustion is completed, ensuring no further emissions occur post-shutdown.

4.1.3 Environmental Impact

If the scrubber circulation flow is reduced, the system’s ability to capture particulate matter (PM) decreases, potentially leading to increased emissions. However, SCADA monitoring ensures that a low flow alarm is triggered before emissions exceed regulatory limits.

In routine operation, if the scrubber flow is low but not low enough to trigger an alarm, it is inspected during planned preventative maintenance (PPM) to prevent further deterioration.

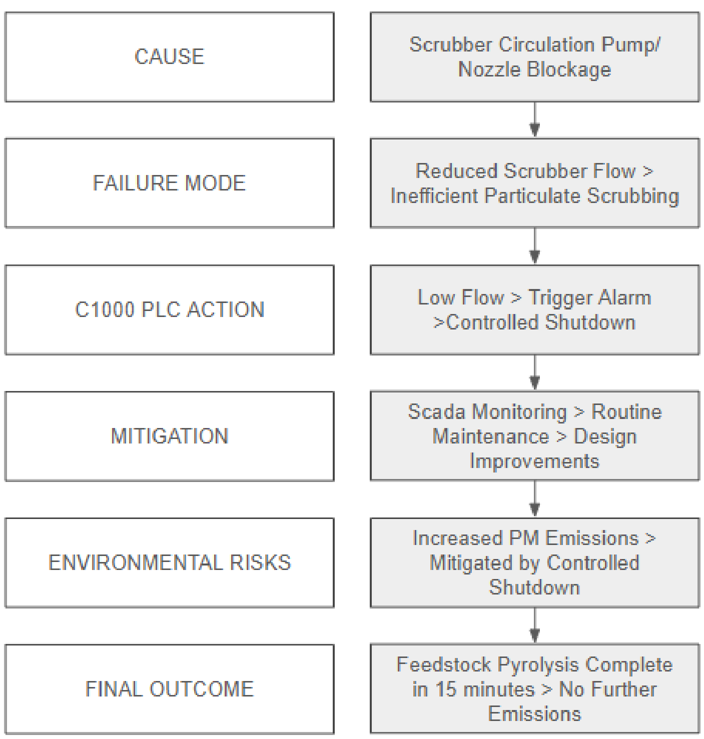
4.1.4 Mitigation Measures

To prevent long-term environmental impact, the following mitigation measures are in place:

-SCADA monitoring detects gradual reductions in scrubber circulation flow before total failure.
-A low flow alarm triggers a controlled shutdown before emissions exceed limits.
-Routine servicing includes inspection and cleaning of scrubber nozzles, circulation pumps, and the hydro cyclone.
-If scrubber flow is slightly reduced but not alarming, it is scheduled for review in planned preventative maintenance (PPM).
-Potential design improvements include alternative nozzle layouts and backup pumps for redundancy.
-Feedstock pyrolysis is limited to 15 minutes, ensuring no sustained emissions post-shutdown.

4.1.5 Block Diagram - Scrubber Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a scrubber circulation pump/nozzle blockage failure scenario.



4.1.6 Decision Matrix - Scrubber Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with scrubber failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Scrubber Circulation Pump/Nozzle Blockage	Reduced scrubber flow → Inefficient PM removal	Detect low flow → Trigger alarm → Controlled Shutdown	SCADA Monitoring → Routine Maintenance → Design Improvements	Temporary PM increase, mitigated by controlled shutdown
Scrubber Circulation Pump Failure	No scrubber circulation → Total PM scrubbing loss	Motor trip → Controlled Shutdown	Routine servicing of motor → Backup pump design improvements	Temporary PM increase, mitigated by controlled shutdown and reduced combustion

4.2 SCADA Environmental Emissions - Exhaust Fan Failure

4.2.1 Failure Scenario: Exhaust Fan Failure

The exhaust fan is PID-controlled to maintain negative pressure in the secondary furnace. In the event of an exhaust fan failure, the negative pressure will fall out of range, triggering an alarm and initiating a controlled shutdown.

SCADA Detection & Response

The SCADA system continuously monitors exhaust fan operation and responds to failures in the following ways:

-Motor Failure: If the exhaust fan motor fails, the PLC triggers an alarm and initiates a controlled shutdown.
-Mechanical Casing Failure: If the exhaust fan casing is damaged, efficiency drops, and the fan is unable to maintain negative pressure within range. This triggers an alarm and a controlled shutdown.
-Negative Pressure Monitoring: If the negative pressure in the secondary furnace falls outside the acceptable range, SCADA initiates a controlled shutdown as per the previously documented negative pressure limits.

4.2.2 Environmental Impact

No Increase in PM or NOx Emissions: The scrubber system continues to operate, ensuring that emissions do not rise despite the exhaust fan failure.

-Main Risk is Positive Pressure in the C1000 Furnace: If the exhaust fan fails completely, the loss of negative pressure could result in positive pressure inside the C1000 furnace. This increases the risk of post-pyrolysis gas escaping through unintended paths.
-Explosion Hatch Safety Measure: The C1000 roof to heat exchanger flue duct service access door doubles as an explosion hatch. In the event of excessive post-pyrolysis gas pressure, this hatch serves as the highest safety release point, mitigating risk to ground-level operators.
-Natural Venting via Flue Stack: After an exhaust fan failure and the initiation of a controlled shutdown, post-pyrolysis gases and flue gases will continue to vent naturally through the flue stack due to the negative draft created by the hot gases.
-The Longer the Controlled Shutdown Continues, the More the Risk is Mitigated. Over time, the gradual reduction in temperature and fuel feed ensures a safe transition to a non-operational state.

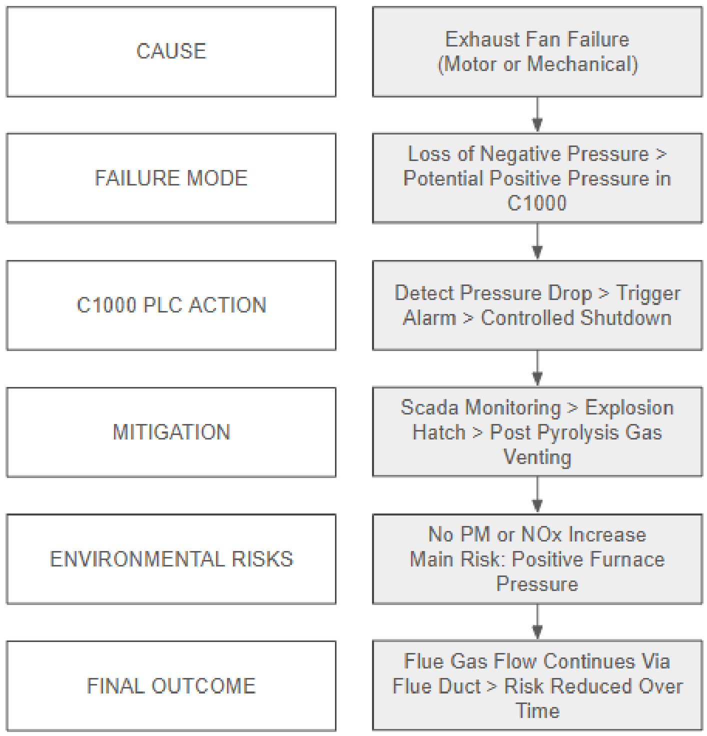
4.2.3 Mitigation Measures

To prevent environmental risks and ensure operational safety, the following mitigation measures are in place:

-SCADA negative pressure monitoring ensures early detection of fan efficiency loss.
-Controlled shutdown prevents continued operation with compromised negative pressure.
-Explosion hatch design provides a controlled release of pressure in extreme cases.
-The scrubber system remains operational, ensuring NOx and PM levels do not increase.
-Post pyrolysis gases naturally vent through the flue stack due to hot gas draft, reducing emissions.

4.2.4 Block Diagram - Exhaust Fan Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for an exhaust fan failure scenario.



4.2.5 Decision Matrix - Exhaust Fan Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with exhaust fan failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Exhaust Fan Motor Failure	Loss of negative pressure → Potential positive pressure in C1000	Detect pressure drop → Trigger alarm → Controlled Shutdown	SCADA Monitoring → Explosion Hatch → Post-Pyrolysis Gas Venting	No PM or NOx Increase → Main Risk: Positive Furnace Pressure
Exhaust Fan Mechanical Casing Failure	Reduced fan efficiency → Unable to maintain negative pressure	Detect fan inefficiency → Trigger alarm → Controlled Shutdown	Routine fan maintenance → Monitoring of mechanical integrity	Minimal emissions impact → Higher risk of furnace pressure fluctuation

4.3 SCADA Environmental Emissions - Primary Air Fan Failure

4.3.1 Failure Scenario: Primary Air Fan Failure

The Primary Air Fan is responsible for supplying controlled airflow to maintain the pyrolysis temperature in the Primary Furnace. It is PID-controlled, ensuring that the air feed is adjusted based on real-time temperature readings from the infrared sensor and thermocouples. In the event of a Primary Air Fan failure, the furnace temperature will drop, triggering a RAMP mode transition or, if sustained, a controlled shutdown.

SCADA Detection & Response

The SCADA system continuously monitors the Primary Air Fan and responds to failures in the following ways:

-Motor Failure: If the Primary Air Fan motor fails, an immediate alarm is triggered, and the system initiates a controlled shutdown.
-Mechanical Casing Failure: If the fan casing is damaged, airflow efficiency is reduced, causing a drop in pyrolysis temperature. This will result in the system entering RAMP mode. If the temperature continues to fall below 250°C (RAMP1), a controlled shutdown is initiated**.
-Temperature-Based Adjustments: If airflow is reduced but not completely lost, SCADA will adjust the Fuel Feed Rate (FFR) and Active Grate Movement to maintain safe operation.
-Operator Actions: Operators are required to check the power supply, motor condition, airflow path, and control wiring** before attempting a restart.

4.3.2 Environmental Impact

NOx and PM Levels Remain Stable If Partial Airflow Exists: If the Primary Air Fan is still partially operating, NOx and PM emissions will not be significantly impacted as combustion remains controlled.

If the Primary Air Fan Completely Fails: The system will enter RAMP mode, reducing feedstock combustion. This lowers emissions but can result in incomplete pyrolysis if the temperature is too low. If the system drops to RAMP1 for more than 10 minutes, a controlled shutdown is triggered, preventing prolonged instability.

Controlled Shutdown Ensures Safe Operation: If airflow is insufficient to maintain proper combustion conditions, the system will shut down in a controlled manner, ensuring no excessive emissions or combustion events.

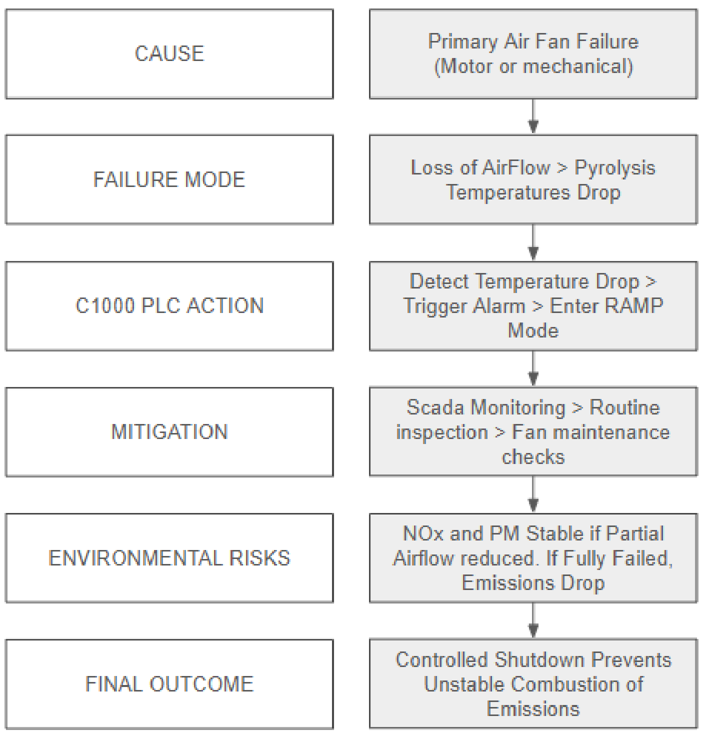
4.3.3 Mitigation Measures

To prevent environmental risks and ensure operational safety, the following mitigation measures are in place:

-SCADA continuously monitors fan performance to detect early signs of failure.
-Operators conduct routine inspections of the fan motor, casing, and airflow paths to prevent unexpected failures.
-Temperature-based RAMP mode adjustments help stabilize operations if airflow is reduced but not completely lost.
-A controlled shutdown sequence is triggered if airflow is lost, preventing incomplete combustion and excessive emissions.

4.3.4 Block Diagram - Primary Air Fan Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Primary Air Fan failure scenario.



4.3.5 Decision Matrix - Primary Air Fan Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with Primary Air Fan failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Primary Air Fan Motor Failure	Loss of airflow → Pyrolysis temperature drops → System enters RAMP mode	Trigger alarm → Enter RAMP mode → If sustained, controlled shutdown	SCADA Monitoring → Routine inspections → Fan redundancy planning	NOx and PM stable if airflow remains → If fully failed, emissions drop due to reduced combustion
Primary Air Fan Mechanical Casing Failure	Reduced fan efficiency → Lower airflow → Gradual temperature drop	Monitor temperature drop → Adjust FFR → If below 250°C for 10 min, controlled shutdown	Routine casing inspections → SCADA power and airflow monitoring	Minimal impact if airflow remains → If airflow loss, emissions reduce due to lower combustion

4.4 SCADA Environmental Emissions - Secondary Air Fan Failure

4.4.1 Failure Scenario: Secondary Air Fan Failure

The Secondary Air Fan is responsible for supplying controlled airflow to maintain the target 7% oxygen (O_2) level in the Secondary Furnace. It operates within a set range and adjusts its speed based on real-time O_2 readings from the oxygen sensor. In the event of a Secondary Air Fan failure, oxygen levels drop, leading to low O_2 alarms and potential controlled shutdown.

SCADA Detection & Response

The SCADA system continuously monitors the Secondary Air Fan and responds to failures in the following ways:

-Motor Failure or Mechanical Breakdown: A sudden loss of airflow leads to a drop in O_2 readings.
-Low O_2 Warning: If O_2 levels fall below 5% for 5 seconds, a warning alarm is triggered.
-Controlled Shutdown: If O_2 levels remain below 5% for 20 seconds, the system initiates a controlled shutdown.
-Secondary Furnace Temperature Feedback: Operators and remote engineers can monitor high furnace temperatures, which may indicate an airflow loss.
-Routine O_2 Sensor Calibration: The O_2 sensor is checked and calibrated during planned shutdown servicing to maintain accuracy.

4.4.2 Environmental Impact

No Expected Increase in PM or NOx Emissions: The failure of the Secondary Air Fan does not significantly impact emissions.

High Secondary Furnace Temperature as an Indicator: Loss of airflow can cause an increase in the secondary furnace temperature, which is visible to operators and remote engineers as a secondary indication of airflow loss.

Controlled Shutdown Prevents Instability: If oxygen levels fall too low, the system shuts down in a controlled manner, preventing improper combustion and ensuring environmental compliance.

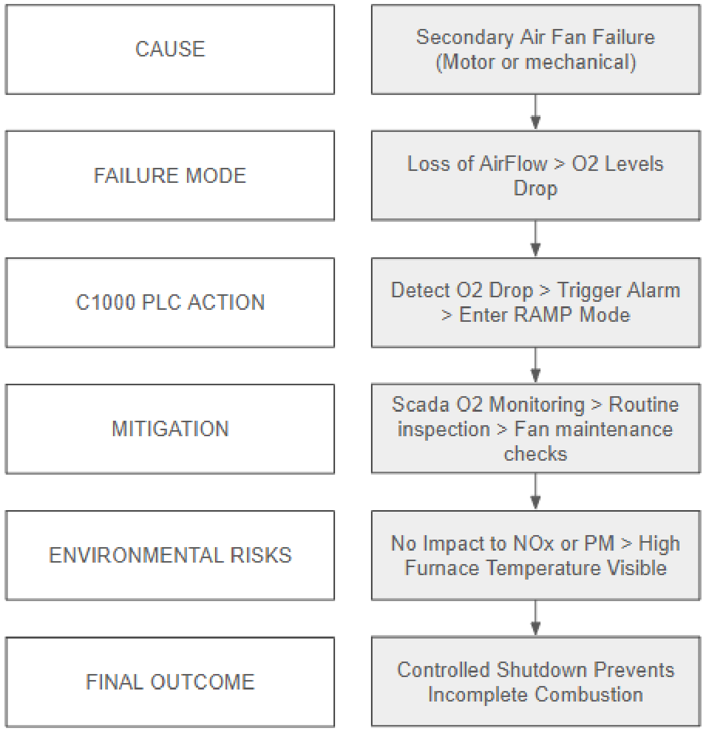
4.4.3 Mitigation Measures

To prevent environmental risks and ensure operational safety, the following mitigation measures are in place:

-SCADA continuously monitors O_2 levels and fan performance to detect early failure signs.
-Operators and remote engineers monitor secondary furnace temperature trend to identify airflow issues.
-Routine inspections include O_2 sensor calibration to ensure proper readings.
-A controlled shutdown is initiated if airflow loss is detected, ensuring no emissions exceedances.

4.4.4 Block Diagram - Secondary Air Fan Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Secondary Air Fan failure scenario.



4.4.5 Decision Matrix - Secondary Air Fan Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with Secondary Air Fan failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Secondary Air Fan Motor Failure	Loss of airflow → O_2 levels drop → Below 5% triggers shutdown	Trigger alarm → If O_2 <5% for 20s, controlled shutdown	SCADA O_2 monitoring → Routine fan inspections → Operator checks	No impact on NOx or PM emissions → High furnace temperature visible
Secondary Air Fan Mechanical Casing Failure	Reduced fan efficiency → Gradual drop in airflow → O_2 deviation	Monitor O_2 drop → If below 5% for 20s, controlled shutdown	Routine casing inspections → SCADA fan and temperature monitoring	Minimal emissions impact → Operator can verify furnace temperature trends

4.5 SCADA Environmental Emissions - Oil/Lubricant Leak

4.5.1 Failure Scenario: Oil/Lubricant Leak

The C1000 system contains multiple motor gearboxes that require lubrication to function efficiently. If one of these gearboxes fails, it may leak oil or lubricant, potentially creating an environmental hazard. However, all motor gearboxes are designed so that any leaked fluid will not contact hot surfaces, reducing the risk of fire or contamination.

SCADA Detection & Response

The SCADA system continuously monitors motor gearbox loads to detect signs of potential failure before an oil or lubricant leak occurs:

-Motor Load Monitoring: The SCADA system tracks motor load averages. If the load exceeds a high set threshold, it will trigger a notification alarm for early intervention.
-Planned Preventative Maintenance (PPM) Inspections: Engineers regularly check motor gearbox loads for deviation, allowing for **preventative action before failure occurs.
-Remote Monitoring for Operators: If a high load is detected, site operators can inspect the gearbox with remote support, ensuring timely identification of issues before a leak happens.

4.5.2 Environmental Impact

Minimal Fire Risk: The design of the C1000 ensures that any leaked oil or lubricant will not reach heated surfaces, eliminating the risk of ignition.

Leak Containment Measures in Place: In the event of a leak, the site is equipped with spill sand for rapid containment, ensuring that the environment is not contaminated.

SCADA Pre-Alarms Allow Proactive Maintenance: Because motor gearbox loads are monitored continuously, potential failures are detected before they cause significant environmental or operational hazards.

4.5.3 Mitigation Measures

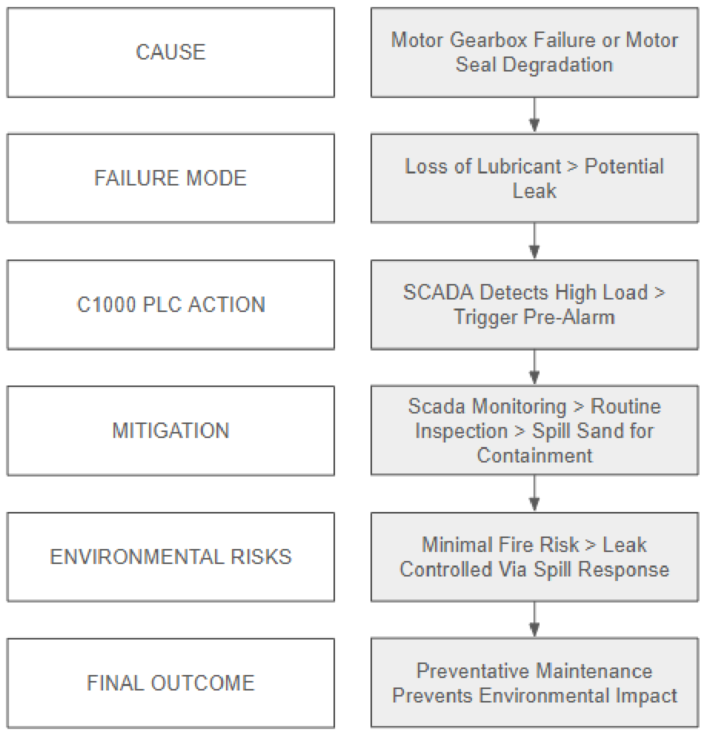
To prevent environmental risks and ensure operational safety, the following mitigation measures are in place:

-SCADA continuously monitors motor gearbox loads to detect early failure signs.
-Planned Preventative Maintenance (PPM) checks ensure that all motor gearboxes are regularly inspected.
-Site spill sand is available for rapid containment of any leaks.

-Remote monitoring allows operators and engineers to detect and address potential gearbox failures before leaks occur.

4.5.4 Block Diagram - Oil/Lubricant Leak Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for an Oil/Lubricant Leak scenario.



4.5.5 Decision Matrix - Oil/Lubricant Leak

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with Oil/Lubricant Leaks.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Motor Gearbox Failure	Loss of lubrication → Increased friction → Potential leak	SCADA detects high load → Triggers pre-alarm for inspection	Routine inspections → SCADA monitoring → Spill sand for containment	Minimal fire risk → Leak containment via spill response measures
Mechanical Seal Degradation	Gradual oil/lubricant seepage → Contamination risk	SCADA detects high load → Notification alarm triggers maintenance check	Scheduled maintenance → Site operator & engineer inspections	No direct emissions impact → Contained within the plant

4.6 SCADA Environmental Emissions - Low Water Level in the Scrubber

4.6.1 Failure Scenario: Low Water Level in the Scrubber

The Wet Flue Gas Scrubber is responsible for particulate removal and gas scrubbing before flue gases exit through the exhaust stack. Water for the scrubber is pumped from the C1000 Water Quenching Base when the low-level inductive sensor detects a drop in water level. A low water level in the scrubber can result from pump failure, pipe blockage, or sudden leaks, leading to reduced scrubbing efficiency and potential environmental emissions.

SCADA Detection & Response

The SCADA system continuously monitors the scrubber water level and responds to failures in the following ways:

-Water Level Monitoring: If the scrubber's low-level sensor remains active for 20 seconds, a warning alarm is triggered.
-Controlled Shutdown Trigger: If the low water level persists for 60 seconds, the system initiates a controlled shutdown.
-Pump Failure or Pipe Blockage Detection: If the scrubber flow sensor detects no flow for 60 seconds, an alarm is triggered for inspection.
-Planned Preventative Maintenance (PPM): The pump, pipes, and seals are inspected during scheduled shutdowns to prevent unexpected failures.
-Drainage Sump & Water Recovery: All C1000 plant rooms include a drainage sump that collects leaked water and allows it to be pumped back into the system after repairs.

4.6.2 Environmental Impact

Scrubber water is not highly hazardous, and the plant design includes safety features to contain leaks.

Loss of scrubbing function can result in increased PM emissions, but the system mitigates this risk by triggering a controlled shutdown before emissions exceed acceptable levels.

Minor pump seal failures usually result in small drips, allowing operators to identify and address the issue before a major failure occurs.

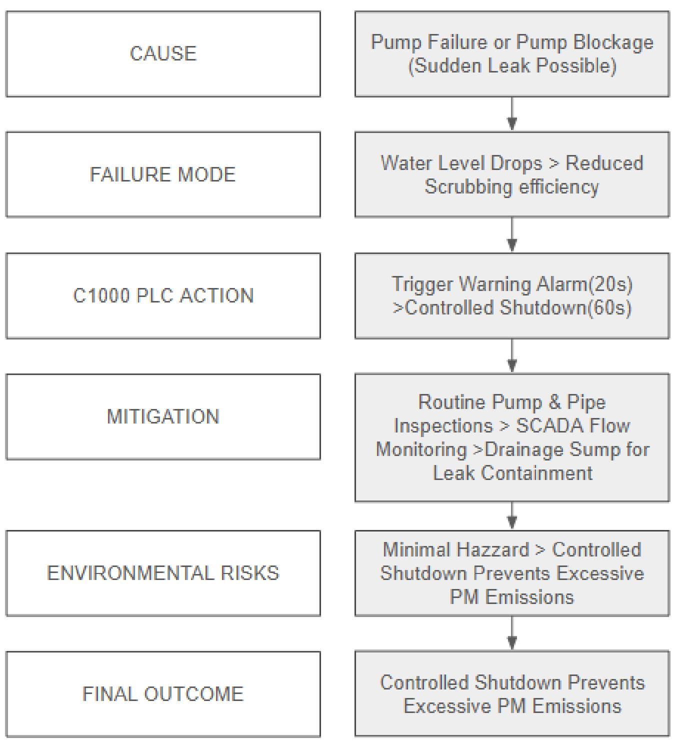
4.6.3 Mitigation Measures

To prevent environmental risks and ensure operational safety, the following mitigation measures are in place:

-SCADA continuously monitors water level sensors and triggers alarms if levels drop.
-Scrubber pump and pipes are inspected as part of routine maintenance.
-Drainage sump captures leaked water, preventing environmental contamination.
-If a water level drop occurs, operators inspect the system and verify pump operation before restarting.

4.6.4 Block Diagram - Low Water Level in the Scrubber Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Low Water Level in the Scrubber scenario.



4.6.5 Decision Matrix - Low Water Level in the Scrubber

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with Low Water Level in the Scrubber failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Pump Failure	Water level drops → Scrubbing efficiency reduced	Trigger warning alarm (20s) → Controlled shutdown (60s)	Routine pump inspections → SCADA flow monitoring → Drainage sump for leak containment	Minimal hazard → Controlled shutdown prevents excessive PM emissions
Pipe Blockage	Restricted water flow → Insufficient scrubbing	Trigger warning alarm → Inspect pipes & unblock	Routine pipe cleaning → SCADA flow monitoring	No hazardous emissions → Temporary increase in PM possible
Sudden Leak or Pipe Failure	Rapid water loss → Immediate scrubbing failure	Trigger warning alarm → Controlled shutdown	Drainage sump captures water → Immediate operator inspection	Leak contained in plant room sump → Water can be recovered after repair

4.7 SCADA Environmental Emissions - Low Water Level in the Water Quenching Base

4.7.1 Failure Scenario: Low Water Level in the Water Quenching Base

The Water Quenching Base serves two critical functions: 1) Quenching biochar to stop the pyrolysis process, and 2) Acting as an airlock to maintain negative pressure within the C1000 Furnace. A low water level in the quenching base can lead to a loss of furnace negative pressure and potential combustion instability.

SCADA Detection & Response

Water Level Monitoring: If the quenching base's low-level sensor remains active for 60 seconds, a warning alarm is triggered.

-Controlled Shutdown Trigger: If the low water level persists beyond 60 seconds, the system initiates a controlled shutdown.
-Automatic Water Infeed Activation: The system opens the water infeed valve for 60 seconds or until the high set level is reached.
-Failure to Recover Water Level: If the water level remains low despite the infeed operation, a shutdown alarm is triggered.

4.7.2 Environmental Impact

Loss of airlock in the water quenching base could affect furnace draft stability, leading to combustion inconsistencies.

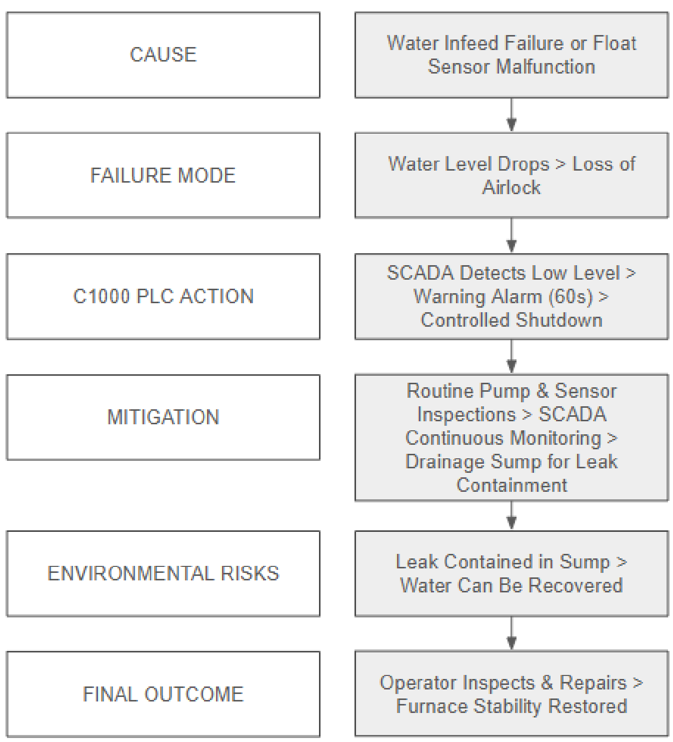
Sudden leaks will flow into the plant room drainage sump, allowing for containment and recovery.

4.7.3 Mitigation Measures

-Routine inspection of float sensors and water levels to ensure proper operation.
-SCADA continuously monitors water levels to prevent dry base conditions.
-Operators inspect water circuits during planned shutdowns to ensure system integrity.
-Drainage sump captures sudden leaks, preventing environmental contamination.

4.7.4 Block Diagram - Low Water Level in the Water Quenching Base Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Low Water Level in the Water Quenching Base scenario.



4.7.5 Decision Matrix - Low Water Level in the Water Quenching Base

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with low water level failures in the Water Quenching Base.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Water Infeed Failure	Water level drops → Quenching disrupted	Trigger warning alarm (60s) → Controlled shutdown	Routine pump inspections → SCADA float sensor monitoring	Risk of incomplete pyrolysis → Possible furnace instability
Float Sensor Malfunction	Incorrect water level reading → System does not refill properly	Warning alarm → Operator required to inspect	Regular float sensor calibration & inspections	Minimal risk if detected early
Sudden Leak or Pipe Failure	Rapid water loss → Loss of airlock	Trigger warning alarm → Controlled shutdown	Drainage sump captures water → Immediate operator inspection	Leak contained in plant room sump → Water can be recovered after repair

4.8 SCADA Environmental Emissions - High Water Pressure & PRV Failure

4.8.1 Failure Scenario: High Water Pressure & PRV (Pressure Release Valve) Failure

The Water Circuit in the C1000 operates within a controlled pressure range, ensuring safe operation of the heat exchanger and furnace cooling system. The standard pressure settings are:
- Minimum Pressure Switch: 1.0 bar
- Maximum Pressure Switch: 4.5 bar

If water pressure exceeds the maximum limit and the Pressure Release Valve (PRV) fails to activate, this can lead to overpressure in the system, pipe damage, and water discharge.

SCADA Detection & Response

-High Water Pressure Alarm Activation: If system pressure exceeds 4.5 bar, the system initiates a safety circuit shutdown.
-PRV Activation (Mechanical Safety Mechanism): If the pressure continues rising, the Pressure Release Valve (PRV* will mechanically release excess pressure*+0.4 bar above the maximum setpoint to prevent system damage. This operates independently of SCADA controls.
-Safety Circuit Shutdown Activation: In the event of a high water pressure failure, the system ensures safe cooldown by allowing the exhaust fan, water circulation pump, and back-end protection valve to operate for 1 hour, ensuring heat dissipation.

4.8.2 Environmental Impact

High water pressure could lead to pipe leaks, component damage, or excessive water loss.

If the PRV fails, water discharge may occur, which will drain into the plant room sump for containment.

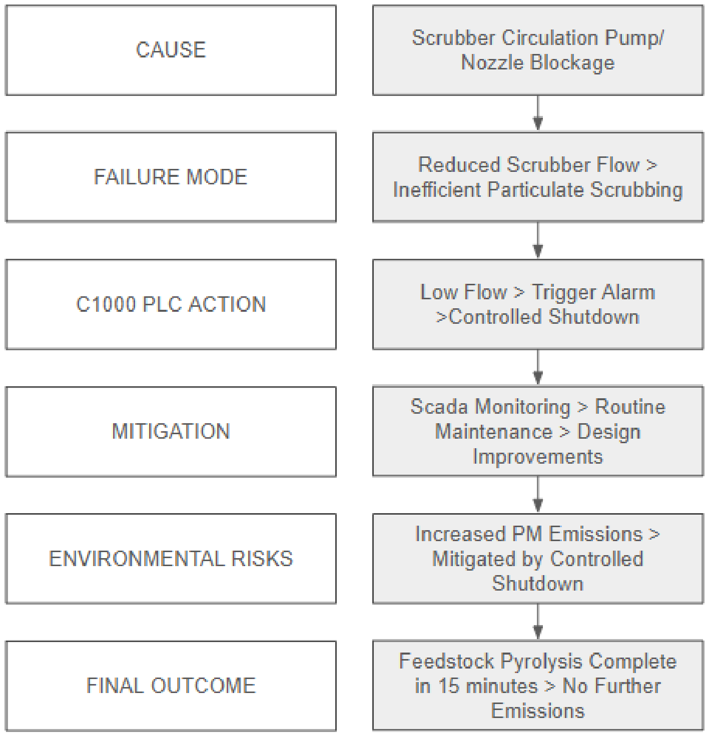
Pressure Release Valves are piped to floor level and can be directed to an external drain, but it is preferable to vent into the sump. Thewater contains inhibitors and must be tested by the site operator before confirming if it can be pumped into the Water Quenching Base or requires disposal.

4.8.3 Mitigation Measures

-Routine inspection & testing of PRVs to ensure functionality.
-SCADA continuously monitors water pressure for early failure detection.
-Operators inspect pressure relief pipe outlets for unexpected releases.
-Regular maintenance of heat exchanger seals and pipework to prevent high-pressure leaks.
-PRV’s are tested and calibrated annually.
-Site operator to test sump water quality before confirming if it can be reused in the Water Quenching Base or must be removed.

4.8.4 Block Diagram - High Water Pressure & PRV Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a High Water Pressure & PRV Failure scenario.



4.8.5 Decision Matrix - High Water Pressure & PRV Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with high water pressure failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Excessive System Pressure	Water pressure exceeds 4.5 bar → Risk of overpressure damage	Warning alarm (3s) → Safety circuit shutdown (10s)	SCADA pressure monitoring → Regular PRV inspections	Potential pipe damage → Risk of water discharge
PRV Failure	PRV does not activate at overpressure → buildup	Safety circuit shutdown to prevent damage	Routine PRV functionality tests → Inspection of relief pipe outlets	Sudden water release to plant room sump
Seal or Pipe Damage	High pressure causes leakage or pipe rupture	SCADA detects pressure drop → Alarm triggered	Routine pipework inspections → Preventative maintenance	Leakage contained in plant room sump → Water must be tested before reuse

4.9 SCADA Environmental Emissions - Liquid Seal Failure

4.9.1 Failure Scenario: Liquid Seal Failure

The Liquid Seal in the C1000 system ensures proper operation by preventing leaks and maintaining negative pressure in key areas, including:
- Water Pump Seals
- Water Pipe Integrity
- Scrubber Structural Integrity
- Water Quenching Base Seal

If a liquid seal fails, it may lead to water leakage, pressure loss, or system inefficiency, affecting overall operation.

SCADA Detection & Response

Leak Detection & Alarm Activation: If water flow drops below minimum setpoint, SCADA triggers a low water flow alarm. If water levels drop in the scrubber or quenching base, SCADA triggers a low water level alarm.

Controlled Shutdown Trigger: If the failure persists for 60 seconds, the system initiates a controlled shutdown to prevent further damage and maintain operational safety.

Site Drainage & Sump Containment: Any leaked water will flow into the plant room drainage sump, preventing environmental contamination and allowing for potential water recovery.

4.9.2 Environmental Impact

Leaked water is not hazardous, but sump water must be tested before reuse.

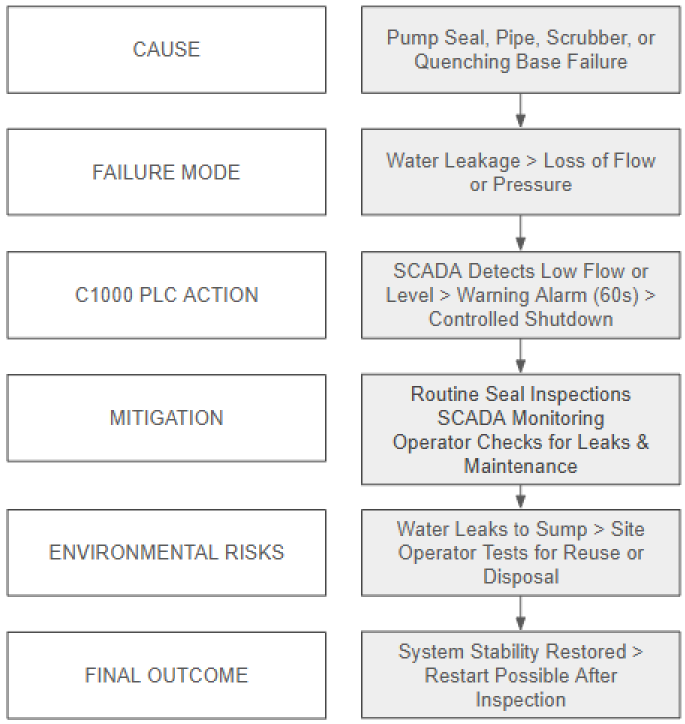
If a major leak occurs, water loss can impact the cooling and scrubbing efficiency, affecting combustion control.

4.9.3 Mitigation Measures

-Routine inspections of pump seals, water pipes, and scrubber structure to detect wear or damage.
-SCADA continuously monitors water levels and flow rates to detect early signs of failure.
-Operators perform visual inspections of key sealing components during planned maintenance.
-Plant room drainage sump prevents environmental contamination by containing leaked water.
-If sump water accumulates, it must be tested before reuse or removed if unsuitable.

4.9.4 Block Diagram - Liquid Seal Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Liquid Seal Failure scenario.



4.9.5 Decision Matrix - Liquid Seal Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with liquid seal failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Pump Seal Failure	Water leaks from the pump, reducing flow	SCADA detects low flow → Warning alarm → Controlled shutdown (60s)	Routine seal inspections → SCADA flow monitoring	Water enters plant room sump → Must be tested before reuse
Water Pipe Leak	Loss of pressure and possible operational instability	SCADA detects pressure drop → Alarm triggered	Routine pipework inspections → Preventative maintenance	Leakage contained in plant room sump → Water recovery possible
Scrubber Structural Failure	Water escapes from scrubber causing operational inefficiency	SCADA detects level drop → Low water alarm → Controlled shutdown (60s)	Routine scrubber inspections → Structural integrity checks	Leak contained in plant room sump → Water testing required
Water Quenching Base Seal Failure	Loss of water level affecting airlock function	SCADA detects low level → Warning alarm → Controlled shutdown	Routine maintenance of base sealing components	Leak contained in sump → Water must be tested before reuse

4.10 SCADA Environmental Emissions - Gas Seal Failure

4.10.1 Failure Scenario: Gas Seal Failure

The Gas Seal in the C1000 system maintains negative pressure inside the furnace, preventing gas release into unintended areas. Key areas where a Gas Seal Failure could occur include:
- Excessive Furnace Pressure (Over-Pressurization)
- Base to Primary Furnace Connection Leak
- Flue Gas Pipe Failure
- Smoke Exhaust Fan Casing Leak

A failure in any of these components may result in pressure loss, emissions deviation, or operational inefficiency.

SCADA Detection & Response

Negative Pressure Sensor Alarm:
- Furnace operates at 50 Pa negative pressure, with a range of 20-80 Pa.
- If pressure drops below 20 Pa for 20 seconds, a warning alarm is triggered.
- If pressure reaches 0 Pa for 3 seconds, a controlled shutdown is initiated.

Explosion Hatch Activation:
- If overpressure occurs, the explosion hatch (service access door on ducting between C1000 and heat exchanger) acts as a last-resort safety release.

Controlled Shutdown:
- If pressure loss persists, the system shuts down to maintain emissions compliance and operational safety.

4.10.2 Environmental Impact

A pressure loss could lead to pyrolysis gases venting through the furnace structure.

Explosion hatch activation could temporarily release gases but helps regulate overpressure safely.

4.10.3 Mitigation Measures

-Routine negative pressure sensor calibration and inspections.

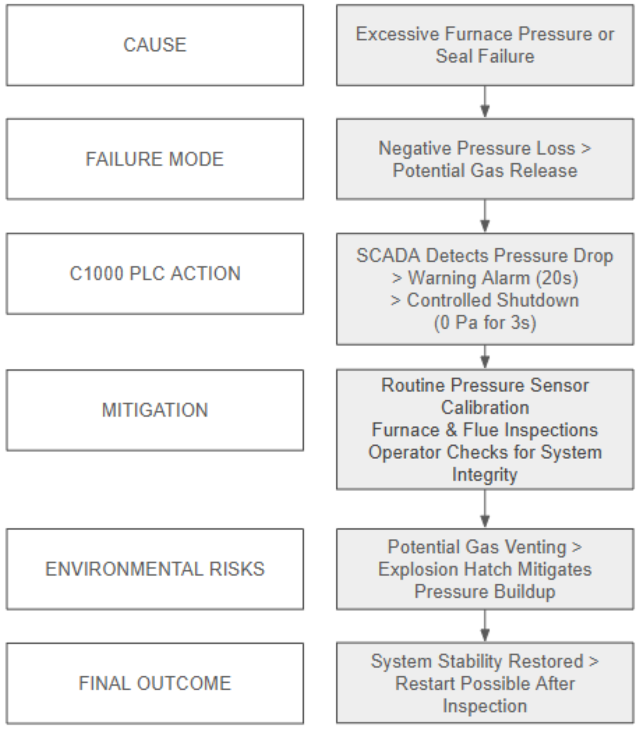
-SCADA continuously monitors furnace pressure.

-Operators inspect explosion hatch integrity and fan casing seals.

-If a gas seal leak occurs, the site must assess external emissions impact and record observations.

4.10.4 Block Diagram - Gas Seal Failure Flowchart

The diagram below represents the failure sequence, PLC action, mitigation strategies, and environmental impact for a Gas Seal Failure scenario.



4.10.5 Decision Matrix - Gas Seal Failure

The table below provides a structured overview of failure causes, failure modes, PLC responses, mitigation measures, and environmental risks associated with gas seal failures.

Cause	Failure Mode	C1000 PLC Action	Risk Mitigation	Environmental Risk
Excessive Furnace Pressure	Gas expansion exceeds negative pressure limit	SCADA detects 0 Pa → Controlled shutdown	Routine negative pressure sensor calibration	Risk of post-pyrolysis gas release
Base to Primary Furnace Leak	Seal failure results in air intake affecting combustion	SCADA detects pressure deviation → Warning alarm	Regular furnace connection inspections	Minor emissions increase
Flue Gas Pipe Leak	Gases escape before scrubbing, affecting emissions	SCADA detects pressure loss → Alarm triggered	Routine inspections of flue gas pipe integrity	Potential increased PM emissions
Smoke Exhaust Fan Casing Leak	Leak reduces pressure control efficiency	SCADA detects fan speed deviation → Alarm	Fan casing inspections and preventative maintenance	Negligible emissions increase due to continued scrubbing