MAES Study Sheet Guide

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Contents

1 List of Acronyms

EPA U.S. Environmental Protection Agency

GHGRP Greenhouse Gas Reporting Program

VRU vapor recovery unit

PRV pressure release valve

OP Operating

NOP non-operating pressurized

NOD non-operating depressurized

PRV pressure relief valve

4SLB 4-stroke lean burn

2SLB 2-stroke lean burn

4SRB 4-stroke rich burn

MC Monte Carlo

MAES Mechanistic Air Emissions Simulator

MTBF mean time before failure

MTTR mean time to repair

EF emission factors

AF	activity factors
GC	Gas Composition
LU	liquid unloading
O&G	oil and gas

2 Introduction

This document provides definitions and instructions for completing Mechanistic Air Emissions Simulator (MAES) Study Sheets, one of the key input files required for running MAES. MAES is an updated version of the Methane Emission Estimation Tool (MEET). For details on additional input files, curated emissions data, and activity data, please refer to the main MAES documentation. The content addresses terms found in each tab and includes examples where applicable. Note that this document does not cover equipment operating states; for that information, consult the MAES help documentation at MEET2/README.html, then select "MEET Model Reference" from the left-side menu.

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3 Global Simulation Parameters

This tab contains key simulation parameters to run MAES.

3.1 Simulation Start Date

- Simulation start date.
- Example: 1/1/2021.

3.2 Simulation Duration [Days]

- Simulation duration.
- Units: days.
- Example: 365.

3.3 Number of Monte Carlo (MC) Iterations

- Number of Monte Carlo (MC) iterations to run.
- Example: 100.

3.4 Output Directory Template

- Path where simulation output files generated by MAES will be stored.

3.5 Activity / Emission Factor Name

- This file path leads to a master file, often named "Factors.csv", which stores the paths to datasets containing activity factors (AF) and emission factors (EF) for different equipment types. These EF and AF are essential for accurately estimating emissions in the simulation. In the Study Sheet, users are asked to specify a "Factor Tag" within some equipment tabs (e.g., compressors, tanks, etc.). These "Factor Tags" are defined in "Factors.csv" and indicates the files location containing the specific AF and EF relative to it. For instance, you can establish a factor tag using the name of a particular project. When you define this tag in "Factors.csv," you can connect AFs and EFs for all equipment types pertinent to that project.

3.6 Facility Type

- This specifies the type of facility to simulate, offering options of 'Production', 'Midstream', or 'Common'. Once the sector is defined, MAES restricts the usage of irrelevant AF and EF from other sectors. For example, if your Facility Type is 'Production' and your study sheet attempts to utilize EF and AF from a dataset derived from midstream field data, MAES will brake and send an error message. However, a facility type set as 'Common' can utilize factors from both sectors.

4 Facilities

This tab contains information about the facility that is going to be simulated in MAES.

4.1 Facility ID

- Unique and permanent identifier for the facility.
- Example: Facility_A.

4.2 Latitude

- Facility latitude coordinates.

4.3 Longitude

- Facility longitude coordinates.

4.4 Gas Composition References

For an overview about the fields below and how a Gas Composition (GC) file is structured please refet to Section 25.

4.4.1 Leak Gas Composition

- Path to GC file used for the facility. This file is an input for MAES and must be provided in a specific template.
- Example: input/Studies/MEET2/TestCompositionsFF.csv

4.5 Model ID

- A JSON model filename defining the model parameters for the facility. These models are already built-in into MAES.
- Model ID: Facility.json

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5 Source

This tab contains inputs of fluids (condensate, gas, water) from a fixed source to the facility. This tab is typically used to define the source of fluid flows through the facility when a more specific source type is not available. For example, when simulating midstream facilities *Source* is used to define the gas flowing through the facility, and when simulating production a *well* (i.e. wellhead model) is used to define all fluid flows.

5.1 Facility ID

- Unique and permanent identifier for the facility connected to the source.

5.2 Unit ID

- Source unique identifier
- Example: Source_1

5.3 Latitude

- Latitude coordinates of the source location

5.4 Longitude

- Longitude coordinates of the source location

5.5 Oil Production [bbl/day]

- Oil production rate from the source.
- Units: barrels per day
- Example: 10

5.6 Water Production [bbl/day]

- Water production rate from the source
- Units: barrels per day
- Example: 2

5.7 Gas Production [Mscf/day]

- Gas production rate from the source.
- Units: Thousands standard cubic feet per day.
- Example: 100

5.8 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

5.8.1 Flow Gas Composition

- Path to GC file used for this facility.
- Example: input/Studies/MEET2/TestCompositionsFF.csv

5.8.2 Flow Tag

- Specifies an identifier to ensure the accurate matching of gas composition in the GC file for fluid flows.

5.8.3 Leak GC Name

- Specifies an identifier to ensure the accurate matching of gas composition in the GC file for leaks.

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6 Continuous Wells

This tab defines continuous well parameters. Continuous wells are wells that produce continuously and only shut-in during unloading.

6.1 Facility ID

- Unique and permanent identifier for the facility with the continuous well.

6.2 Model ID

- A JSON model filename defining the model parameters for the facility.
- Model ID: Well.json

6.3 Unit ID

- Well unique identifier.
- Example: well_1

6.4 Latitude

- Well latitude coordinates.

6.5 Longitude

- Well longitude coordinates.

6.6 Oil Production [bbl/day]

- Oil rate production of the well per day.
- Units: barrels per day

6.7 Water Production [bbl/day]

- Water rate production of the well per day.
- Units: barrels per day

6.8 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatic actuator type on the well
- The pneumatic count does not need to be specified in the study sheet because it gets AF from "Factors.csv".
- Values: Gas, Air, Electric or Gas Mechanistic.

6.9 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

6.9.1 Component Leak Survey Frequency [days]

- The frequency of well component leak survey in days.
- Note: LDAR surveys are generally done yearly, quarterly, or monthly).
- Units: Days.
- Example: 365

6.9.2 Component Count

- The count of all components in a well that can leak.
- Example: 48

6.9.3 Component pLeak

- The probability of detecting a leaking component in the well at any given time.
- Example: 0.02

6.10 Production Decline Rate

For more detail about production decline rate, please refer to Section 21.

6.10.1 Di per month

- Note: This is a parameter for decline curves, which is not yet implemented on MAES.
- Example: 3

6.10.2 b Hyperbolic

- Note: This is a parameter for decline curves, which is not yet implemented on MAES.
- Example: 0.5

6.10.3 Age Months

- This refers to the time elapsed in months since production started. It is a measure of how long a well has been in production.
- Note: This is a parameter for decline curves, which is not yet implemented on MAES.
- Units: Months

6.11 Pre-Production

Section 22 details the pre-production stage of an oil and gas well.

6.11.1 Simulation Start Stage [Pre-production, Production]

- Specifies the initial state of the simulation; the default value is ”Production”. Setting *Simulation Start Stage* to ”Pre-production” will start the simulation in the planning state, and use the parameters listed below to transition the well through multiple pre-production stages prior to production. Conversely, setting this parameter to ”Production” will start the simulation the production stage of the well’s life cycle, where it will remain for the entire simulation time. When set to “Production”, the user does not need to specify the pre-production columns below.
- Values: Pre-production, Production

6.11.2 Approx Planning Time [days]

- Approximate duration for planning.
- Units: Days.
- Note: in the fields below, all the approximate values are uniform random variables with a +/- 20% window from the specified time.

- Completion Durations Name
- Approx Delay After Completion [days]
- Approx Planning Time [days]
- Approx Delay After Planning [days]
- Approx Delay After Drilling [days]
- Approx Flow Back Time [days]
- Approx Delay After Flow Back [days]

6.11.3 Approx Delay After Planning [days]

- This is the approximate additional time after the initial planning phase that may be required due to unexpected issues.
- Units: Days

6.11.4 Approx Drilling Time [days]

- Approximate duration for drilling.
- Units: Days

6.11.5 Approx Delay After Drilling [days]

- This is the approximate additional time / extension in the project schedule after the completion of the drilling phase.
- Units: Days

6.11.6 Completion Durations Name

- Path to a curated data file that specifies the distribution of well completion duration.
- Example: WellCompletions/Allen2013/DurationsFake.csv
/MEET2/input/Studies/MEET2/WellsTest.xlsx

6.11.7 Approx Delay After Completion [days]

- Approximated buffer time (delay time) after well completion in days. This delay could be due to post-completion work.
- The simulation will pick a random value uniformly distributed within a 20% window around the time specified.
- Example: If the specified number of days is 100, the simulation will randomly select a number within a 20% range of 100 days. This range spans from 80 days to 120 days, including both endpoints.
- Units: Days

6.11.8 Approx Flow Back Time [days]

- The approximate flowback duration.
- Units: Days

6.11.9 Approx Delay After Flow Back [days]

- Approximate buffer time (delay time) after flowback and before production starts.
- Units: Days

6.12 Well Unloading

Section 23 details the well-unloading process.

6.12.1 Optional Unloading [True, False]

- Boolean variable [True/False] that specifies if we want to simulate well-unloading.
- Well unloading is the process of removing fluid from the tubing in a well to reduce the bottomhole pressure at the perforations in the wellbore. This procedure is aimed at enhancing the flow of the well.
- Default: False.
- Values: True/False
- Setting this parameter to False will nullify all the unloading parameters, i.e.:

→ Min Time Between Unloadings
→ Max Time Between Unloadings
→ Unloading Type
→ Weekdays Only
→ LU Shut-In Duration Mim
→ LU Shut-In Duration Max

→ Unloading Duration Min
→ Unloading Duration Max
→ Destination of Unloading Gas

6.12.2 Min Time Between Unloadings [days]

- Minimum time between unloadings.
- Units: Days

6.12.3 Max Time Between Unloadings [days]

- Maximum time between unloadings.
- Units: Days

6.12.4 Unloading Type [Manual, Automatic]

- Specifies whether the unloadings are automatic or manual.
- The default parameter is set to 'Manual'.
- Values: Automatic/Manual

6.12.5 Weekdays Only [Yes, No]

- Specifies whether the unloadings are happening on weekends or weekdays.
- Note: This is a parameter for decline curves (not yet implemented on MAES).
- 'Yes' for weekdays only; 'No' to include weekends.
- Values: Yes/No

6.12.6 LU Shut-In Duration Min [hours]

- Minimum liquid unloading (LU) shut-in duration.
- Units: hours

6.12.7 LU Shut-In Duration Max [hours]

- Maximum LU shut-in duration.
- Units: hours

6.12.8 Unloading Duration Min [hours]

- Minimum unloading duration.
- Units: hours

6.12.9 Unloading Duration Max [hours]

- Maximum unloading duration.
- Units: hours

6.12.10 Destination of Unloading Gas

- Facility ID where the gas is released during unloading.
- Note: This function is not yet implemented on MAES.

6.13 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

6.13.1 Flow Tag

- Specifies an identifier to ensure the accurate matching of gas composition in the GC file for fluid flows.

6.13.2 Leak GC Name

- Specifies an identifier to ensure the accurate matching of gas composition in the GC file for leaks.

6.13.3 Flow Gas Composition

- Path to GC file associated with the facility.

6.14 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in ”Factors.csv”.

7 Cycling Wells

This tab outlines the parameters for cycling wells. Cycled wells operate in multiple modes, including, at a minimum, a shut-in period when underground pressure is allowed to build, and a flowing period when the well produces. There are numerous variations on cycling; MAES implements a basic model consisting of two main states:

- The well is not producing, or shut-in, and no fluid flows are passed to downstream equipment.
- The well creates fluid flows that are passed to downstream equipment at a uniform flow rate.

These two states represent a simplification of more complex behavior seen in field operations. For example, flowing periods in field operations may occur of a period where gas and liquids are produced, followed by a period where gas flows with minimal liquids; this latter period flushes the flowline between the well and surface equipment. MAES does not currently implement this type of behavior. Instead, during the flowing period both liquids and gas flow at a uniform rate.

The cycling implemented in MAES may be the result of automated cycling using plunger lift or similar systems[1], or represent less frequent cycling initiated by personnel onsite. These two cases are differentiated only by the duration of the flowing and shut in periods.

7.1 Facility ID

- Unique and permanent identifier for the facility with the cycling well.

7.2 Model ID

- A JSON model filename defining the model parameters for the facility.
- Example: CycledWell.json.

7.3 Unit ID

- Well unique identifier.
- Example: well_1

7.4 Latitude

- Well latitude coordinates.

7.5 Longitude

- Well longitude coordinates.

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[1] As a visual example of how a plunger lift cycles well, see “PCS Ferguson Plunger Lift Overview” on YouTube™ https://youtu.be/cSB90AuHQtg?si=O0sfn4413qH_Hq3l

7.6 Oil Production [bbl/day]

- Oil rate production from the well.
- Units: barrels per day

7.7 Water Production [bbl/day]

- Water rate production from the well.
- Units: barrels per day

7.8 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on the facility.
- The pneumatic count does not need to be specified in the study sheet because it gets AF from "Factors.csv".
- Values: Gas, Air, Electric, or Gas Mechanistic.

7.9 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

7.9.1 Component Leak Survey Frequency [days]

- The frequency of well component leak survey in days.
- LDAR surveys are usually done yearly, quarterly, or monthly.
- Units: Days.
- Example: 365

7.9.2 Component Count

- The count of all components in a cycling well that can leak.
- Example: 48

7.9.3 Component pLeak

- The probability of detecting a leaking component in the cycling well at any given time.
- Example: 0.00523243 (for a production facility from a wellhead study located at MEET2/input/CuratedData/Wellhead/ComponentLeaks/EmissionFactor_Wellheads_AllStudies.csv [1, 2, 3, 4, 5])

7.10 Pre-Production

Section 22 details the pre-production stage of an oil and gas well.

7.10.1 Simulation Start Stage [Pre-production, Production]

- Specifies the initial state of the simulation; the default value is ”Production”. Setting *Simulation Start Stage* to ”Pre-production” will start the simulation in the planning state, and use the parameters listed below to transition the well through multiple pre-production stages prior to production. Conversely, setting this parameter to ”Production” will start the simulation the production stage of the well’s life cycle, where it will remain for the entire simulation time. When set to “Production”, the user does not need to specify the pre-production columns below.
- Values: Pre-production, Production.

7.10.2 Approx Planning Time [days]

- Approximate duration for planning.
- Units: Days.
- Note: in the fields below, all the approximate values are uniform random variables with a +/- 20% window from the specified time.

- Completion Durations Name
- Approx Delay After Completion [days]
- Approx Planning Time [days]
- Approx Delay After Planning [days]
- Approx Delay After Drilling [days]
- Approx Flow Back Time [days]
- Approx Delay After Flow Back [days]

7.10.3 Approx Delay After Planning [days]

- This is the approximate additional time after the initial planning phase that may be required due to unexpected issues.
- Units: Days

7.10.4 Approx Drilling Time [days]

- Approximate duration for drilling.
- Units: Days

7.10.5 Approx Delay After Drilling [days]

- This is the approximate additional time / extension in the project schedule after the completion of the drilling phase.
- Units: Days

7.10.6 Completion Durations Name

- Path to a curated data file that specifies the distribution of well completion duration.
- Example: WellCompletions/Allen2013/DurationsFake.csv
/MEET2/input/Studies/MEET2/WellsTest.xlsx

7.10.7 Approx Delay After Completion [days]

- Approximated buffer time (delay time) after well completion in days. This delay could be due to post-completion work.
- The simulation will pick a random value uniformly distributed within a 20% window around the time specified.
- Example: If the specified number of days is 100, the simulation will randomly select a number within a 20% range of 100 days. This range spans from 80 days to 120 days, including both endpoints.
- Units: Days

7.10.8 Approx Flow Back Time [days]

- The approximate flowback duration.

  - Units: Days

7.10.9 Approx Delay After Flow Back [days]

- Approximate buffer time (delay time) after flowback and before production starts.
- Units: Days

7.11 Total Liquids Produced [bbl/dump]

- Specifies the total amount of liquids that are dumped per cycle
- Units: barrels per dump.
- Example: 1

7.12 Mean Production Time [s]

- Mean Production Time (MPT) is the average time a well takes to produce a unit of liquids (bbl) before shut-in.
- Units: seconds.
- Example: 60

7.13 Production Time Variation [s]

- Specifies the uncertainty in time around 'Mean Production Time [s]'.
- Units: seconds
- Example: 10.

7.14 Shut In Time Variation [percent]

- Percentage of uncertainty in time around the shut-in duration.
- The shut-in duration is not specified but internally calculated by MAES as a function of total liquids produced per day, total liquids produced per dump, and the mean production time.
- Shut-in duration calculation:

$$\text{Number of Cycles per Day} = \frac{\text{Total Daily Liquid Production}}{\text{Total Liquid Produced per Dump}} \tag{1}$$

$$\text{One Cycle Time (sec)} = \frac{\text{Seconds in One Day}}{\text{Number of Cycles per Day}} \tag{2}$$

$$\text{Shut-in Duration (sec)} = \text{One Cycle Time} - \text{Mean Production Time} \tag{3}$$

- Units: percent.
- Example: 15 (this means a random value within a 15% range around the shut-in duration time will be selected. If the shut-in duration is calculated as 120 sec, that means its variation will be between 102 (85%) and 138 (115%) seconds, including both endpoints).

7.15 Well Unloading

Section 23 details the well-unloading process.

7.15.1 Optional Unloading [True, False]

- Is a on/off switch that specifies if we want to simulate well-unloading.
- Default: False.
- Values: True/False.
- Setting this parameter to False will nullify all the unloading parameters, i.e.:

→ Min Time Between Unloadings
→ Max Time Between Unloadings
→ Unloading Type
→ Weekdays Only
→ LU Shut-In Duration Min
→ LU Shut-In Duration Max
→ Unloading Duration Min
→ Unloading Duration Max
→ Destination of Unloading Gas

7.15.2 Min Time Between Unloadings [days]

- Minimum duration between unloadings.
- Units: Days

7.15.3 Max Time Between Unloadings [days]

- Maximum duration between unloadings.
- Units: Days

7.15.4 Unloading Type [Manual, Automatic]

- Specifies whether the unloadings are automatic or manual.
- This parameter should only be specified if ‘Optional Unloading’ is ‘True’.
- Default: Manual.
- Values: Automatic/Manual.

7.15.5 Weekdays Only [Yes, No]

- Specifies whether the unloadings are happening on weekends or weekdays.
- Use ’Yes’ for weekdays only, and ’No’ to include weekends
- Note: Function not implemented yet.
- Values: Yes/No

7.15.6 LU Shut-In Duration Min [hours]

- Minimum LU shut-in duration.
- Units: hours

7.15.7 LU Shut-In Duration Max [hours]

- Maximum LU shut-in duration.
- Units: hours

7.15.8 Unloading Duration Min [hours]

- Minimum unloading duration.
- Units: hours

7.15.9 Unloading Duration Max [hours]

- Maximum unloading duration.
- Units: hours

7.15.10 Destination of Unloading Gas

- Destination Unit ID of gas that is released during unloading.
- Note: Function not implemented yet.

7.16 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

7.16.1 Flow Tag

- Specifies an identity to ensure the correct matching of gas composition in the GC file for fluid flows.

7.16.2 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.

7.16.3 Flow Gas Composition

- Path to GC file associated with the facility.

7.17 Factor Tag

- Specifies an identity to ensure the correct matching of EF and AF in ”Factors.csv”.

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8 Continuous Separators

MAES models two types of separators commonly found in production operations - continuous and dumping separators. Each type of separator has its own specific tab with the required information clearly outlined, as MAES uses different models for each type. Both types are modeled after physical, gravity-driven, separation processes that separate low density gas from higher density oil (condensate) and water.[2] While models were developed for on-shore production operations, they will often model any separation process with sufficient fidelity, provided the gas composition file is properly constructed to represent the separated gas and fluid streams from the equipment.

The model inputs described in this section are for *continuous* separators, which are managed to maintain constant fluid levels and pressures inside the separation vessel. As a result, fluid entering the separator is balanced at all times with fluid exiting the separator.

The MAES model is a physical simplification of the complex separation process. First, input fluid flows immediately cause exit fluid flows; there is no delay for control operation, surging, residence time, or flashing. In most cases, this is a minor approximation, as it only shifts the production by seconds to minutes earlier than would occur in a physical system. Second, the model assumes perfect fluid level and pressure control (when operating normally); there is no deadband in throttling level controls or change in temperature as fluid flows into the separator change.

Typical field equipment simulated by this model include bulk separators with throttled exit valves and harp' type separators. In practical terms, separators later in the separation train at a larger well pad (e.g. vapor recovery towers or long-residence time heater-treaters) may be approximated by this continuous separator model.

The continuous separator model is often utilized for the first stages of separation after a cycling well model. While separators in these applications are often cycling separators, the cycling of the well causes flow through the continuous separator to also cycle, reducing the need to simulate the cycling fill-then-dump action in the dumping separator model. While this is an approximation, it produces realistic changes in downstream fluid flow and emissions, without the additional computational overhead of the dumping separator model.

In separators, emissions may also result from pneumatic actuation. These pneumatic emissions can be modeled either through the traditional EF times AF approach or a mechanistic method, where actuations are based on equipment state but emissions are still estimated using an EF, as explained in section 12. In the traditional model, pneumatic emissions are calculated by multiplying EF and AF for each second of the simulation. In mechanistic modeling, *continuous pneumatics* emit constantly, whereas *intermittent pneumatics* emit only during actuation.

A continuous separator operates in two states: operating or stuck dump valve. Intermittent pneumatics emit during state transitions and in response to input flow rate changes, referred to as "pseudo state changes." For intermittent pneumatics, emissions occur for less than 3 minutes during normal flow variations, in compliance with EPA standards [6]. However, during continuous flow, such as from a continuous well, intermittent pneumatics will

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[2] Kimray™provides good examples of separator operation in a series of YouTube™videos; search for the Kimray, Inc channel or “Intro to 2-Phase & 3-Phase Separators [Oil & Gas Training Basics]”

not emit unless the separator changes states (operating to stuck dump valve, or vice-versa). In contrast, cycling wells cause periodic flow changes in a continuous separator, leading to more frequent pneumatic emissions. Continuous pneumatics emit continuously, regardless of pseudo state changes.

8.1 Facility ID

- Unique and permanent identifier for the facility with the continuous separator.

8.2 Unit ID

- Unique identifier for the continuous separator.
- Example: sep_stage1_1, sep_stage2_1.

8.3 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

8.3.1 Component Leak Survey Frequency [days]

- The frequency of the separator's component leak survey.
- LDAR surveys are done yearly, quarterly, or monthly.
- Units: days.
- Example: 365

8.3.2 Component Count

- The count of all components in a continuous separator that can leak.
- Example: 62

8.3.3 Component pLeak

- The probability of detecting a leaking component in the separator at any given time.
- Example: 0.00523243 (from a production facility from a wellhead study MEET2/input /CuratedData/Wellhead/ComponentLeaks /EmissionFactor_Wellheads_AllStudies.csv [1, 2, 3, 4, 5])

8.4 Dump Valve

This subsection outlines the parameters needed to model the dump valve failure condition, which is detailed in Section 24.

8.4.1 Stuck Dump Valve Component Count

- Count of stuck dump valve components
- Example: 1 dump valve per separator.

8.4.2 Stuck Dump Valve pLeak

- Probability of the dump valve getting stuck open.
- Example: 0.0057
- Note: If we assume that the Mean Time to Repair (MTTR) of a stuck dump valve is 10.5 days, we can calculate the Mean Time Between Failures (MTBF) by:

$$\mathrm{MTBF} = \mathrm{MTTR} \times \left(\frac{1 - \mathrm{p_{Leak}}}{\mathrm{p_{Leak}}} \right) \tag{4}$$

In this case, we would have an MTBF of 1832 days. This means there will be one stuck dump valve at approximately every 5 years.

8.4.3 Stuck Dump Valve Failure Duration Min [days]

- Specifies the minimum duration of the dump valve failure.
- Units: days.

8.4.4 Stuck Dump Valve Failure Duration Max [days]

- Specifies the maximum duration of the dump valve failure. The 'Stuck Dump Valve Failure Duration Max' plus the 'Stuck Dump Valve Failure Duration Min', divided by two is the Mean Time to Repair (MTTR).
- Units: days.

8.5 Fraction of Flash Released

- Path to the file containing the fraction of all gas in the separator released through a stuck dump valve to the next downstream equipment (i.e., primary equipment), which is the subsequent equipment in the facility where the gas flashes are channeled. The remaining gas goes to the gas sales / pipeline.
- MAES draws from the histogram distribution in this file. The default file contains fractions generated by reanalyzing data from a study made by Omara et al. [7].
- Example: MEET2/input/CuratedData/FlashFractions/FlashFractionsTest.csv

8.6 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on the continuous separator.
- Values: Gas, Air, Electric, or Gas Mechanistic.

8.7 Primary Water Takeoff Ratio

- Specifies a fraction of total water that goes to the primary downstream equipment.
- Example: Consider the facility depicted in Figure 1. The first stage separator is connected to a water tank (primary flow) and a second stage separator (secondary flow). If the "Primary Water Takeoff Ratio" = 0.75, 75% of the water goes to the water tank and the remaining 25% goes to the second stage separator. The primary and secondary flows are defined in the

FFLinks tab (secondary IDs), see Section 18.

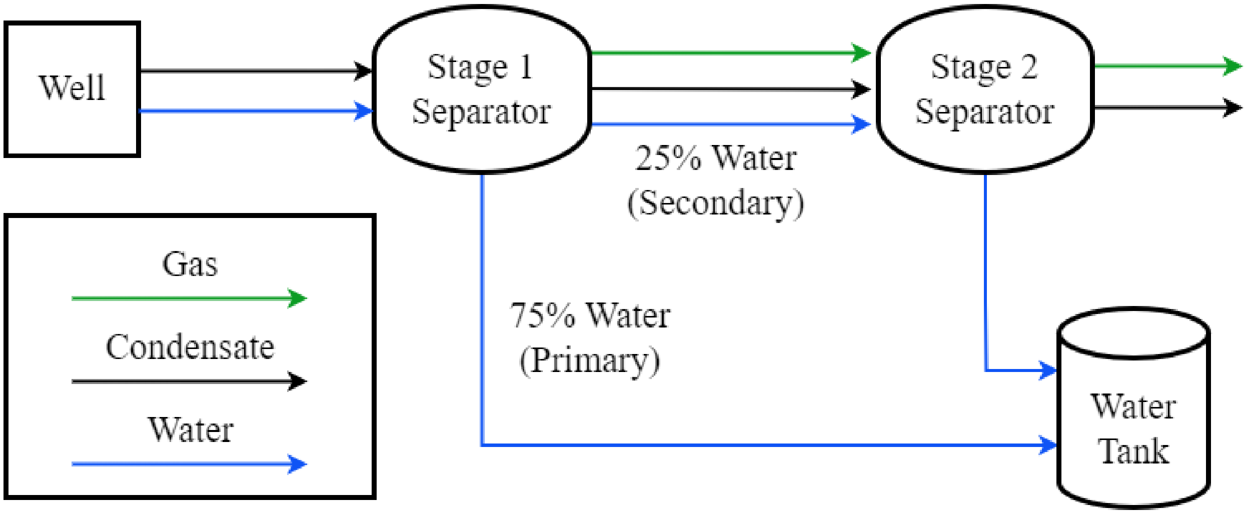

Figure 1: Fluid Flows Diagram

8.8 Model ID

- A JSON model filename defining the model parameters for the separator.
- Model ID: ContinuousSeparator.json.

8.9 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

8.9.1 Flow GC Tag

- Specifies an identity to ensure the correct matching of gas composition in the GC file for fluid flows
- Example: Stage1, Stage2, Stage3 for the first, second and third stage of separation, respectively.

8.9.2 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Well-Condensate.Stage1-Flash for separator stage 1 flash, as specified in the gas composition file.

8.10 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in "Factors.csv".
- Example: wellpad_sep, gef_sep.

9 Dumping Separators

MAES models two types of separators commonly found in production operations - continuous and dumping separators. Both types are based upon physical, gravity-driven, separation processes that separate low density gas from higher density oil (condensate) and water.[3] While models were developed for on-shore production operations, they will often model any separation process with sufficient fidelity, provided the gas composition file is properly constructed to represent the separated gas and fluid streams from the equipment.

The model inputs described in this section are for *dumping* separators, where liquid levels inside the separator are managed by snap-acting dump valves. In general a 3-phase dumping separator contains three valves with corresponding controllers: a pressure regulator or an actively controlled exit gas valve maintains a near-constant pressure in the separator, and two snap-acting liquid 'dump valves' control the water and oil liquid levels in the separator. (Note: Behavior of the separation process is largely driven by the pressure and temperature in the separator. These parameters are used to generate the gas composition file.) As the separator fills, a sensor (often a float) monitors the fluid level, and trips a liquid drain valve when liquid levels exceed a preset value. The valve closes when the liquid level drops below a preset value.

Equipment downstream of a dumping separator sees the fill-drain cycle of the separator as intermittent fluid flows – i.e. periods with no fluid flow interspersed with short periods with much larger fluid flows. While flow rates in field conditions are complex and variable, MAES approximates these flows by uniform rate flows.

While cycled wells and dumping separators may be used together, combining these two models is requires substantial computational resources, due to the number of events incurred in the simulation. For many models, sufficient fidelity is assured by using cycled wells with continuous separators, or by modeling higher-flowing wells with continuous wells, and using dumping separators to produce intermittent fluid flows for downstream equipment.

9.1 Facility ID

- Unique and permanent identifier for the facility with the dumping separator.

9.2 Unit ID

- Unique identifier for the dumping separator.
- Example: sep_stage1_1, sep_stage2_1.

9.3 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

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[3] Kimray™provides good examples of separator operation in a series of YouTube™videos; search for the Kimray, Inc channel or "Intro to 2-Phase & 3-Phase Separators [Oil & Gas Training Basics]"

9.3.1 Component Leak Survey Frequency [days]

- The frequency of the separator's component leak survey.
- LDAR surveys are done yearly, quarterly, or monthly.
- Units: days.

9.3.2 Component Count

- The count of all components in a dumping separator that can leak.
- Example: 62

9.3.3 Component pLeak

- The probability of detecting a leaking component in the dumping separator at any given time.
- Example: 0.00523243 (from MEET2/input/CuratedData/Wellhead /ComponentLeaks/EmissionFactor_Wellheads_AllStudies.csv [1, 2, 3, 4, 5]).

9.4 Dump Volume [bbl]

- The volume of liquid discharged by the dumping separator during each dumping operation.
- Units: barrels.

9.5 Dump Time [s]

- Duration of each dump.
- Note: MAES will automatically increase this time if inlet flow rates are faster than outlet flow rates. Consequently, it will show an error in the console.
- Units: seconds.

9.6 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on the dumping separator.
- Values: Gas, Air, Electric, or Gas Mechanistic.

9.7 Dump Valve

This subsection outlines the parameters needed to model the dump valve failure condition, which is detailed in Section 24.

9.7.1 Stuck Dump Valve Component Count

- Count of stuck dump valve components
- Example: 1 dump valve per separator.

9.7.2 Stuck Dump Valve pLeak

- Probability of the dump valve getting stuck open.
- Example: 0.0057
- Note: if we assume that the Mean Time to Repair (MTTR) of a stuck dump valve is 10.5 days, we can calculate the Mean Time Between Failures (MTBF) by:

$$\mathrm{MTBF} = \mathrm{MTTR}\left(\frac{1 - \mathrm{p_{Leak}}}{\mathrm{p_{Leak}}}\right) \tag{5}$$

In this case, we would have an MTBF of 1832 days. This means there will be one stuck dump valve at approximately every 5 years.

9.7.3 Stuck Dump Valve Failure Duration Min [days]

- Specifies the minimum duration of the dump valve failure.
- Units: days.

9.7.4 Stuck Dump Valve Failure Duration Max [days]

- Specifies the minimum duration of the dump valve failure. The 'Stuck Dump Valve Failure Duration Max' plus the 'Stuck Dump Valve Failure Duration Min', divided by two is the Mean Time to Repair (MTTR).
- Units: days.

9.8 Fraction of Flash Released

- Path to the file containing the fraction of all gas in the separator released to the next primary equipment, which is the subsequent equipment in a facility where the flashes are channeled. The remaining gas goes to the gas sales / pipeline.
- This file has a histogram distribution, from which MAES selects a random number. The fractions were generated from a study made by Omara et al. [7].
- Example: MEET2/input/CuratedData/FlashFractions /FlashFractionsTest.csv

9.9 Primary Water Takeoff Ratio

- Specifies a fraction of total water that goes to the primary downstream equipment.
- Example: suppose you have a facility depicted in 1. The first stage separator is connected to a water tank (primary flow) and a second stage separator (secondary flow). If the "Primary Water Takeoff Ratio" = 0.75, that means 75% of the water goes to the water tank and the remaining 25% goes to the second stage separator. The primary and secondary flows are defined in the FFLinks tab (secondary IDs), which is detailed in Section 18.

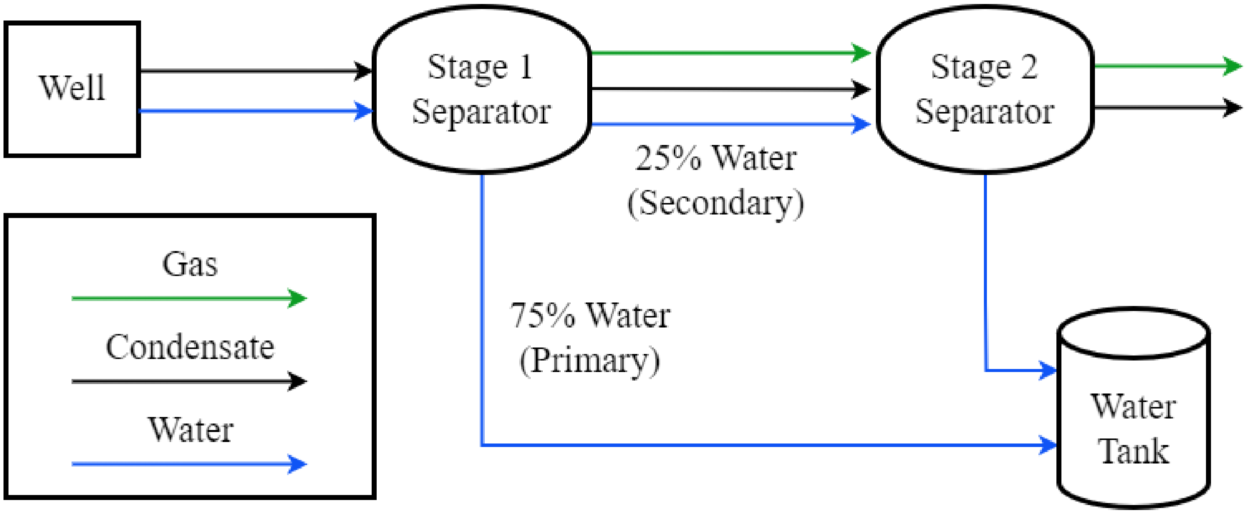

Figure 2: Fluid Flows Diagram

9.10 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

9.10.1 Flow GC Tag

- Specifies an identity to ensure the correct matching of gas composition in the GC file for fluid flows
- Example: Stage1, Stage2, Stage3 for the first, second and third stage of separation, respectively.

9.10.2 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Well-Condensate.Stage1-Flash for separator stage 1 flash, as specified in the GC file.

9.11 Model ID

- A JSON model filename defining the model parameters for the separator.
- Model ID: DumpingSeparator.json.

9.12 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in Factors.csv.
- Example: wellpad_sep, gef_sep.

---

10 Dehydrators

This tab defines parameters for dehydrators. Dehydration units are used to remove water from natural gas flow to meet gas pipeline specifications. US specification are 7 lb/MMSCF (0.11 g/m^3) while the Canadian specification is 4 lb/MMSCF (0.064 g/m^3).

Operation of dehydrators is complex, and the reader is encouraged to refer to an appropriate reference text[4]. In short, wet natural gas is contacted with lean glycol in counter flow inside a contactor. The glycol rich in water from the contactor is routed through several vessels to a regenerator where the glycol is heated to drive off the absorbed water. The recovered 'lean' glycol is then recirculated to the contactor tower.

Tri-ethylene glycol (TEG) is widely used as an absorbent in these dehydration units. Other absorbents include ethylene glycol (EG) and diethylene glycol (DEG). In addition to water, other components of the gas being dehydrated are also absorbed by the lean glycol during the contact process. These compounds are driven out of the glycol in the regenerator, entrained with the water removed from the gas. Disposal or escape of these gasses generates one of the emission streams from a dehydrator.

In larger facilities, such as gas plants or large compressor stations, regeneration may be physically separated from the contact tower and associated equipment. For example, a single boiler/regenerator may regenerate glycol for several dehydrator units. MAES considers each contact tower flow separately, with independent emission streams. With the exception of capturing the specific spatial location of the emissions, this simplification should cause few issues with emissions simulation, as emission parameters are dominated by each separate contactor flow.

Stripping gas may be used at the regenerator to aid recovering the glycol at lower temperatures. The gas used for stripping escapes with the water vapor at the still vents hence increasing emission rates. Also, the glycol pump can be operated either electrically or pneumatically by supply gas or instrument air. Gas driven pumps are another emission source from dehydrators.

MAES implements a simplified, mechanistic, dehydrator model that captures the principal emission sources for dehydrators. The model uses a polynomial fit to estimate absorption rates for various gas species, extracted from ProMax, across different temperatures, pressures, and glycol circulation rates.

In addition to the component count and leaks which are associated with all equipment models, the dehydrator model includes emissions from:

- Flash Tank: Some dehydrators have a flash tank (separator) that reduces the pressure of the rich glycol, causing the absorbed gas to flash off. The flashed gas is typically rerouted to the still vent column, used as fuel in the reboiler, sent to an emission control device (e.g., flares or VRUs), or vented to the atmosphere.

- Still Vent: The still vent column is part of the glycol regeneration process, removing water vapor and other components from the glycol. The gas released from the still vent can be vented to the atmosphere or redirected to a recovery system.

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[4] Example: Kidnay, Arthur J., William R. Parrish, and Daniel G. McCartney. Fundamentals of natural gas processing. CRC press, 2019

10.1 Facility ID

- Unique and permanent identifier for the facility with dehydrator.

10.2 Unit ID

- A unique identifier for each dehydrator unit.
- Examples: dehy_1, dehy_2, dehy_n.

10.3 Flash Tank

- If the dehydrator unit contains a flash tank or a separator
- Values: True, False.

10.4 Operating Hours

- Number of hours per year that the dehydrator unit operates.
- Units: hours per year

10.5 Glycol Pump

- Glycol pump driving mechanism source.
- Values: Electric, Gas, Air

10.6 Wet Gas Water Content

- Water content in the inlet wet gas.
- Units: lb/MMSCF

10.7 Dry Gas Water Content

- Water content in the outlet dry gas.
- Units: lb/MMSCF

10.8 Lean Glycol Circulation Rate

- Rate of lean glycol circulation in gallons per minute.
- Units: gallong per minute (gpm)

10.9 Lean Glycol Circulation Ratio

- Gallons of lean glycol needed to be circulated for every pound of water to be removed from the wet natural gas.
- Units: gallons of glycol per pounds of water removed. - Note: this columns is locked, and calculates the circulation ratio based on information provided on columns ”Wet Gas Water Content”, ”Dry Gas Water Content”, and ”Lean Glycol Circulation Rate”.

10.10 Wet Gas Temperature

- Temperature of the inlet wet gas
- Units: Fahrenheit

10.11 Wet Gas Pressure

- Pressure of the inlet wet gas
- Units: psia

10.12 Wet Gas Flow Rate

- Natural gas flow rate at the inlet of the dehydrator unit
- Units: MMscf/D

10.13 Glycol Type

- Glycol type (absorbent) used by the dehydration unit
- Values: TEG, DEG, EG

10.14 Uses NG as Stripping Gas?

- Weather the dehydrator uses natural gas as stripping gas
- Values: True or False

10.15 Stripping Gas Rate

- If the dehydrator uses natural gas as stripping gas, what is the stripping gas flow rate
- Values: SCFM

10.16 Model ID

- A JSON model file defining the model parameters for intermittent pneumatics.
Name: Dehydrator.json

11 Heaters

This tab defines parameters for heaters. Heating units occur in conjunction with many other major equipment units, including separators and gas upgrading equipment. However, combustion sources are often reported to the Greenhouse Gas Reporting Program (GHGRP) and other reporting program separately from the major equipment units. The MAES model supports modeling combustion processes where heat input requirements are known separately from other operational parameters.

They are essential for regulating the temperature of produced fluids, particularly during colder seasons, offering several advantages. They reduce the viscosity of produced oil, aiding in its transportation and processing. Also, they prevent the formation of hydrates, which occur at lower temperatures and could potentially obstruct pipelines and equipment. Additionally, heaters improve the efficiency of the separation process of oil, gas, and water, which typically operates more effectively at higher temperatures.

Combustion in the model is a function of inlet fluid flows, lower heating values and heater power. When heaters are added to a model, some of the inlet flows are used for the combustion process. These combusted emissions will be subtracted before sending the flows to downstream.

11.1 Facility ID

- Unique and permanent identifier for the facility with the heater.

11.2 Model ID

- A JSON model file defining the model parameters for the heater.
- Model ID: Heater.json

11.3 Unit ID

- The unique identifier for each heater unit.
- Examplse: heater_1, heater2, heater3.

11.4 Heater Power [kW]

- Heater rated power.
- Units: kW

11.5 Operating Duration Min [days]

- The minimum duration for which the heater is in operating state.
- Units: days.
- Example: 30

11.6 Operating Duration Max [days]

- The maximum duration for which the heater is in operating state.
- Units: days.
- Example: 90

11.7 Operating Duration Efficiency

- The destruction efficiency of gas combustion during the operating state.
- Example: 0.98 (it may vary depending on the equipment model, size and/or manufacturer).

11.8 pMalfunction

- The probability of transitioning from the operating state to malfunction state.
- Example: 0.85 (you can estimate this probability based on field study observations. This process is described in Section 26).

11.9 Malfunction Duration Min [days]

- The minimum duration for which the heater is in malfunction state.
- Units: days.
- Example: 1

11.10 Malfunction Duration Max [days]

- The maximum duration for which the heater is in malfunction state.
- Units: days.
- Example: 13

11.11 Malfunction Destruction Efficiency

- The destruction efficiency of gas combustion during the malfunction state.
- Example: 0.9 (it may vary depending on the equipment model, size and/or manufacturer).

11.12 pShutIn

- The probability of transitioning from the operating state to shut-in state.
- Example: 0.15 (you can estimate this probability based on field study observations. This process is described in Section 26).

11.13 Shut In Duration Min [days]

- The minimum duration for which the heater is in shut-in state.
- Units: days.
- Example: 1

11.14 Shut In Duration Max [days]

- The maximum duration for which the heater is in shut-in state.
- Units: days.
- Example: 3

---

12 Pneumatics

Pneumatic devices are often used at oil and gas (O&G) sites to control valves and actuators. They can be operated with natural gas, instrument air or electrically. Such devices can be categorized based on how they operate, i.e., intermittent vent or continuous vent. When operated with natural gas, a continuous pneumatic device continuously emit gas to maintain pressure and control, while an intermittent pneumatic emits only during actuations. The U.S. Environmental Protection Agency (EPA) includes in their classification how much gas they release and categorizes them into low bleed, high bleed, and intermittent.

MAES offers two approaches for simulating emissions from pneumatics: traditional methods (using an EF multiplied by AF) or mechanistic models. In some equipment tabs, there's a column labeled 'Actuator Type [Gas, Electric, Air, Equipment Model]' for equipment that may utilize pneumatic actuation (e.g., wells, separators, tanks, etc.).

If the user chooses 'Air' or 'Electric', no emission will occur, since the pneumatic devices are not operated by gas. If they choose 'Gas', pneumatic emissions will be estimated by MAES traditionally (AF x EF), without any state change. However, if the user opts for estimating pneumatic emissions using a specific equipment model for pneumatics, they should input the 'Equipment Model' option. This implies that the pneumatic devices will have their on states (normal and abnormal emissions). Then, they need to populate the tabs "Intermittent Pneumatics" or "Continuous Pneumatics" based on the pneumatic type present in the facility being simulated.

The model for intermittent pneumatics is mechanistically set by the equipment state machine it is attached to, but it still uses the traditional method to estimate emissions.

The model for continuous pneumatics is not set mechanistically and their emissions are estimated traditionally, but it will have state transitions (normal and abnormal) unlike the emissions estimates for the option 'Gas'. A continuous pneumatic device continuously emits gas to maintain pressure and control, while an intermittent pneumatic emits only when they open or close valves. The EPA includes in their classification how much gas they release and categorizes them into low bleed, high bleed, and intermittent.

1. Low bleed: continuous pneumatics with a bleed rate of less than or equal to 6 standard cubic feet per hour (scfh).
2. High bleed: continuous pneumatics having a bleed rate of greater than 6 scfh.

To select low bleed or high bleed continuous pneumatics, the user needs to input relevant factor tags that contains bleed type emission factors.

If the user selects 'Gas' in the 'Actuator Type [Gas, Electric, Air, Equipment Model]' column, populates the 'Intermittent Pneumatics' or 'Continuous Pneumatics' sections, and includes one of these in the 'Master Equipment' tab (which tells MAES what to run), MAES will estimate emissions from pneumatic devices twice: once for the 'Gas' option and once for the 'Equipment Model'. This situation should be avoided.

12.1 Intermittent Pneumatics

12.2 Facility ID

- Unique and permanent identifier for the facility with intermittent pneumatics.

12.3 Model ID

- A JSON model file defining the model parameters for intermittent pneumatics.
- Model ID: InternmittentPneumatics.json

12.4 Unit ID

- A unique identifier for intermittent pneumatics.
- Example: Inter_1.

12.5 Number of pneumatics

- Number of intermittent pneumatics.
- Example: 3

12.6 Intermittent Wait Duration Min [s]

- Minimum wait duration between actuations. - Units: seconds.
- Example: 500 (from Luck et al. [6]).

12.7 Intermittent Wait Duration Max [s]

- Maximum wait duration between actuations. - Units: seconds.
- Example: 3000 (from Luck et al. [6]).

12.8 Abnormal Emissions

12.8.1 Abnormal Intermittent Actuation Emission Duration Min [s]

- Distribution (histogram) for minimum intermittent vent duration.
- Units: seconds.
- Example: 180 [6]

12.8.2 Abnormal Intermittent Actuation Emission Duration Max [s]

- Distribution (histogram) for maximum intermittent vent duration.
- Units: seconds.
- Example: 21600 [6]

12.8.3 Abnormal Emissions pLeak

- The probability of detecting intermittent pneumatic abnormal emissions.
- Example: 0.05

12.8.4 Abnormal Emissions MTTR Min [days]

- The minimum duration to repair abnormal intermittent pneumatic emissions.
- Units: days.
- Example: 20

12.8.5 Abnormal Emissions MTTR Max [days]

- The maximum duration to repair abnormal intermittent pneumatic emissions.
- Units: days.
- Example: 20

12.9 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

12.9.1 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Default-LeakGC.

12.10 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in "Factors.csv".
- Note: we require the use of AF and EF to estimate emissions for pneumatics. While their time of actuation is simulated mechanistically, emissions are still estimated using traditional methods.
- Example: Allen (defined based on field data reported by David Allen's paper on pneumatics. [8]).

12.11 Continuous Pneumatics

12.12 Facility ID

- Unique and permanent identifier for the facility with continuous pneumatics.

12.13 Model ID

- A JSON model file defining the model parameters for continuous pneumatics.
- Model ID: ContinuousPneumatics.json

12.14 Unit ID

- A unique identifier for continuous pneumatics.
- Examples: Cont1, Cont2, Cont3.

12.15 Number of pneumatics

- Number of continuous pneumatics.
- Example: 1.

12.16 Abnormal Emissions

12.16.1 Abnormal Emissions pLeak

- The probability of detecting continuous pneumatics abnormal emissions.
- Example: 0.03.

12.16.2 Abnormal Emissions MTTR Min [days]

- The minimum duration to repair continuous pneumatics abnormal emissions.
- Units: days.
- Example: 20.

12.16.3 Abnormal Emissions MTTR Max [days]

- The maximum duration to repair continuous pneumatics abnormal emissions.
- Units: days.
- Example: 20.

12.17 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

12.17.1 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Default-LeakGC.

12.18 Factor Tag

- Specifies an identity to ensure the correct matching of EF and EF in ”Factors.csv”.
- Note: we require the use of AF and EF to estimate emissions for pneumatics. While their time of actuation is simulated mechanistically, emissions are still estimated using traditional methods. We can use this column to select low bleed and high bleed factors.
- Example: Allen (defined based on David Allen’s paper on pneumatics) [8].

13 Tank Battery

This tab defines parameters for oil and water atmospheric tank batteries. A tank battery is a collection of storage tanks, commonly found at oil and gas sites. They store fluids such as water or oil after the extraction process from wells and subsequent separation stages. These tanks are interconnected by piping and equipped with monitoring and measurement systems to manage the stored fluids effectively. MAES simulates instantaneous flash from these tanks, but not working flash. Instantaneous flashes happen due to a sudden depressurization in the liquids, which causes some of the hydrocarbon liquid to vaporize. Most liquids arriving at the tank are already depressurized, but a small pressure drop from the upstream equipment to the tank's atmospheric pressure can still cause flashes. This flashed gas is the main contributor of tank batteries emissions. Conversely, working flash is not an instantaneous vapor release, but happens over some time period, and is usually caused when oil is exposed to air and mechanical action (e.g., agitation, filling).

Tanks are often equipped with a pressure relief valve (PRV), which protects the tank from explosion in case of a pressure surge. Whenever the pressure in the tank goes beyond a threshold, due to a unexpectedly high pressure of gas, the PRV is activated and releases excess gas to the atmosphere. Another emission source in tanks is due to thief hatches left open. Thief hatches are fittings on top of tanks that can be opened to provide personal access to inside of the unit for a variety of purposes such as assessing the level of liquid and taking samples for analysis. If these hatches are not properly sealed or are left open, flashed gas will emit to the atmosphere.

In MAES, emissions from tanks can be simulated either traditionally (EF x AF) or mechanistically, according to the user preference. If simulated traditionally, it uses EF and AF to estimate emissions for the following types of failures:

- Tank Thief Hatch
- Tank Thief Hatch Large Emitter
- Tank Battery Vent
- Tank Battery Vent Large Emitter

As shown below, each of these failure types have parameters to be set for normal emissions and large emissions. The EF for 'Tank Thief Hatch Large Emitter' and 'Tank Battery Vent Large Emitter' were collected during the GEF study [9] during failure occurrences only.

Alternatively, if the user wants to simulate emissions mechanistically, MAES will set their time and estimate emissions based on the tank states and the fluid flows going through the equipment. In this mode, all emissions from failures are grouped into a category named "Overpressure Vents Large Emitter", with specific parameters to be set, as explained bellow.

13.1 Facility ID

- Unique and permanent identifier for the facility with the tank battery.

13.2 Model ID

- A JSON model file defining the model parameters for the tank battery.
- Model ID: TankBattery.json

13.3 Unit ID

- The unique identifier for each tank battery unit.
- Example: Water_Tank_Battery or Oil_Tank_Battery.

13.4 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on the tank battery.
- Values: Gas, Air, Electric, or Gas Mechanistic.

13.5 Battery type [Condensate Tank, Water Tank]

- Type of the tank battery.
- Values: Condensate Tank or Water Tank.

13.6 Fluid [Water, Condensate]

- Type of fluid in the tanks.
- Values: Water (for water tank battery) or Condensate (for condensate tank battery).

13.7 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

13.7.1 Component Count

- Number of all components in a tank battery that can leak.
- Example: 50

13.7.2 Component Leak Survey Frequency [days]

- The frequency of tank battery component leak survey.
- LDAR surveys usually are done yearly, quarterly, or monthly.
- Units: Days.
- Example: 365

13.7.3 Component pLeak

- The probability of detecting a leaking component in the tank battery at any given time.
- Example: 0.005

13.8 Number of Thief Hatches

- Specifies the number of thief hatches, which also implies the number of tanks in a tank battery.
- Example: 3 (in case a water tank battery has 3 tanks).

13.9 Number of Vents

- Number of vents on a tank battery.
- Vent Configurations: 1) Single Vent per Tank: This is a common configuration where each tank in a battery has its own vent. This design allows for more precise control and monitoring of emissions from each tank; 2) Common Single Unit Vent for Tank Battery: In this setup, multiple tanks in a battery are connected to a single vent. This design can be more economical and easier to maintain, but it may offer less control over emissions from individual tanks; 3) One Vent per Facility for Tank Battery with Multi-Unit Vent: This implies a larger-scale setup where multiple tanks across the facility are connected to a single vent system. This approach is typically used in larger facilities where space and operational efficiency are key considerations or for facilities that have controlled tanks where flashed gas is routed to flares or vapor recovery unit (VRU)s.
- Note: Generally, there is 1 vent per tank battery with a common single unit vent or 1 vent per facility for tank battery with multi-unit vent.

13.10 Mechanistic Emissions Flag [True, False]

- A switch to choose between traditional and mechanistic emissions for tank batteries. If this field is set to FALSE, MAES will model the tank battery with traditional emissions, reading the AF and EF correspondent to the tag set in 'Factor Tag' column to estimate the emissions. When tanks are modeled with traditional emissions, MAES will utilize information from the following parameters defined in the study sheet:

- Tank Thief Hatch
- Tank Thief Hatch Large Emitter
- Tank Battery Vent
- Tank Battery Vent Large Emitter

- In case this field is set to TRUE, MAES will model the tank battery with mechanistic emissions, which depend on the fluids throughput and equipment state. When tanks are modeled with mechanistic emissions, MAES will utilize information from the following parameters defined in the study sheet:

- Overpressure Vents Large Emitter

This single mechanistic model called "Overpressure Vents Large Emitter" combines overpressure vents (normal and large emission), thief hatch (normal and large emission) and PRV leaks.
- Values: True or False.

13.11 Traditional Emissions Estimates

13.11.1 Tank Thief Hatch MMTR min [days]

- The minimum duration for repairing a thief hatch leak.
- Units: Days.
- Example: 0

13.11.2 Tank Thief Hatch MMTR max [days]

- The maximum duration for repairing a thief hatch leak.
- Units: Days.
- Example: 365

13.11.3 Tank Thief Hatch Pleak

- The probability of detecting a leaking thief hatch component at any given time.
- Example: 0.34167 (according to the GEF study: MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Tank Thief Hatch.csv.[9]).

13.11.4 Tank Battery Vent MTTR min [days]

- The minimum duration for repairing a tank battery vent.
- Unit: Days.
- Example: 0

13.11.5 Tank Battery Vent MTTR max [days]

- The maximum duration for repairing a tank battery vent.
- Units: Days.
- Example: 365

13.11.6 Tank Battery Vent pLeak

- The probability of detecting a tank battery vent at any given time.
- Example: 0.14961 (according to the GEF study: MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Tank Common Multi-Unit Vent.csv.[9]).

13.11.7 Tank Thief Hatch Large Emitter MMTR min [days]

- The minimum duration for repairing a thief hatch large emitter leak.
- Units: Days.
- Example: 3

13.11.8 Tank Thief Hatch Large Emitter MMTR max [days]

- The maximum duration for repairing a thief hatch large emitter leak.
- Units: Days.
- Example: 7

13.11.9 Tank Thief Hatch Large Emitter pLeak

- The probability of detecting a thief hatch large emitter at any given time.
- Example: 0.003984 (from GEF study: MEET2/input/CuratedData
/Midstream/GEFCombinedMidstream/EmissionsData
/GEFC_EF_Tank Thief Hatch Large Emitter.csv.[9]).

13.11.10 Tank Battery Vent Large Emitter MTTR min [days]

- The minimum duration for repairing a tank battery vent large emitter.
- Unit: Days.
- Example: 3

13.11.11 Tank Battery Vent Large Emitter MTTR max [days]

- The maximum duration to repair a tank battery vent large emitter.
- Units: Days.
- Example: 7

13.11.12 Tank Battery Vent Large Emitter pLeak

- The probability of detecting a tank battery vent large emitter at any given time.
- Example: 0.022727 (from the GEF study: MEET2/input
/CuratedData/Midstream/GEFCombinedMidstream/EmissionsData
/GEFC_EF_Tank Multi-Unit Vent Large Emitter.csv.[9]).

13.12 Mechanistic Emissions Estimates

13.12.1 Overpressure Vents Large Emitter MTTR min [days]

- The minimum duration for repairing overpressure vent large emitters.
- Units: Days.
- Example: 1

13.12.2 Overpressure Vents Large Emitter MTTR max [days]

- The maximum duration for repairing overpressure vents large emitters.
- Units: Days.
- Example: 15

13.12.3 Overpressure Vents Large Emitter pLeak

- The probability of detecting an overpressure vent large emitter at any given time.
- Example: 0.0188
- Note: If you have pLeak, you can calculate the Mean Time Between Failure (MTBF) or vice-versa. The following example shows how to estimate MTBF from pLeak:

$$\text{Mean Time to Repair (MTTR)} = \frac{\text{MTTR}_{\text{min}} + \text{MTTR}_{\text{max}}}{2} \tag{6}$$

$$\text{MTBF} = \text{MTTR}\left(\frac{1 - \text{p}_{\text{Leak}}}{\text{p}_{\text{Leak}}}\right) \tag{7}$$

For a pLeak of 0.0188 and MTTR = 8 days, MTBF = 418 days. This means that for a pLeak = 0.0188, it takes on average 418 days for the tank battery to have an overpressure vent large emitter event.

13.13 PRV Threshold [scfh]

- The inlet flow rate at the tank battery that causes the tank's PRV to open. Flow rates are used here instead of pressure for the threshold because MAES does not simulate pressures.
- Units: scf/h

13.14 Max Downstream Equipment Capacity [scfh]

- The maximum achievable flow rate directed into the primary equipment (e.g., flare) from the tanks. Any excess gas beyond this capacity is released through the tank battery PRV.
- Units: scf/h.
- Note: You can estimate the "Max Downstream Equipment Capacity" with the formula below. This calculation considers the daily oil production [bbl/day], the gas release per barrel of oil [scf/bbl], the conversion from daily to hourly rates, and the safety factor, which reflects the capacity of the flare system relative to the inlet flow:

$$\text{Inlet Flow} = \left(\frac{\text{Oil Production} \times \text{Flashed Gas per Barrel}}{24\,\text{hours}}\right) \times \text{Safety Factor} \tag{8}$$

For example, if the facility produces 1125 bbl/day, and the tank releases 96 scf of gas per barrel, the total gas sent to the flare is calculated as follows for a Safety Factor of 2:

$$\text{Inlet Flow} = \left(\frac{1125 \times 96}{24}\right) \times 2 = 9000\,\text{scf/h} \tag{9}$$

13.15 Tank Inlet Flow at Max Downstream Equipment Capacity [scfh]

- The tank battery's inlet flow value when the primary equipment downstream of the tank, such as flares, reaches its maximum flow capacity. - Units: scf/h.
- Example: Suppose we have the "PRV Threshold" set to 3000 scf/h, "Max Downstream

Equipment Capacity" at 9000 scf/h, and "Tank Inlet Flow at Max Downstream Equipment Capacity" at 10,000 scf/h. This means that when there are 10,000 scf/h flowing into the tank battery, the flare will be operating at its maximum combustion capacity, which is 9000 scf/h. Consequently, the remaining 1000 scf/h will be discharged into the atmosphere through the PRV.

13.16 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

13.16.1 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Well-Water.Stage1-Water.Stage2-Water.Tank-Flash.

13.17 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in "Factors.csv".
- Example: wellpad_tanks.

---

14 Compressors

This tab describes parameters for gas compressors, which are devices designed to increase the pressure of the natural gas they receive. They have several applications and can function as midstream compressors, or gas lifts and VRUs in production sites. Midstream compressors are generally located at gathering and boost stations, where they consolidate gas production from multiple sites, and natural gas processing plants. These compressors elevate the gas pressure, enabling its transportation through pipelines over long distances to distribution points. Gas lifts are primarily deployed at production sites to improve the extraction of oil and gas from reservoirs. They inject extracted gas into the reservoir to facilitate fluid displacement and aid in bringing fluids to the surface. VRUs are utilized at production sites to recover flashed gas from separators and storage tanks; they compress the gas to pipeline pressure and redirect it back into the sales line.

14.1 Facility ID

- Unique and permanent identifier for the facility with the compressor.

14.2 Unit ID

- The unique identifier for each compressor unit.
- Examples: Comp_1, Comp_2, Comp_3.

14.3 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

14.3.1 Component Leak Survey Frequency [days]

- The frequency of compressor component leak survey.
- LDAR surveys are usually done yearly, quarterly, or monthly.
- Units: Days.
- Example: 365

14.3.2 Component Count

- Number of all compressor components that can leak (the number of components depends on the size and type of equipment).
- Example: 265

14.3.3 Component pLeak

- The probability of detecting a leaking component in the compressor at any given time.
- Example: 0.0043276 (from the GEF study: MEET2/input

/CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Component.csv [10]).

14.4 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on the compressor.
- Values: Gas, Air, Electric or Gas Mechanistic.

14.5 Compressor Info

14.5.1 Compressor Type [Centrifugal, Reciprocating, Other]

- Type of the compressor.
- Values: Centrifugal, Reciprocating, or Other.

14.5.2 Seal Type [Dry, Wet, Rod Packing]

- Compressor seal type.
- Values: Dry, Wet, or Rod Packing.
- Note: For reciprocating compressors, the seal type should always be "Rod Packing". For centrifugal compressors it could be either "Wet" or "Dry".

14.5.3 Compressor Efficiency

- Efficiency of the compressor.
- Example: 0.8 [11].

14.6 Compressor Driver

14.6.1 Driver Type [Turbine, 2SLB, 4SLB, 4SRB, Electric]

- Compressor driver type.
- Values: Turbine, 2-stroke lean burn (2SLB), 4-stroke lean burn (4SLB), 4-stroke rich burn (4SRB), or Electric.

14.6.2 Driver Rated Power [kW]

- Compressor rated power.
- Units: kW.

14.6.3 Driver Fuel Consumption File

- This field specifies the path to a CSV file containing an equation describing natural gas consumption in relation to the fractional load of the driver/engine. If the user does not have such a file, they can leave this field blank, and MAES will automatically select a fuel consumption equation from its internal Curated Data. It will choose based on a similar engine type with the closest rated power available. If the driver is electric or a turbine, you

can also leave this field blank. MAES currently lacks natural gas fuel consumption data for turbine drivers, and electric drivers do not consume any natural gas. - Note: MAES uses fuel consumption as an indicator to detect whether the driver is overloaded during the simulation. It logs error messages accordingly. Therefore, if this field is left blank, MAES will not be able to determine if the driver is ever overloaded or not.
- Example: MEET2/input/CuratedData/Common/EnginesfuelConsumpEq/
4SRB/4SRB_95HP_G3304_Caterpillar.csv

14.6.4 Driver Efficiency

- Compressor's driver efficiency.
- Example: 0.35

14.7 Exhaust Factors

- Specifies a tag that links to a file containing the driver-specific destruction efficiency.
- Example:

- DestEffAll4SRB (for 4SRB drivers)
- DestEffAll4SLB (for 4SLB drivers)
- DestEffAll2SLB (for 2SLB drivers)
- DestEffAllElectric (for electric drivers)
- DestEffAllTurbine (for turbines)

- Example: MEET2/input/CuratedData/Common/
CompressorDestructionEfficiencies/DestEffAll4SLB.csv

14.8 Load and Operating Time

14.8.1 Average Loading

- Considering a compressor's operational range from 0 to 1 of its rated capacity, this sets the mean value for a normal distribution representing the compressor load.
- Example: 0.9

14.8.2 Std Loading

- Considering a compressor's operational range from 0 to 1 of its rated capacity, this sets the standard deviation value for a normal distribution representing the compressor load.
- Example: 0.035.

14.8.3 Operating Fraction

- The fraction of the total simulation time during which the compressor is actively in operation.
- Example: 0.5 (i.e., if the simulation is conducted over a one-year period, this implies that the compressor is in operation for approximately half a year or 4380 hours).

14.8.4 Total Duration Lower Limit [Hours]

- Minimum duration during which the compressor remains in Operating state before switching to non-operating states.
- Units: Hours.
- Example: 508 hours, from the GEF study [10].

14.8.5 Total Duration Upper Limit [Hours]

- Minimum duration during which the compressor remains in Operating state before switching to non-operating states.
- Units: Hours.
- Example: 1008 hours, from the GEF study [10].

14.8.6 NOP Fraction of NOP/NOD

- The model for a compressor includes five states: start, Operating (OP), non-operating pressurized (NOP), blowdown, and non-operating depressurized (NOD). This field represents the fraction of time when the compressor is not in operation and does not undergo a blowdown process NOP, compared to the combined duration of the NOP and NOD states.

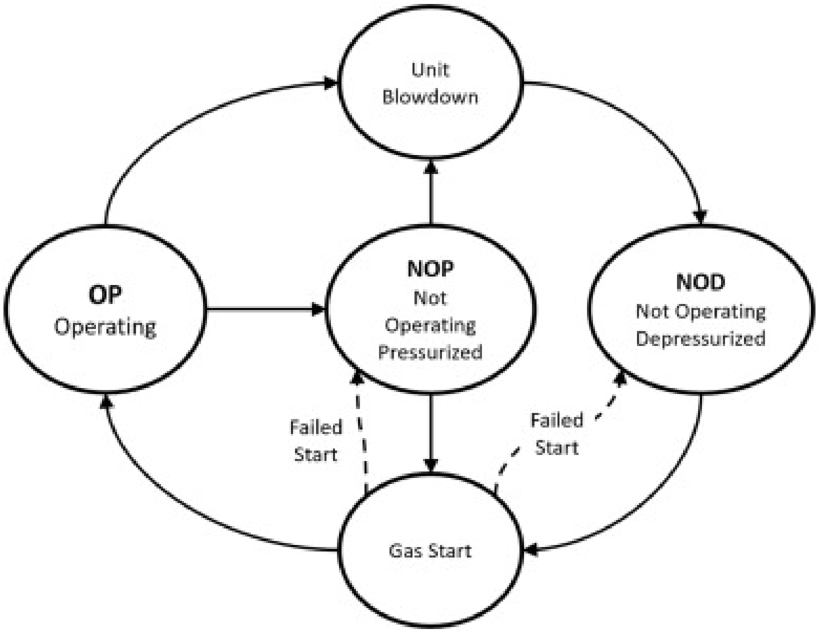

Figure 3: Compressor state machine.

- Example: 0.75 (this means the compressor blowdowns three times a year); 0.01 (this means the compressor blowdowns twelve times a year).
- Note: The user can make use of the Markov Transition Matrix to estimate the number of blowdowns per year for a given "NOP Fraction of NOP/NOD" value. Section 26.3 outlines an example demonstrating how setting "NOP Fraction of NOP/NOD" = 0.75 results in approximately 3 blowdowns per year.

14.9 Blowdowns

14.9.1 Blowdown Event Duration [s]

- Duration of a blowdown event.
- Note: to estimate an average blowdown duration, one can sum the duration of all blowdown events of an engine during a time period and divide it by the number of blowdown events in that period.
- Units: seconds.
- Example: 90

14.9.2 Blowdown Event Emission Volume [scf]

- Volume of whole gas emitted during a blowdown event. The volume of gas released during such an event can vary widely depending on several factors, including the size of the compressor, the pressure of the system, and the specific design of the blowdown system.
- Units: scf.
- Example: 163

14.9.3 Blowdown Vent Component Count

- Number of blowdown vents.
- Example: 1 per compressor according to GEF study [10].

14.9.4 Blowdown Vent MTTR Min [days]

- Minimum duration to repair a blowdown vent component leak.
- Units: days.
- Example: 0

14.9.5 Blowdown Vent MMTR Max [days]

- Maximum duration to repair a blowdown vent component leak.
- Units: days.
- Example: 182.5

14.9.6 Blowdown Vent pLeak

- The probability of detecting a leaking component in the blowdown vents at any given time.
- Example: 0.21635 (from the GEF study MEET2/input/

CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Blowdown Vent.csv) [10].

14.10 Single Unit Vents

14.10.1 Single Unit Vents [TRUE, FALSE]

- A switch to turn on/off single unit vent large emitters. In compressor stations, it's common for operators to have all vents connected together into a single vent.
- Value: True or False.

14.10.2 Common Single-Unit Vent Component Count

- Number of single-unit vent components that can leak. - Example: 1 per compressor according to GEF study [10].

14.10.3 Common Single-Unit Vent MTTR Min [days]

- The minimum duration required to repair a common single-unit vent component that is leaking.
- Units: days.
- Example: 0

14.10.4 Common Single-Unit Vent MTTR Max [days]

- The maximum duration required to repair a common single-unit vent component that is leaking.
- Units: days.
- Example: 182.5

14.10.5 Common Single-Unit Vent pLeak

- The probability of detecting a leaking component in the common single-unit vent at any given time. - Example: 0.083141 (from the GEF study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Common Single-Unit Vent.csv [10]).

14.10.6 Common Single-Unit (Large Emitter) Component Count

- Number of single-unit vent components that can cause large emissions. - Example: 1 per compressor according to the GEF study [10].

14.10.7 Common Single-Unit (Large Emitter) MTTR Min [days]

- The minimum duration required to repair a common single-unit large emitter vent component that is leaking.
- Units: days.
- Example: 0

14.10.8 Common Single-Unit (Large Emitter) MTTR Max [days]

- The maximum duration required to repair a common single-unit large emitter vent component that is leaking.
- Units: days.
- Example: 121.7

14.10.9 Common Single Unit (Large Emitter) pLeak

- The probability of detecting a large emitter component in the common single-unit vent at any given time. - Example: 0.0027855 (from the GEF Study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Single-Unit Vent Large Emitter.csv [10]).

14.11 Seal Vents

14.11.1 Seal Vent Component Count

- Number of seal vent components that can leak.
- Example: 1 Rod Packing vent per compressor according to GEF study [10].

14.11.2 Seal Vent MTTR Min [days]

- The minimum duration for repairing a seal vent leak.
- Units: days.
- Example: 0

14.11.3 Seal Vent MTTR Max [days]

- The maximum duration for repairing a seal vent leak.
- Units: days.
- Example: 182.5

14.11.4 Seal Vent pLeak

- The probability of detecting a leaking component in the seal vent at any given time.
- Example: 0.47816 (from rod packing vent pleak according to the GEF study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Rod Packing Vent.csv [10]).

14.11.5 Seal Vent (Large Emitter) component Count

- Number of seal vents that can cause large emissions.
- Example: 1 Compressor Rod Packing vent per compressor according to GEF study [10].

14.11.6 Seal Vent (Large Emitter) MTTR Min [days]

- The minimum duration for repairing a large emitter seal vent leak.
- Units: days.
- Example: 0

14.11.7 Seal Vent (Large Emitter) MTTR Max [days]

- The maximum duration for repairing a large emitter seal vent leak
- Units: days.
- Example: 121.7

14.11.8 Seal Vent (Large Emitter) pLeak

- The probability of detecting a large emitter component in the large emitter seal vent at any given time.
- Example: 0.0026738 (from a compressor rod packing large emitter vent pLeak according to the GEF study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Rod Packing Vent Large Emitter.csv [10]).

14.12 Starter Vent

14.12.1 Starter Type [Gas, Electric, Air]

- Compressor starter type. The primary function of a starter is to safely and effectively initiate the compressor's operation.
- Values: Gas, Electric, or Air.

14.12.2 Starter Event Emission Duration [s]

- Emission duration during a stater event.
- Units: seconds.
- Example: 3.

14.12.3 Starter Event Emission Volume [scf]

- Whole gas emission volume during a starter event.
- Units: scf.
- Example: 0 (for electric or air starters).

14.12.4 Compressor Starter Vent Component Count

- Number of compressor starter vent components that can leak.
- Example: 1 per compressor according to GEF study [10].

14.12.5 Compressor Starter Vent MTTR Min [days]

- The minimum duration for repairing a compressor starter vent leak.
- Units: days.
- Example: 0

14.12.6 Compressor Starter Vent MTTR Max [days]

- The maximum duration for repairing a compressor starter vent leak.
- Units: days.
- Example: 121.7

14.12.7 Compressor Stater Vent pLeak

- The probability of detecting a leaking component in the starter vent at any given time.
- Example: 0.11268 (from the GEF Study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Compressor Starter Vent.csv [10]).

14.13 Model ID

- A JSON model file defining the model parameters for the compressor.
- Model ID: Compressor.json

14.14 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

14.14.1 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Default-LeakGC

14.14.2 Combustion GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for compressor combustion emissions.
- Example: Default-LeakGC

14.15 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in "Factors.csv".
- Example: gef_comp.

---

15 Flares

This tab provides definitions for parameters associated with flares. They are typically used to combust hydrocarbons released during the natural gas processing rather than venting it to the atmosphere directly. This process helps minimize environmental impact by converting the majority of these gases into less harmful substances such as carbon dioxide and water vapor. Flares are typically connected to storage tanks and separators, to control their emissions. A flare can operate in three distinct states: Operating, Malfunction and Unlit. Section 26 describes the transition process used to calculate the duration of time spent in each of these states after the system reaches equilibrium over a long period of time.

15.1 Facility ID

- Unique and permanent identifier for the facility with the flare.

15.2 Unit ID

- The unique identifier for each flare unit.
- Example: Flare_1, Flare_2, Flare_3.

15.3 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

15.3.1 Component Count

- Number of all flare components that can leak.
- Example: 45.

15.3.2 Component Leak Survey Frequency [days]

- The frequency of flare component leak survey.
- Units: Days.
- LDAR surveys are usually done yearly, quarterly, or monthly.
- Example: 365 days

15.3.3 Component pLeak

- The probability of detecting a leaking component in the flare at any given time.
- Example: 0.00523243 (for production facilities MEET2/input /CuratedData/Production/Wellhead/ComponentLeaks/EmissionFactor _Wellheads_AllStudies.csv [12, 13, 8]).

15.4 Malfunction State

15.4.1 pMalfunction

- This field represents the probability of a flare transitioning from the operating state to the malfunction state (you can estimate this probability based on field study observations. This process is described in Section 26).
- Example: 0.64

15.4.2 Malfunction Duration min[days]

- The minimum duration for which a flare remains in the malfunction state.
- Units: Days
- Example: 1 day (assumption made based on field observations).

15.4.3 Malfunction Duration max [days]

- The maximum duration for which a flare remains in the malfunction state.
- Units: Days
- Example: 7 days (assumption made based on field observations).

15.4.4 Malfunction Destruction Efficiency

- Flare's destruction efficiency when in malfunction state.
- Example: 0.819 (based on field observations for the Bakken region, according to Plant et al. [14]). This value may vary depending on the specific study or the region under analysis.

15.5 Unlit State

15.5.1 pUnlit

- This field represents the probability of a flare transitioning from the operating state to the unlit state (pUnlit = 1 - pMalfunction). You can estimate this probability based on field study observations. This process is described in Section 26.
- Example: 0.36

15.5.2 Unit Duration min [days]

- The minimum duration for which a flare remains in the unlit state.
- Units: Days.
- Example: 1 day (assumption made based on field observations).

15.5.3 Unlit Duration max [days]

- The maximum duration for which a flare remains in the unlit state.
- Units: Days.
- Example: 3 days (assumption made based on filed observations).

15.5.4 Unlit Destruction Efficiency

- Flare's destruction efficiency when in unlit state.
- Example: 0 (there's no combustion of any gas species when a flare is unlit).

15.6 Operating State

15.6.1 Operating Duration min [days]

- The minimum duration for which a flare remains in the operating state.
- Units: Days.
- Example: 30 days (assumption made based on field observations).

15.6.2 Operating Duration max [days]

- The maximum duration for which a flare remains in the operating state.
- Units: Days.
- Example: 90 days (assumption made based on field observations).

15.6.3 Operating Destruction Efficiency

- Flare's destruction efficiency when in operating state.
- Example: 0.975 (based on field observations for the Bakken region, according to Plant et al. [14]). This value may vary depending on the specific study or the region under analysis.

15.7 Model ID

- A JSON model file defining the model parameters for the flare.
- Model ID: Flare.json

15.8 Gas Composition References

For an overview about the fields below and how a GC file is structured please refet to Section 25.

15.8.1 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Default-LeakGC.

15.9 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in ”Factors.csv”.
- Example: gef_flare (from the GEF study [10]).

16 Other

This tab contains simulation parameters for other miscellaneous equipment on a wellpad or compressor station such as piping, metering, and instrumentation.

16.1 Facility ID

- Unique and permanent identifier for the facility with miscellaneous equipment.

16.2 Unit ID

- A unique identifier for miscellaneous equipment.

16.3 Component Leak Model

To learn more details about how component leak models are simulated on MAES, please refer to Section 20.

16.3.1 Component Leak Survey Frequency [days]

- The frequency of miscellaneous equipment component leak survey.
- LDAR surveys are usually done yearly, quarterly, or monthly.
- Units: Days.
- Example: 365 days

16.3.2 Component Count

- Number of all components in miscellaneous equipment that can leak.
- Example: 500

16.3.3 Component pLeak

- The probability of detecting a leaking component in the miscellaneous equipment at any given time.
- Example: 0.0052343 (for compressor station from the GEF study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_YardPiping Component.csv).

16.4 Actuator Type [Gas, Electric, Air, Gas Mechanistic]

- Pneumatics actuator type on miscellaneous equipment.
- Values: Gas, Air, Electric, or Gas Mechanistic.

16.5 Model ID

- A JSON model file defining the model parameters for miscellaneous equipment.
- Example: MiscWellpad.json for a production site and MiscCompressorStation.json for a midstream site.

16.6 Leak GC Name

- Specifies an identity to ensure the correct matching of gas composition in the GC file for leaks.
- Example: Default-LeakGC.

16.7 Facility Common Vent

16.7.1 Facility Common Vent [True/False]

- A switch to turn on/off Facility Common Vent, which is a vent for the entire facility. This is not associated with any specific equipment on site, and usually means it's venting something from upstream.
- Values: True/False.

16.7.2 Common Facility Vent Component Count

- Number of common vents on the facility.
- Example: 1

16.7.3 Common Facility Vent MTTR Min [days]

- Minimum days to repair a common facility vent.
- Units: Days.
- Example: 0

16.7.4 Common Facility Vent MTTR Max [days]

- Maximum days to repair common facility vent.
- Units: Days.
- Example: 182.5

16.7.5 Common Facility Vent pLeak

- The probability of leak on common facility vent.
- Example: 0.073 (for a compressor station from GEF study MEET2/input /CuratedData/Midstream/GEFCombinedMidstream/EmissionsData /GEFC_EF_Station Common Station Vent.csv [10]).

16.7.6 Facility Vent (Large Emitter) MTTR Min [days]

- Minimum time in days to repair 'Facility Common Vent' large emitters.
- Units: Days.
- Example: 0

16.7.7 Facility Vent (Large Emitter) MTTR Max [days]

- Maximum time in days to repair 'Facility Common Vent' large emitters.
- Units: Days.
- Example: 121.7

16.7.8 Facility Vent (Large Emitter) MTTR pLeak

- The probability of leak on 'Facility Common Vent' large emitter. - Example: 0.011364 (for a compressor station from GEF study MEET2/input
/CuratedData/Midstream/GEFCombinedMidstream/
EmissionsData/GEFC_EF_Station Station Vent Large Emitter.csv [10]).

16.8 Facility Components Large Emitter

16.8.1 Facility Components Large Emitter [True/False]

- A switch to turn on/off facility components large emitter. This is more common in midstream sites, where one may find components in the facility piping that is a large emitter due to an exceptional failure condition.
- Values: True/False.

16.8.2 Facility Components (Large Emitter) MTTR Min [days]

- Minimum days to repair facility components large emitter.
- Units: Days.
- Example: 0

16.8.3 Facility Components (Large Emitter) MTTR Max [days]

- Maximum days to repair facility components large emitter.
- Units: Days.
- Example: 182.5

16.8.4 Facility Components (Large Emitter) pLeak

- The probability of leak on facility components large emitter.
- Example: 0.011364 (for a compressor station from GEF study MEET2/input
/CuratedData/Midstream/GEFCombinedMidstream/EmissionsData
/GEFC_EF_Station Components Large Emitter.csv [10]).

16.9 Factor Tag

- Specifies an identity to ensure the correct matching of AF and EF in "Factors.csv".
- Example: gef_misc from GEF study.

---

17 Probes

This tab provides definitions for the parameters necessary to configure probes on MAES. Probes can be connected to specific equipment to measure their fluid flows (including gas, oil, and water).

17.1 Facility ID

- Unique and permanent identifier for the facility with a probe.

17.2 Unit ID

- A unique identifier for the probe.
- Example: probe_c for condensate probe, probe_w for water probe, and probe_g for gas probe.

17.3 Model ID

- A JSON model file defining the model parameters for probe.
- Model ID: Probe.json

---

18 FFLinks

This section details the parameters for equipment interconnection and the definition of fluid flow links (FFLinks). After specifying the parameters for each major piece of equipment in the preceding tabs, it's crucial for MAES to understand the interconnections between equipment units and how the flow of fluids play out.

18.1 Wells

Wells have no incoming fluid flow, and produces condensate and water. Fluid flows can have an identification associated with them referred to as "Secondary IDs" which could provide more information indicating their source or destination. Fluids from wells have no Secondary IDs, but fluids from Separators do, as shown in the next subsection.

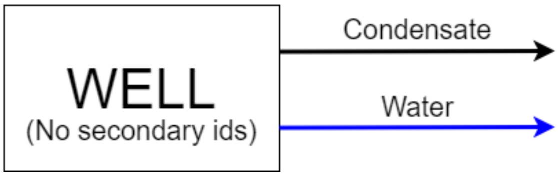

Figure 4: Wells Fluid Flows

18.2 Separators

Separators can receive condensate, water and vapor from an upstream equipment (with the exception of Stage 1 Separators that may not receive vapor flows from being connected to wells). In MAES, flashes are calculated as functions of incoming condensate and water flows. Figure 5 shows the outcoming fluid types and their respective Secondary IDs.

Separators have dump valve designed to release water and oil to the next downstream equipment. A common failure in separators occur when a dump valve gets stuck open, allowing gas to pass to the next stage unintentionally. This often lead to an excess volume of fluids beyond what downstream equipment such as a tank can manage, causing the tank's PRV to open and release the excess gas to the atmosphere.

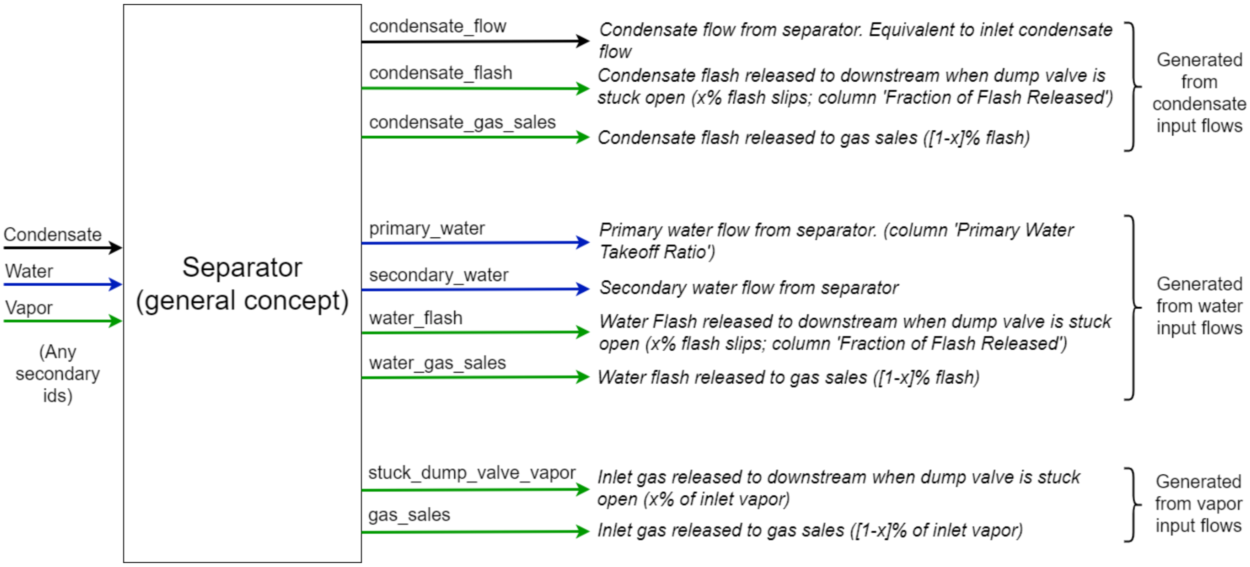

Figure 5: General Separator Fluid Flows

18.2.1 Stage 1 Separators

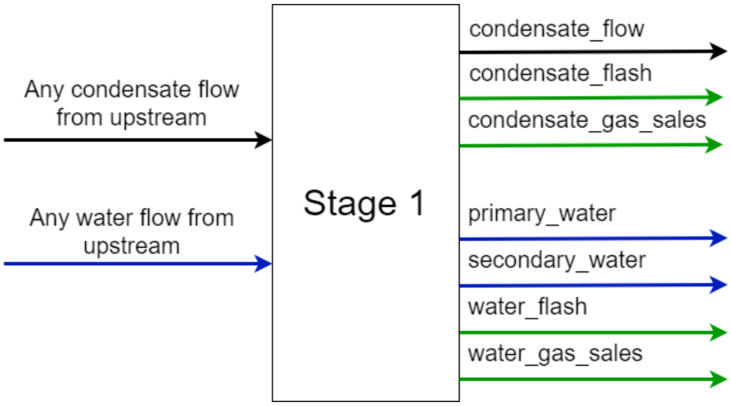

Figure 6: Stage 1 Separator Fluid Flows

18.2.2 Stage 2 Separators

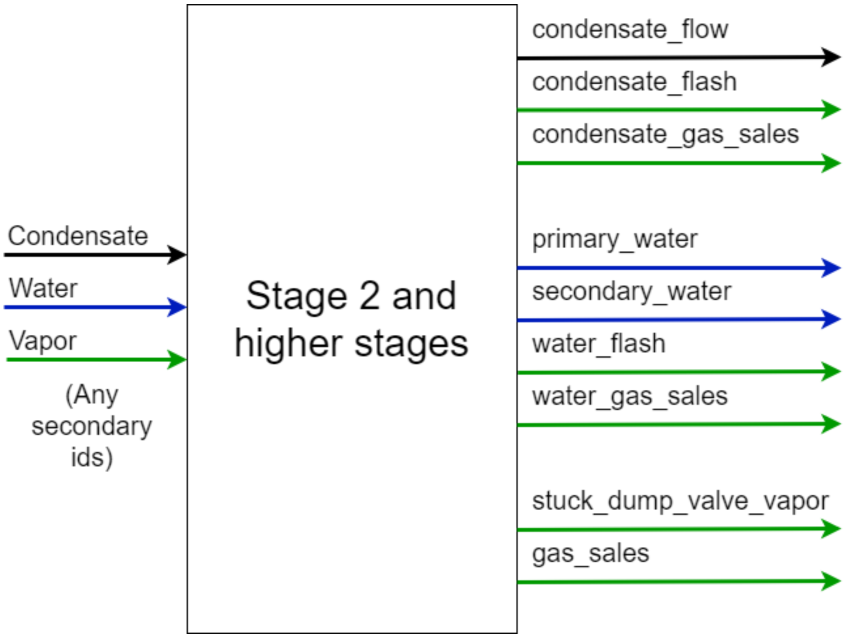

Figure 7: Stage 2 Separator and Higher Separation Stages Fluid Flows

18.3 Tank Battery

Tanks at oil and gas sites are typically used to store oil or water. Most fluids are already depressurized before entering tanks, however, due to a small pressure drop in tanks, some gases may still flash. If a tank is connected to a flare or VRU, these gas flashes can be channeled and controlled, as shown in the schematics below.

18.3.1 Oil Tank Battery

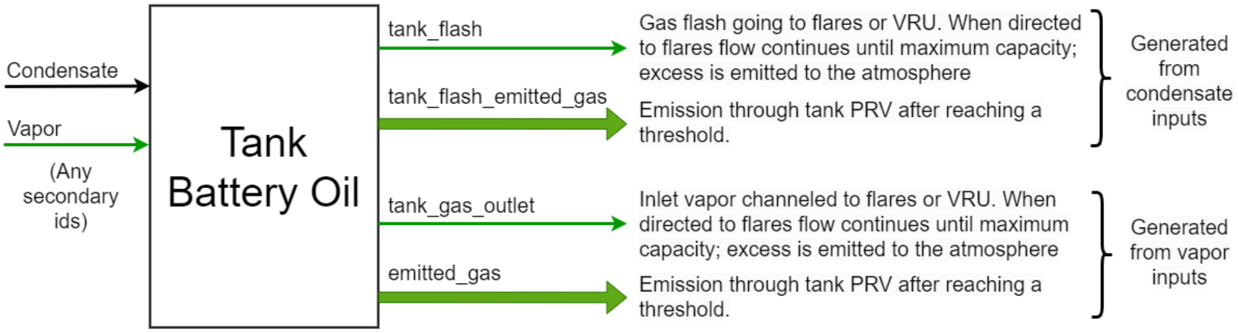

Figure 8: Tank Battery Oil Fluid Flows

18.3.2 Water Tank Battery

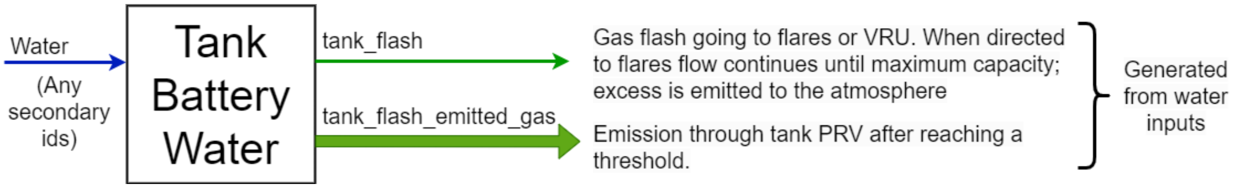

Figure 9: Tank Battery Water Fluid Flows

18.4 Compressors

Compressors intake vapor only. Outlet gas flow can be directed to gas sales when compressed, or to flares if VRUs go offline.

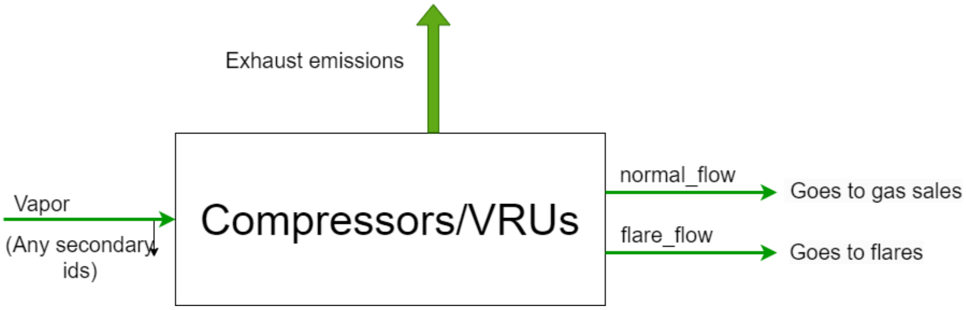

Figure 10: Compressor/VRU Fluid Flows

18.5 Flares

Flares intake vapor only. Gases are combusted, resulting emissions released into the atmosphere.

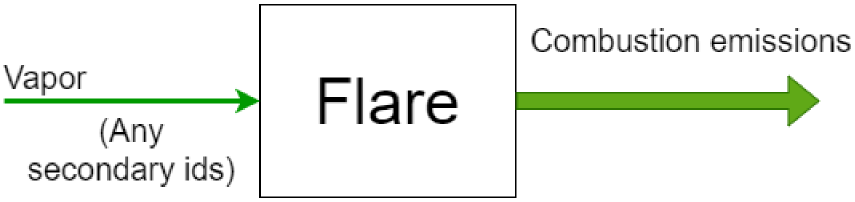

Figure 11: Flare Fluid Flows

18.6 Heaters

Heaters are attached to other equipment such as separators and bypass all fluid flows from this main equipment. They consume gas from the main equipment for operation. Combustion slip is emitted into the atmosphere, while the remaining inlet gas passes to the next downstream equipment.

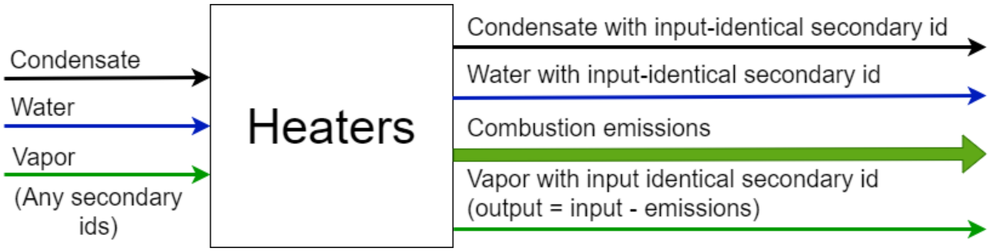

Figure 12: Heaters Fluid Flows

18.7 Pneumatics

Pneumatics operate similarly to heaters, attached to other equipment with the same fluid flows passing through them. The states of the main equipment determine when intermittent pneumatics will actuate, with emission estimates calculated using traditional methods (AF multiplied by EF). However, continuous pneumatics do not behave intermittently and will only use traditional methods for estimations.

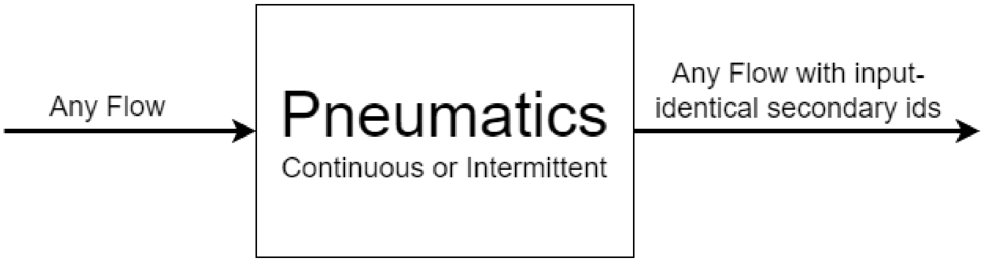

Figure 13: Pneumatics Fluid Flows

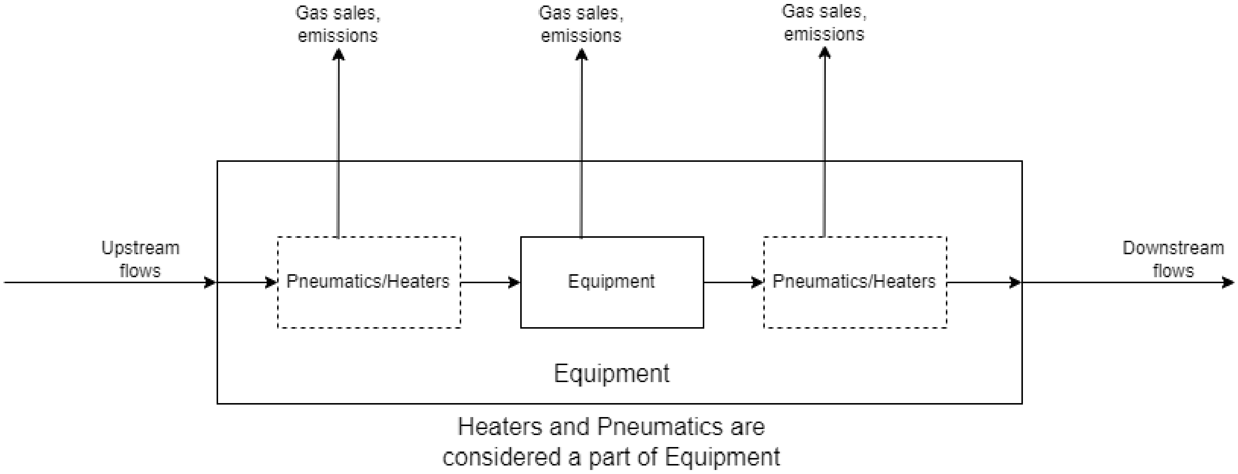

Figure 14: Heaters and Pneumatics Schematic

18.8 Facility Example

The following example illustrates FFlinks for an entire facility, demonstrating the interconnection of fluids among equipment.

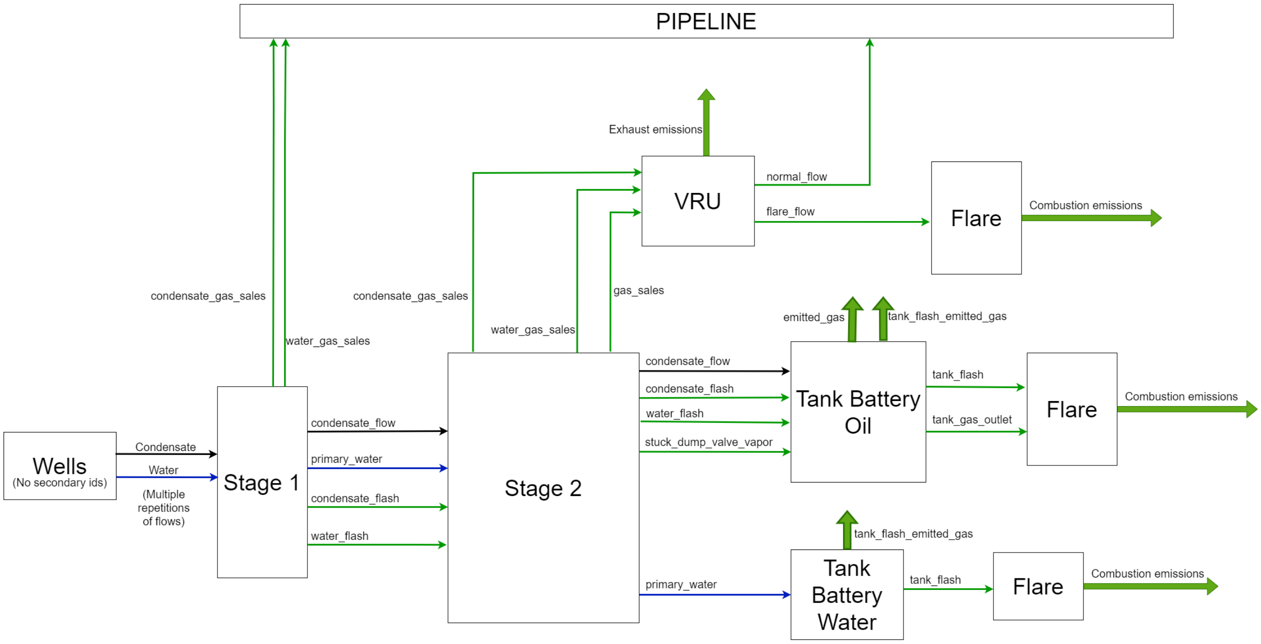

Figure 15: Example Facility Fluid Flows

19 Master Equipment

This tab determines which tabs within the study sheet MAES will run during the site simulation. While you have the freedom to create extra tabs in your study sheet, it's important to note that if these tabs aren't listed in the "Master Equipment" tab, MAES won't incorporate them into the simulation. The "Master Equipment" tab must be filled following the order that the equipment are connected to each other.

19.1 Tab

- Name of equipment tabs the user would like to run on MAES.

20 Component Leak Model

Leaks are modeled at the component-level. A single component may leak more than one time during the simulation. A single component may not have two leaks with overlapping time intervals. The leak timing model generates a list of leaks, where each leak is defined with the following key value pairs:

- `'name'`: Unique name of leak instance
- `'type'`: component type
- `'component'`: component number
- `'tstart'`: time into simulation at which failure occurs and component begins to leak
- `'tstop'`: time into simulation at which repair occurs and component stops leaking

A leak rate model then assigns an emission rate to each leak in the leak list.

20.1 Standard Failure Model

Since MAES is a time-domain simulator, it is necessary to simulate failure conditions such that simulated failures replicate observed failure frequencies from field work. Field observations are almost exclusively snapshot observations of the fraction of components in a given component population in a failed state. The leak model ties the observed failure rate, at a given observation interval, to the time-domain parameters needed by MAES.

For components subject to periodic screening, emitting components from any population of components are discovered during the screening activity. Assuming unbiased sampling, the observed failure frequency is a direct estimate of the probability a component is leaking:

$$\mathrm{p_{leak}} = \frac{\mathrm{n_L}}{\mathrm{n_c}}$$

where $\mathrm{n_L}$ is the number of components in the population found leaking, and $\mathrm{n_c}$ is the total number of components in the screened population.

Since surveys are snapshots in time, to estimate timing of failures, it is necessary to select a probability distribution relating the probability of failure to the time the component is in service. The common assumption for probability of failure is a Poisson process governed by the exponential distribution, which has a cumulative distribution function of

$$\mathrm{p_f} = 1 - \mathrm{e}^{-\lambda \mathrm{t}}$$

Over a sufficiently long Poisson process, the average number of events, N(t), converges to a known value:

$$\lim_{\mathrm{t}\to\infty} \frac{\mathrm{N(t)}}{\mathrm{t}} = \lambda$$

Assuming that the time to repair a leak is substantially smaller than the time between failures (i.e. MTTR $\ll$ MTBF), $\lambda \approx \frac{1}{\mathrm{MTBF}}$, and the probability of failure (i.e. a leak) of a component during a period of length t is:

$$p_f(t) = 1 - e^{-t/\mathrm{MTBF}}$$

For a periodically surveyed component population, p_{leak} is related to MTBF by using the time between surveys, t_s:

$$p_{\mathrm{leak}} = 1 - e^{-t_s/\mathrm{MTBF}}$$

For example, using hours, $t_s = 8760$ would indicate annual inspections. Solving for MTBF:

$$\mathrm{MTBF} = -\frac{t_s}{\log(1 - p_{\mathrm{leak}})}$$

In most cases, components operate without failure for periods much longer than time between surveys, i.e. $t_s \ll$ MTBF. In this case, the first two terms of Taylor series approximation to e^x:

$$e^x \approx 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

can be used to simplify the equation:

$$p_{\mathrm{leak}} = 1 - \left(1 - \frac{t_s}{\mathrm{MTBF}}\right) = \frac{t_s}{\mathrm{MTBF}}$$

Additionally, p_{leak} represents a snapshot observation of the ratio of failed components to total components. In the limit – i.e. observing all times – the fraction of time in a failed state must be equal to p_{leak}:

$$p_{\mathrm{leak}} = \frac{\mathrm{MTTR}}{\mathrm{MTBF} + \mathrm{MTTR}}$$

Therefore, the assumption that failures are represented by a Poisson process ties the probability of observing a leak to the durations of both leaking and non-leaking states. Other useful forms:

$$\mathrm{MTTR} = \left(\frac{p_{\mathrm{leak}}}{1 - p_{\mathrm{leak}}}\right)\mathrm{MTBF}$$

$$\mathrm{MTBF} = \mathrm{MTTR}\left(\frac{1}{p_{\mathrm{leak}}} - 1\right)$$

It is useful to note that for the common case of $p_{\mathrm{leak}} \ll 1$, MTTR $\approx p_{\mathrm{leak}} \cdot$ MTBF; this assumption was already used to set $\lambda = \frac{1}{\mathrm{MTBF}}$, and the underlying assumption in the Poisson process.

This model assumes there are no other interventions occurring that would change the fraction of components leaking. In this case, the MTTR and MTBF values from these equations produce a balanced simulation where the rate of repair of leaks by an undirected inspection and maintenance program is, on average, equal to the rate of failure of components.

20.2 Practical Implementation of Leak Timing

To calculate leak timing the model requires five inputs:

- $N_{components}$ = the total number of components of a specific type to be simulated
- p_{leak} = the probability of a leak at a snapshot in time = the number of components leaking divided by the total number of components observed.
- MTBF = mean time between failures
- MTTR = mean time to repair
- Type = component type

The leak timing model follows the flowchart in Figure 1 to define the start and stop time of leaks in the simulation.

20.3 Active leaks at start of simulation

To determine the number of components leaking at the start of the simulation, random numbers are drawn for each of N_c components and compared to p_{leak}, where rand() produces a uniform random number on the interval $[0, 1]$.

$$n_{t_0} = \sum_{i=1}^{N_c} (rand_i \leq p_{leak})$$

This calculation represents a binomial process with N_c with probability p_{leak}. The Poisson process is the continuous-time limit of a binomial process. Therefore, the startup condition is a discrete time implementation, at $t = 0$, of the same process as the failure model in Subsection 20.1.

20.4 Subsequent leaks

To determine the additional number of components which fail (at least once) during a simulation of duration t_{max}, a random number drawn for each component not leaking at the start of the simulation is compared to $p_f(t_{max}) = 1 - e^{-t_{max}/MTBF}$:

$$n_{t+} = \sum_{i=1}^{N_c - n_{t_0}} (rand_i \leq p_f(t_{max}))$$

The total number of components which will leak (at least once) during the simulation is:

$$n = n_{t_0} + n_{t+}$$

The inverse CDF is used to randomly draw a time to failure from the exponential distribution. Solving the CDF probability expression for t_f:

$$t_f(p_f) = -MTBF \log(1 - p_f)$$

Time before the first failure for each leak is a random draw from the inverse CDF:

$$\mathrm{t_{failure,i,1} = -MTBF\,ln(1 - rand_i)}$$

For each component, i, which will leak during the simulation, the time to repair can be calculated by drawing a new random number and using a similar expression with the mean time to repair, MTTR,

$$\mathrm{\Delta t_{repair,i,1} = -MTTR\,ln(1 - rand_i)}$$

The time at which the repair occurs, is then

$$\mathrm{t_{repair,i,1} = t_{failure,i,1} + \Delta t_{repair,i,1}}$$

At this point a leak is added to the leak list for component i with parameters:

- `'name'` = component type + current leak count
- `'type'` = component type
- `'component'` = i
- `'tstart'`: $\mathrm{t_{failure,i,1}}$
- `'tstop'`: $\mathrm{t_{repair,i,1}}$

20.5 Repeat Failures

If $\mathrm{t_{repair,i,1} < t_{max}}$, the $\mathrm{i^{th}}$ component could fail again before the end of the simulation. Therefore, the process is repeated until a failure results in a repair time that exceeds the length of the simulation. Programmatically, using k as the counter for failures of a single component:

```
k = 1
while ($\mathrm{t_{repair,i,k} < t_{max}}$) do:
    Calculate a new time to failure:
        $\mathrm{\Delta t_{failure,i,k} = -MTBF\,ln(1 - rand_k)}$
    A new time to repair:
        $\mathrm{\Delta t_{repair,i,k} = -MTTR\,ln(1 - rand_k)}$
    And a new 'failure' and 'repaired' times:
        $\mathrm{t_{failure,i,k} = t_{repair,i,k-1} + \Delta t_{failure,i,k}}$
        $\mathrm{t_{repair,i,k} = t_{failure,i,k} + \Delta t_{repair,i,k}}$
end while
```

Each failure is added to the leak list with the following parameters:

- `'name'` = component type + current leak count
- `'type'` = component type
- `'component'` = i
- `'tstart'`: $t_{\text{failure,i,k}}$
- `'tstop'`: $t_{\text{repair,i,k}}$

20.6 Leak Emission Rates

After a leak list is generated including the simulation time at which the leaks occur, an emission rate is assigned to each leak in the leak list using either (a) an emission factor, or (b) a distribution of emission rates.

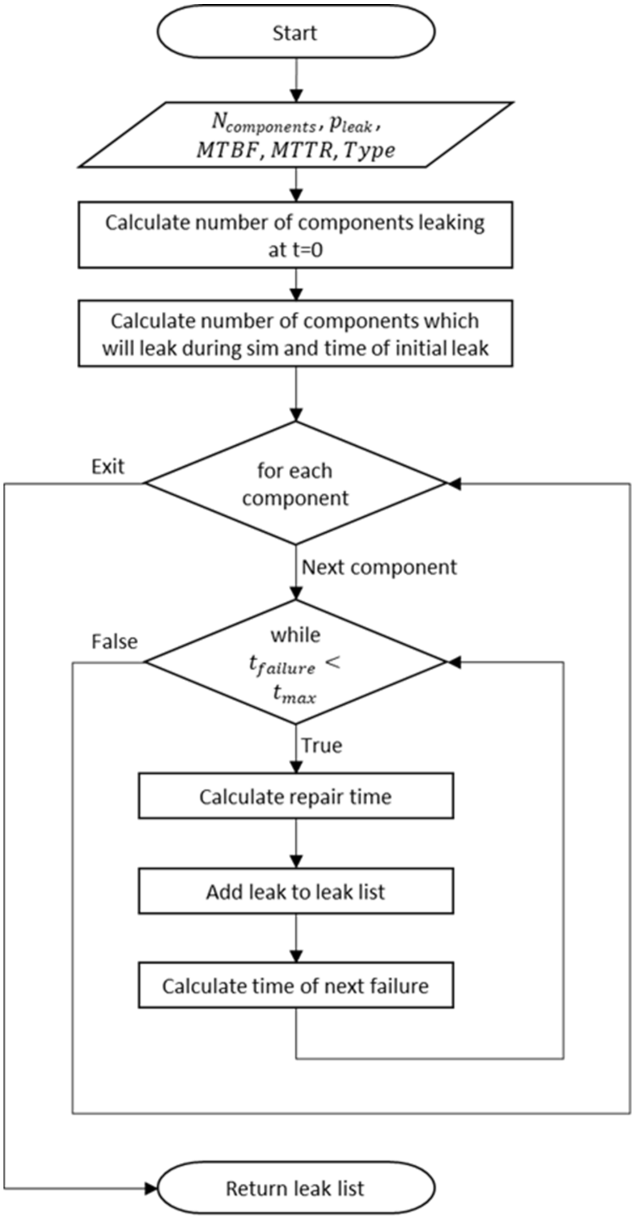

Figure 16: Calculating leak timing

21 Production Decline Rate

As an oil/gas production well becomes older, its production starts to decay with time. Decline curves are curve fits utilized for predicting future production performances and estimating recoverable reserves of oil or gas. A production decline curve can be represented by the equation below, where $\mathrm{q_t}$ is the production rate over time, $\mathrm{q_i}$ is the initial production rate in barrels of oil per day, $\mathrm{D_i}$ is the initial decline rate per year and b the hyperbolic factor:

$$\mathrm{q_t} = \frac{\mathrm{q_i}}{(1 + \mathrm{b} \cdot \mathrm{D_i} \cdot \mathrm{t})^{\frac{1}{\mathrm{b}}}} \tag{10}$$

Hyperbolic is a type of a decline curve to predict future production rates. The b factor is a constant value representing the degree of curvature of the line or how quickly the decline rate decreases.

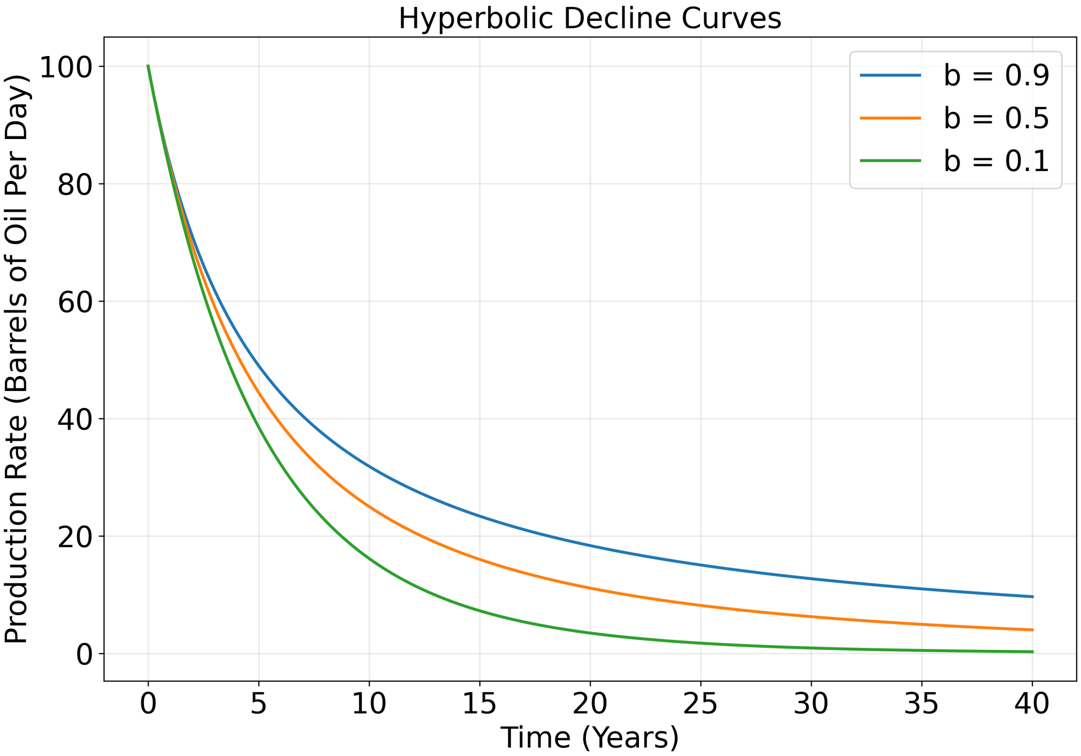

Figure 17: Example of production decline curves for different b factors, considering an initial production rate ($\mathrm{q_i}$) of 100 barrels of oil per day, and an initial decline rate per year ($\mathrm{D_i}$) of 0.2.

22 Pre-Production

Before a well start its operation, there is usually a comprehensive planning phase. This is the time taken to plan and prepare for different phases, such as exploration, drilling, development, completion, or production. Even with the planning phase, unexpected issues or challenges such as logistic issues, regulatory hurdles, and unexpected technical problems may arise, so it is important to also account for these.

Once drilling beings, some time is required for the process to be completed. Delays could also occur in this phase due to post-completion work such as safety assessment, compliance checks, and quality assurance.

The completion of the well involves the casing and cementing of the wellbore, the hydraulic fracturing (fracking) which injects fracturing fluid comprising water, sand, and chemical additives into the wellbore, and the installation of the major equipment at the site.

After the completion phase, comes the flowback stage. The flowback phase is a crucial period during which most of the fracturing fluid that was previously injected into the wellbore to fracture the rock and enhance the flow of oil or natural gas, is returned to the surface.

Once the flowback is completed, the well transitions to the production stage, where oil, water and gas are extracted and processed.

23 Well Unloading

With time, the wellbore accumulates fluids such as water, debris and other fluids, which may affect the flow of hydrocarbons from the reservoir to the well. A common practice in the O&G industry is to remove these fluids from time to time in an operating well to restore production. This process is also done in new wells to help removing fluids from the pre-production stage.

A common methods used for well unloading is the use of a gas lift. In this methods, a compressor injects the produced gas back into the wellbore to increase the reservoir pressure and help bringing undesired liquids to the surface. Another method often used is Swabbing, where a swabbing cup goes into the wellbore. This swabbing tool creates a seal when inserted, and when they are pulled out, the differential pressure helps bringing the fluids to the surface.

24 Dump Valves

Separators have oil and water dump valves that release accumulated fluids once a preset volume is reached. In the continuous and dumping separator models, a single dump valve is used to represent both the oil and water dump valves. If a dump valve fails and gets stuck open, gas is unintentionally released to the next stage. This volume of gas could potentially increase the pressure in downstream equipment like other separators and tanks. Therefore, when a stuck dump valve occurs in a separator, the emissions from that upset condition will likely be seen in the downstream equipment. If this gas exceeds the rated pressure of a tank, for instance, a pressure release valve is open to prevent the separator from exploding.

25 Gas Composition File

For a facility to be simulated in MAES, we need to provide a GC as an input. This CSV file follows a specific template, and is divide into two main sections: metadata and gas composition information.

The metadata section will have information about the number of stages of separation in the facility, their respective pressures [psia], process temperature [F], gas to oil ratio [scf/stock tank barrels], and American Petroleum Institute (API) gravity, which measures how heavy the oil produced at the site is compared to water. If API is greater than 10 the oil is lighter than water, if it is below 10, it is heavier.

The gas composition information includes data for each stage of the facility in various units (e.g., molar fraction, mass per barrel). The gas composition changes depending on various factors, including process temperature, pressure, and facility configuration. Therefore, the gas composition at the first stage of separation, for instance, will differ from that at the second stage, due to the pressure drop.

There are two uses of the GC files. One for fluid flows and another for emissions. In the MAES study sheet, certain tabs will require the stage name (e.g., Stage1, Stage2, Tanks) from the GC file (entered in the ”Flow Tag” field) and the name of a row reference for gas composition (entered in the ”Leak GC Name” field). The ”Flow Tag” field informs MAES about the gas composition of the fluid flows from the major equipment at that stage, while the ”Leak GC Name” field informs MAES about the gas composition of emissions from that equipment. For example, the gas composition at Stage3 (i.e., flashed gas composition from Separator at Stage 3) can be accessed by the name reference ”Well-Condensate.Stage1-Condensate.Stage2-Condensate.Stage3-Flash”.

26 Markov Transition Matrix

A Markov transition matrix is a square matrix that models the probabilities of state changes within a dynamic system. In each row, you can find the probabilities of transitioning from the state represented by that row to other states. Consequently, the sum of each row in a Markov transition matrix should equals tp one. A Markov matrix is typically denoted as $Q(x'|x)$, where Q is the matrix, which includes the conditional probability of a future state x', given the current state x. In other words, the matrix Q comprises the probability of transitioning from the current state x to a future state x', for all possible combinations of x and x'.

26.1 Example 1

Typically, a flare operates in three distinct states: operating, malfunction, and unlit. To establish the failure rates observed in the field, we make the assumption that when the flare transitions from the operating state, it will transition to a malfunctioning state 85% of the time (pMalfunction) and to an unlit state 15% of the time (pUnlit). Conversely, when transitioning from either the malfunction or unlit states, the flare can only return to the operating state, with a probability of 100%.

In the example above, let's assume the duration for which the flare remains in the operating state ranges from 30 to 90 days (MTTR = 60 days), after which it transitions into either a malfunctioning or unlit state. When it transitions to malfunctioning, we'll assume the duration in this state ranges from 1 to 13 days (MTTR = 7 days); when it transitions to the shut-in state, the duration spans from 1 to 3 days (MTTR = 2 days).

Therefore, for this example, we can define the Flare Transition Matrix (Q) and the matrix T, which represents the average time the equipment is expected to spend in each state during a single visit to that state:

$$\mathrm{Q} = \begin{bmatrix} 0.00 & 0.85 & 0.15 \\ 1.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 \end{bmatrix}$$

$$\mathrm{T} = \begin{bmatrix} 60 \\ 7 \\ 2 \end{bmatrix} \begin{bmatrix} \text{Operating} \\ \text{Malfuctioning} \\ \text{Unlit} \end{bmatrix}$$

Each element Q_{ij} represents the probability of transitioning from state i to state j. The first row represents the probabilities of transitioning from the operating state to other states (operating, malfunctioning and unlit, respectively). The second row represents the probabilities of transitioning from the malfunctioning state to other states. The third row represents the probabilities of transitioning from the shut-in state to other states.

After the Markov's transition matrix (Q) is defined, the next step is to find the stable state matrix, which contains the stead-state probabilities for each state. This matrix is found by solving the equation $\mathbf{v}\mathrm{Q} = \mathbf{v}$, where $\mathbf{v}$ is the vector of steady-state probabilities.

The vector of steady-state probabilities in a Markov chain represents the long-term behavior of the system, showing the proportion of time it will spend in each state after a large number of transitions. This equilibrium condition, independent of the initial state, indicates a state of balance where the probabilities of being in each state remain constant.

We rearrange the steady-state condition to form a linear system $(\mathrm{Q}^{\mathrm{T}} - \mathrm{I})\mathbf{v}^{\mathrm{T}} = 0$, where Q^{T} is the transpose of Q, and I is the identity matrix. Then, we add the constraint that the sum of probabilities in **v** equals 1, and solve the linear system to find the vector **v**.

$$\begin{bmatrix} -1.00 & 1.00 & 1.00 \\ 0.85 & -1.00 & 0.00 \\ 1.00 & 1.00 & 1.00 \end{bmatrix} \begin{bmatrix} \mathrm{v}_1 \\ \mathrm{v}_2 \\ \mathrm{v}_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

After solving the linear system, we find the steady-state vector of probabilities as shown below.

$$\begin{bmatrix} \mathrm{v}_1 \\ \mathrm{v}_2 \\ \mathrm{v}_3 \end{bmatrix} = \begin{bmatrix} 0.500 \\ 0.420 \\ 0.075 \end{bmatrix}$$

Now we need to find out the expected total time the system spends in each state after reaching equilibrium We can do that by element-wise multiplying the frequency of visiting each state (as given by the steady-state probabilities) and the average duration of each visit (as given by matrix T):

$$\text{Days in States (D)} = \begin{bmatrix} 60 \\ 7 \\ 2 \end{bmatrix} \odot \begin{bmatrix} 0.5 \\ 0.425 \\ 0.075 \end{bmatrix} = \begin{bmatrix} 30 \\ 2.975 \\ 0.15 \end{bmatrix}$$

Finally, we can calculate the fraction of time spent in each state over a long period, by dividing the number of days in each state by the total number of days in all states:

$$\text{Fraction of Time in States (F)} = \begin{bmatrix} 30/33 \\ 2.975/33 \\ 0.15/33 \end{bmatrix} = \begin{bmatrix} 0.906 \\ 0.090 \\ 0.004 \end{bmatrix}$$

That means, considering an extended period of time, the flare will find itself in operating, malfunctioning and shut-in states 90.6%, 9.0%, and 0.4% of the time, respectively. Subsection 26.3 provides a python script that summarizes all these calculations.

Note: the matrix T is about the duration of a single stay in each state, while matrix D (Days in States) reflects the cumulative time spent in each state over a long period, accounting for both the duration of stays and the frequency of entering those states.

26.2 Example 2

This example shows how to calculate the number of blowdowns per year for a compressor based on hypotetical study sheet definitions for ”NOP Fraction of NOP/NOD”, ”Total Duration Lower Limit [Hours]”, ”Total Duration Upper Limit [Hours]” as 0.75, 508 hours and

1008 hours. These last two numbers are the duration minimum and maximum values in hours that the compressor stays in operating state before transitioning to any non-operating state. This gives an average of 31.5 days ([508 hours + 1008 hours]/24 hours) in the operating state. If we assume that a compressor stays on average 2 days in NOP and 2 days NOD state, we have the following T matrix:

$$\mathrm{T} = \begin{bmatrix} 31.5 \\ 2 \\ 2 \end{bmatrix} \begin{bmatrix} \mathrm{OP} \\ \mathrm{NOP} \\ \mathrm{NOD} \end{bmatrix}$$

Although compressors can operate at five different states (OP, NOP, NOD, Blowdown, Start), we can simplify its operation to OP, NOP and NOD and build the following Markov transition matrix:

$$\mathrm{Q} = \begin{bmatrix} 0.00 & \text{NOP Fraction of NOP/NOD} & (1 - \text{NOP Fraction of NOP/NOD}) \\ 1.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 \end{bmatrix}$$

$$\mathrm{Q} = \begin{bmatrix} 0.00 & 0.75 & 0.25 \\ 1.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 \end{bmatrix}$$

After solving for $(\mathrm{Q}^{\mathrm{T}} - \mathrm{I})\mathbf{v}^{\mathrm{T}} = 0$, we find the steady-state vector of probabilities to be [0.5, 0.375, 0.125]. With that, we calculate the total time the compressor spends in each state over a long period.

$$\text{Days in States (D)} = \begin{bmatrix} 31.5 \\ 2 \\ 2 \end{bmatrix} \odot \begin{bmatrix} 0.5 \\ 0.375 \\ 0.125 \end{bmatrix} = \begin{bmatrix} 15.75 \\ 0.75 \\ 0.25 \end{bmatrix}$$

Subsequently, the fraction of time spent in each state is calculated by:

$$\text{Fraction of Time in States (F)} = \begin{bmatrix} 15.75/16.75 \\ 0.75/16.75 \\ 0.25/16.75 \end{bmatrix} = \begin{bmatrix} 0.9403 \\ 0.0448 \\ 0.0149 \end{bmatrix}$$

This means, the compressor will be in NOD state 1.49% of the time, which is 5.44 days in a year. If the blowdown operation last 2 days, as assumed previously, this gives us approximately $5.44/2 \approx 3$ blowdowns per year.

26.3 Scripts for Markov Calculations

This subsection provides two python scripts to assist with the Markov calculations, depending on the information that the user has available. The first script estimates the fraction of time in each state, after the system reaches equilibrium. For that, that user needs to input the Markov transition matrix (Q) with the probability of switching from one state to another, and matrix T, with the average time the equipment spend in each state after a single visit to that state (before reaching equilibrium). This was the methodology utilized in the previous examples above and is shown in Subsection 26.3.1.

The second script estimates the Markov transition matrix Q, with the probability of switching from one state to another. For that, the user needs to input the observed fraction of time for non-operating states, and the average time the equipment spend in these non-operating states after a single visit to that state (before reaching equilibrium). This calculation process is exemplified in Subsection 26.3.2

26.3.1 Script to Calculate Matrix F from Matrix Q

This is the methodology utilized in the two previous examples in subsections 26.1 and 26.2.

```
import numpy as np

def calculate_steady_state(Q):
I = np.identity(Q.shape[0])
Q_modified = np.copy(Q.T - I)
Q_modified[-1, :] = np.ones(Q.shape[0])
b = np.array([0] * (Q.shape[0] - 1) + [1])
steady_state_vector = np.linalg.solve(Q_modified, b)
print("Vector of steady-state probabilities:", steady_state_vector)
return steady_state_vector

def calc_cumulative_time_in_states(steady_state_vector, T):
D = T * steady_state_vector
fractionTimeInState = D / np.sum(D)
return D, fractionTimeInState

def main():
# Definition of Markov transition matrix (Q)
Q = np.array([
[0.00, 0.85, 0.15],
[1.00, 0.00, 0.00],
[1.00, 0.00, 0.00]
])

# Definition of matrix T, which represents the average time the equipment is expected to
T = np.array([60, 7, 2])  # operating, malfunctioning, unlit

# Calculate the steady-state vector
steady_state_vector = calculate_steady_state(Q)

# Calculate the cumulative time spent in each state after system reaching equilibrium (D
D, fractionTimeInState = calc_cumulative_time_in_states(steady_state_vector, T)
```

```
# Output the results
print("Days in each state:", D)
print("Fraction of time in each state:", fractionTimeInState)


if __name__ == "__main__":
main()
```

26.3.2 Script to Calculate Matrix Q from Matrix F

Often the user does not have the probabilities of going from the current state to a future state Q(x′|x), but has field observations about the Fraction of Time in States (F) instead. This methodology uses that information to estimate these probabilities and build the Markov Transition Matrix (Q). The process is explained as follows.

Let's assume that, from field observations, a flares appear to be malfunctioning 9% of the time, and unlit 0.4% of the time. Also, when they are malfunctioning they remain in that state between 1-13 days (MTTR=7), and when they are unlit they stay in that state for between 1-3 days (MTTR=2 days).

To estimate the probabilities of switching between states and build the Markov transition matrix (Q), we use the steady-state vector of probabilities and the observed field data to minimize the difference between predicted and observed values.

The Python code below summarizes this process.

```
import numpy as np
from scipy.optimize import least_squares


def calculate_steady_state(Q):
I = np.identity(Q.shape[0])
Q_modified = np.copy(Q.T - I)
Q_modified[-1, :] = np.ones(Q.shape[0])
b = np.array([0] * (Q.shape[0] - 1) + [1])
steady_state_vector = np.linalg.solve(Q_modified, b)
return steady_state_vector


def optimize(x, options):
x_malFraction = x[0]
x_opTime = x[1]
Q = np.array([
[0, x_malFraction, 1 - x_malFraction],
[1, 0.00, 0.00],
[1, 0.00, 0.00]
])
```

```
flareStable = calculate_steady_state(Q)
days_each_mode = np.array([
x_opTime,
np.mean(options[’timeMalfunctioning’]),
np.mean(options[’timeUnlit’])
])
days_in_state = days_each_mode * flareStable
fraction_time_in_state = days_in_state / np.sum(days_in_state)
return options[’observedFailures’][1:3] - fraction_time_in_state[1:3]


def main():
# Field data available
options = {
’observedFailures’: np.array([0.906, 0.090, 0.004]),
’timeMalfunctioning’: np.array([1, 13]),
’timeUnlit’: np.array([1, 3])
}

# Perform optimization with initial values of pMalfuction = 0.1 and the Operating time =
result = least_squares(optimize, x0=[0.1, 100], args=(options,))
optimized_values = result.x

# Generate the Q matrix
Q = np.array([
[0, optimized_values[0], 1 - optimized_values[0]],
[1, 0.00, 0.00],
[1, 0.00, 0.00]
])

# Print results
print(f"pMalfunction: {round(optimized_values[0], 4)}")
print(f"Operating Time: {round(optimized_values[1], 4)}")
print("Transition matrix:")
print(Q)


if __name__=="__main__":
main()
```

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