MODULE FOR CO_2 STORAGE IN SALINE AQUIFERS

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CONTENTS

1 SOURCES

The following have also informed the development of the module:

- "Best Practices for Life Cycle Assessment (LCA) of Direct Air Capture with Storage", U.S. Department of Energy, Office of Fossil Energy and Carbon Management
- "Carbon dioxide capture, transportation, and geological storage — Quantification and verification", Standard ISO/TR 27915:2017:
- "Carbon Dioxide Transport, Injection and Geological Storage", Chapter 5 in Volume 2 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories
- "The GHG Protocol for Project Accounting", World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI)
- "A Greenhouse Gas Accounting Framework for Carbon Capture and Storage Projects", Centre for Climate and Energy Solutions
- "Methodology for the quantification, monitoring, reporting and verification of greenhouse gas emissions reductions and removals from carbon capture and storage projects, Version 1.1., published by the American Carbon Registry"Guidelines for Carbon Capture, Transport and Storage", WRI
- "Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard", California Air Resources Board
- "Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities", UNFCCC
- "Commission Implementing Regulation (EU) 2018/2066" of the European Commission, Directorate-General for Climate Action
- "EU Directive on the geological storage of carbon dioxide" of the European Parliament and of the Council

This module is used in combination with the latest version of the following methodologies, modules, and tools:

- *VM00XX Methodology for Carbon Capture and Storage*

Capture Modules

- *VMD00XX: CO_2 Capture from Air (Direct Air Capture)*
- *VMD00XX: CO_2 Capture from Fossil Fuel or Geothermal Based Power and Heat Generation* (under development)
- *VMD00XX: CO_2 Capture from Industrial Processes* (under development)

- *VMD00XX: CO_2 Capture from Oil and Gas Production and Processing* (under development)
- *VMD00XX: CO_2 Capture from Biogenic Sources (BECCS)* (under development)

Storage Modules

- *VMD00XX: CO_2 Storage in Depleted Oil and Gas Reservoirs* (under development)

Other Modules/Tools

- *VMT00XX: Tool for Differentiation between Emission Reductions and Removals in Carbon Capture and Storage Projects* (under development)
- *VMT00XX: Tool for Baseline Quantification and Allocation of Project Emissions in Projects with VCS and non-VCS-CO_2 flows in Carbon Capture and Storage Projects* (under development)

2 SUMMARY DESCRIPTION OF THE MODULE

This module provides procedures and requirements for project activities that store CO_2 in saline aquifers for eligible Carbon Capture and Storage (CCS) project activities under *VM00XX Methodology for Carbon Capture and Storage*.

3 DEFINITIONS

In addition to the definitions set out in the *Program Definitions* of the VCS Program, the following definitions apply to this module:

CO_2 Conditioning
The process of treatment of an incoming CO_2 stream to achieve the required conditions for transport and/or injection and storage of the CO_2 in a CCS project activity. It may include various processes including but not limited to refrigeration, dehydration, desulphurization, deoxygenation, and compression.

Conformance
The degree of agreement between reservoir model predictions and current measured data and performance from the storage reservoir for a geologic carbon storage (GCS) project.

Geological Reservoir
Subsurface body of rock with sufficient porosity and permeability to receive, transmit and contain fluids, particularly super-critical or dense phase CO_2, including areas or zones for expansion and migration of the CO_2 plume defined by the reservoir modelling.

Geological Storage Complex
The geological storage complex consists of the geological reservoir, and either an overlying impermeable seal (or caprock) which prevents the escape of the fluids or other reliable trapping mechanisms.

Intermediate Storage
Intermediate storage includes the processes and equipment on a site that enables temporary storage of CO_2 in transit, during the transfer of CO_2 from one mode of transport to another (e.g., transfer of CO_2 from a pipeline to transport by ship)

Mandatory Monitoring Point
The locations where equipment is required to be in place to measure the volume of CO_2

Non-condensable Gas
Non-condensable gases are gases that do not condense into the liquid phase within a system's operating temperature. They are relevant for geothermal power/heat plants.

Non-VCS-CO_2
The CO_2 captured outside the project boundary of a CCS project activity registered under VCS that is conditioned, transported, or stored using (some of) the facilities of the registered CCS project activity.

Saline Aquifer
An underground water source with total dissolved solids greater than 3,000 mg/L.

Storage Facility
Any facility used for geological storage of CO_2

4 APPLICABILITY CONDITIONS

This module applies to project activities that store CO_2 safely and permanently in saline aquifers as per the criteria and procedures established under the latest version of the *VM00XX Methodology for Carbon Capture and Storage*.

This module is applicable under the following conditions:

1) The project activity injects a CO2 stream for permanent storage into a saline aquifer.

2) The project activity has mandatory monitoring point(s) for CO2 injection downstream of all intermediate storage, compression, or other CO2 stream conditioning (per Section 8.3), and;

3) The project activity has an isolation valve on the wellhead or within 10m of the point where the CO2 stream enters the subsurface by run-of-pipe, to isolate the surface and sub-surface,

This module is not applicable under the following conditions:

1) Project activities that store CO2 with intentions to produce it in the future for any reason.

2) Efficiency improvement projects: Upgrades to existing CCS storage facilities or changes in operational practices leading to improved storage efficiency cannot be registered as a new project activity by itself. For storage projects already registered under VCS, such improvements may occur and would be considered in the calculation of the baseline and the project emissions over the crediting period for that respective project.

5 MODULE BOUNDARY

The module boundary includes the surface facilities and subsurface equipment at the injection site, including the injection and monitoring wells and all monitoring equipment. The boundary also includes the area of review and the extent of the CO_2 plume within the geological storage complex. Projects with a point of custody transfer may use that as the upstream extent of the module boundary.

Commonly used processes to be considered in determining project emissions under this module are:

- Intermediate storage of CO_2
- Final compression and/or conditioning of CO_2 before injection
- Injection pipelines, wellhead piping, valves, and monitoring instrumentation
- SCADA/communication equipment
- Injection well pad workovers or other maintenance operations
- CO_2 booster pumps, seal losses, and electricity consumption
- CO_2 compression with interstage cooling, valve/seal losses, and electricity consumption or fuel use
- Dehydration units (triethylene glycol or TEG, Desiccants, Refrigeration, etc.) and associated reboilers or regeneration units

The physical boundary of the module is shown in Figure 1.

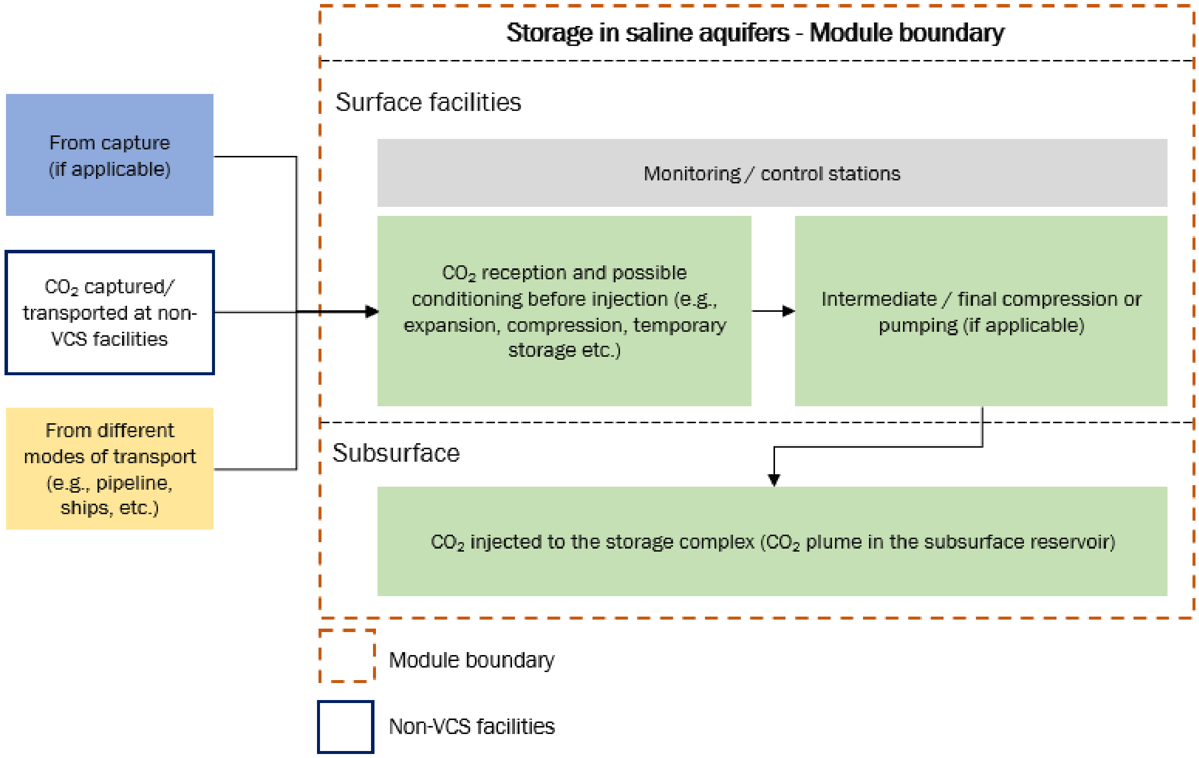

Figure 1- Module boundary for CO_2 storage in saline aquifers Emission *sources, including both primary and secondary effects included in this module are shown in Figure 2*

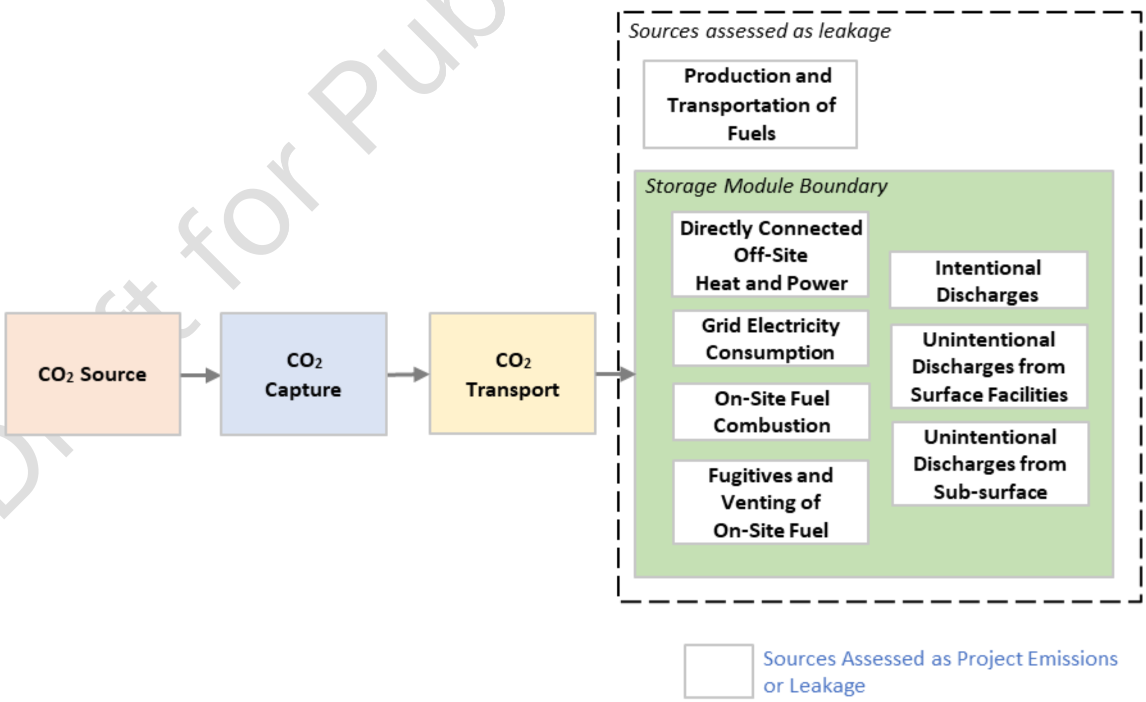

Figure 2- Boundary for Primary and Secondary Project Activity Effects

The GHGs included or excluded from the module boundary are detailed in

Table 1.

Table 1: GHG Sources Included or Excluded from the Project Boundary

Source		Gas	Included?	Justification/Explanation
Project	CO_2 Storage			
	Electricity consumption	CO_2	Yes	Major emission source
		CH_4	Yes	Significant upstream emission source
		N_2O	Yes	Included for completeness
		Other	No	Excluded for simplicity, emissions are considered negligible.
	Fuel consumption	CO_2	Yes	Major emission source
		CH_4	Yes	Significant upstream emission source
		N_2O	Yes	Included for completeness
		Other	No	Excluded for simplicity, emissions are considered negligible.
	CO_2 stream processing	CO_2	Yes	Included. Any loss of CO_2 due to fugitive emissions or venting during capture is inherently deducted from the overall calculation of GHG emission reductions since only injected CO_2 volumes are quantified as the baseline emissions.
		CH_4	No	Excluded as also not considered under the baseline scenario.
		N_2O	No	Excluded as also not considered under the baseline scenario.
		Other	No	Excluded for simplicity, emissions are considered negligible.
	Leaks of CO_2 from the storage site (intentional and unintentional discharge from surface and subsurface)	CO_2	Yes	Major emission source
		CH_4	No	Excluded as also not considered under the baseline scenario.
		N_2O	No	Excluded as also not considered under the baseline scenario.
		Other	No	Excluded for simplicity, emissions are considered negligible.

6 QUANTIFICATION PROCEDURES

6.1 Quantification of Project Emissions

The project emissions are calculated as follows:

$$PE_{Sto,y} = PE_{Comb\_Fuel,y} + PE_{Elec,y} + ID_{Injection,y} + UD_{Injection,y} + ID_{Storage,y} + UD_{Storage,y} - PE_{nonVCS\ CO2,y} \quad (1)$$

Where:

$PE_{Sto,y}$	=	Project emissions from storage in the year *y* (tCO_2e)
$PE_{Comb\_Fuel,y}$	=	Project emissions from fuel combustion to operate equipment for storage processes in the year y (tCO_2e).
$PE_{Elec,y}$	=	GHG emissions from electricity consumption to operate storage processes in the year y (tCO_2e).
$ID_{Injection,y}$	=	Intentional discharges of CO_2 from surface equipment downstream from the mandatory monitoring points (tCO_2e)
$UD_{Injection,y}$	=	Unintentional discharges of CO_2 from surface equipment downstream from the mandatory monitoring points (tCO_2e)
$ID_{Storage,y}$	=	Intentional discharges of CO_2 from subsurface storage (tCO_2e)
$UD_{Storage,y}$	=	Unintentional discharges of CO_2 from subsurface storage (tCO_2e)
$PE_{nonVCS\ CO2,s,y}$	=	Project emissions from processes and equipment related to non-VCS sources. in year y (tCO_2e) to be determined as per the latest version of the *VMT00XX: Tool for Baseline Quantification and Allocation of Project Emissions in Projects with VCS and non-VCS-CO2 flows in Carbon Capture and Storage Projects*. For projects without non-VCS CO_2, $PE_{nonVCS\ CO2,y}$= 0 (tCO_2e)

6.1.1 Project emissions from fuel combustion

Project emissions from fossil fuel combustion for mobile equipment, power and heat generation are calculated as follows:

$$PE_{Comb_{Fuel},y} = \sum_i (Q_{Fuel,i,y} \times EF_{Fuel,CO2,i}) + \sum_i (Q_{Fuel,i,y} \times EF_{Fuel,CH4,i}) \times GWP_{CH_4} + \sum_i (Q_{Fuel,i,y} \times EF_{Fuel,N2O,i}) \times GWP_{N_2O} \quad (2)$$

Where:

$PE_{Comb\_Fuel,y}$	=	Project emissions from fuel combustion for mobile equipment, on and off-site power and heat generation in year y (tCO_2e)
$Q_{Fuel,i,y}$	=	Quantity of each type of fuel i for on-site and off-site mobile equipment, power and heat generation in year y (m^3 or kg or GJ)
$EF_{Fuel,CO2,i}$	=	CO_2 emission factor of fuel i in year y (tCO_2/m^3, tCO_2/kg or tCO_2/GJ)
$EF_{Fuel,CH4,i}$	=	CH_4 emission factor of fuel i in year y (tCH_4/m^3, tCH_4/kg or t CH_4/GJ)
$EF_{Fuel,N2O,i}$	=	N_2O emission factor of fuel i in year y (tN_2O/m^3, tN_2O/kg or tN_2O/GJ)
GWP	=	Global warming potential (for CH_4 and N_2O respectively)

Off-site fuel consumption:

If power or heat are supplied from a directly connected off-site facility, $Q_{Fuel,i,y}$ must be determined as a proportion of the total fuel used to generate the total electricity and heat generated by the directly connected facility with the following equation:

$$Q_{Fuel,i,y} = Q_{fuel\_cogen,i,y} \times \frac{(Heat_{Sto,y} + Electricity_{Sto,y})}{(Heat_{cogen,y} + Electricity_{cogen,y})} \quad (3)$$

Where:

$Q_{Fuel,i,y}$	=	Mass of a fuel type used by a third-party energy source to provide electricity and/or thermal energy to the storage module in year y (metric tons/year)
$Q_{fuel\_cogen,i,y}$	=	Total mass of a fuel type used by the energy facility unit to generate electricity and/or heat in year y (metric tons/year)
$Heat_{Sto,y}$	=	Quantity of useful thermal energy supplied to the storage module by the energy facility unit in year y (MWh/year)
$Electricity_{Sto,y}$	=	Quantity of electricity supplied to the storage module by the facility unit in year y (MWh/year)

$Heat_{Cogen,y}$	=	Total quantity of useful thermal energy produced by the energy facility unit in year y (MWh/year)
$Electricity_{Cogen,y}$	=	Total quantity of electricity produced by the energy facility unit in year y (MWh/year)

Waste heat:

Project emissions from waste heat are zero. Waste heat must meet the conditions in the baseline section.

Biogenic fuel sources:

Project emissions from the combustion of biofuels and biofuels are zero, if they comply with the definition and conditions of renewable and sustainable biomass in the latest version of *VMD00XX: CO_2 Capture from Biogenic Sources.* Otherwise, project emissions from the combustion of biofuel or biomass must be accounted for using Equation (2).

6.1.2 Project emissions from electricity consumption

Project emissions from electricity consumption are calculated as follows:

$$PE_{Elec,y} = Q_{Elec,y} \times EF_{Elec} \quad (4)$$

Where:

$PE_{Elec,y}$	=	Project emissions from consumption of electricity to operate equipment in the storage module the year y (tCO_2e).
$Q_{Elec,y}$	=	Total metered electricity usage to operate equipment in the storage module in year y (MWh/year)
EF_{Elec}	=	Emissions factor for electricity generation (tCO_2e/MWh).

For onsite or directly connected off-site electricity generation, the emissions related to electricity consumption must be determined based on the related fuel consumption as per the provisions under the parameters $PE_{Comb\_Fuel,y}$ and $PE_{Emb\_Fuel,y}$.

For grid electricity consumption, regional emission factors from compliance tools, and data published by State or National government must be used. Project proponents must reference the sources used and provide evidence of the electricity procurement.

Project emissions from renewable energy power plants (i.e., wind, solar, hydro) that are directly connected and off-grid captive are zero. Project proponents must provide evidence of a direct connection.

For electricity consumption from a dedicated geothermal power plant, CO_2 emissions from the release of non-condensable gases must be considered in the emission factor.

6.1.3 Project emissions of intentional discharges

Project emissions from intentional discharges are a result of venting that is downstream of the mandatory monitoring points. Venting events can be differentiated by whether they originate from surface facilities or the subsurface. Surface venting includes activities that are a result of operator intervention (e.g., blowdown of piping, pigging operations), or an automated system response to process conditions (e.g., pressure safety valve releasing in response to high pressure as per its design). For surface venting, the proponent may measure the quantity of CO_2 according to the conditions given in Approach 1, 2, or 3.Subsurface venting includes activities related to injection well maintenance. For subsurface venting, the proponent must determine the quantity of CO_2 according to Approach 1.

Approach 1: Measurement of venting

Under this approach $ID_{Injection/Storage,y}$ must be calculated with one of the following options:

Option 1: Mass flow

$$ID_{Injection/Storage,y} = FR_{mass,x} \times \%CO2_{mass,x} \times T_{x,y} \quad (5)$$

Where:

$ID_{Injection/Storage,y}$	=	Intentional discharges of CO_2 from the surface (i.e., injection) or subsurface (i.e., storage) in year y (tCO_2e)
$FR_{mass,x,y}$	=	Mass flow measured by mass flow meter x (tonnes)
$\%CO2_{mass,x}$	=	CO_2 concentration in the mass flow at mass flow meter x (% mass)
$T_{x,y}$	=	Venting time in year y (hour)

Option 2: Volumetric flow

$$ID_{Injection/Storage,y} = FR_{vol,x(STP)} \times \%CO2_{vol,x(STP)} \times \rho CO2_{x(STP)} \times T_{x,y} \quad (6)$$

Where:

$FR_{vol,x(STP)}$	=	Volumetric flow rate measured by flow meter x at actual conditions and converted to STP conditions (m^3)

$\%CO2_{vol,x(STP)}$	=	Volumetric fraction of CO_2 in flow at flow meter x at STP conditions (% volume)
$\rho CO_{2_{x(STP)}}$	=	Density of CO_2 at STP conditions (tCO_2/m^3)

Please refer to Section 8.1 of *VM00XX Methodology for Carbon Capture and Storage* for the determination of CO_2 flow, density and concentration.

Approach 2: Estimation of surface venting for isolated volumes

If any part of an isolated section of pipe is downstream of the mandatory monitoring point and is depressurized, proponents must estimate the vented mass of CO_2 using the volume of the isolated pipe. This calculation is advanced with Equation (7).

$$ID_{Injection,y} = \sum_{i} V_{i(STP)} \times \%CO2_{vol,x(STP)} \times \rho CO2_{x(STP)} \quad (7)$$

Where:

$ID_{Injection,y}$	=	Intentional discharges of CO_2 downstream the mandatory monitoring point(s) of CO_2 injection in year y (tCO_2e)
$V_{i(STP)}$	=	Internal volume of each pipe, pipe fitting, and component i (m^3) in the isolated vent section using engineering calculations based on the manufacturer's specifications and geometric data for the length of the pipeline converted to volume at STP conditions.
i	=	Vent event index number

Please refer to Section 8.1 of *VM00XX Methodology for Carbon Capture and Storage* to determine CO_2 flow, density and concentration.

Approach 3: Estimation of surface venting for non-isolated volumes

For surface venting when Approach 1 or 2 are not applicable (e.g., if the volume of isolated pipe cannot be determined or if the venting event was from a non-isolated and flowing pipe, etc.), use Approach 3.

The proponent must determine the quantity of vented CO_2 ($ID_{Injection,y}$) by transient flow rate calculations for compressible fluids, appropriate for the expected evolving conditions in the pipeline or component (gaseous, dense, super-critical, etc.), based on the approximate geometry of the escaping flow and pipelines/components connected to the venting.

6.1.4 Project emissions from unintentional discharges at the surface

The potential emission sources for unintentional discharges of CO_2 include but are not limited to:

- Components such as valves, pipe fittings/connectors, open-ended pipes, pressure relief valves, flanges, meters, and instruments; and
- Pipelines.

Two emission sources are considered for unintentional discharge of CO_2 at the surface:

Emission source 1: Fugitive emissions downstream of the mandatory monitoring point

In this scenario, $UD_{injection,y}$ can be determined per the following equations:

For pipeline:

$$UD_{Injection,y} = \sum EF_{pipeline} \times T_{i,y} \times d \times 0.001 \quad (8)$$

For other components:

$$UD_{Injection,y} = \sum EF_{component} \times T_{i,y} \times 0.001 \quad (9)$$

Where:

$UD_{Injection,y}$	=	Unintentional discharges of CO_2 downstream from the mandatory monitoring point(s) of CO_2 injection in year y (tCO_2e)
$EF_{pipeline}$	=	Emission factor derived from IPCC guidelines for GHG inventories, Chapters 4 and 5. A default value of 0.26 kg/(hr*km) for pipelines can be used[1]. Alternatively, the emission factors may be derived from nationally appropriate regulations.
$EF_{component}$	=	Emission factor derived from subpart W of US EPA, mandatory GHG reporting. A default value of 0.005 kg/hr/component can be used. Alternatively, the emission factors may be derived from nationally appropriate regulations, equivalent to the mentioned US EPA reporting guideline.
$T_{i,y}$	=	Pressurized time of the pipeline or component in year y (hours)

[1] Note that $EF_{pipeline}$ and $EF_{component}$ are derived based on US Environmental Protection Agency (EPA), Mandatory Greenhouse Gas Reporting, Subpart W and converted to CO_2 emission factors on a mass basis. The conversion is carried out by using a conversion factor of 0.6 (CH_4 to CO_2) according to Chapter 5 of IPCC Guidelines for National Greenhouse Gas Inventories and a CO_2 density of 0.0526 kg/ft^3 (used in US EPA) at the standard condition (15 °C, 1 atm).

d	=	Length of the pipeline from mandatory monitoring point to injection well (km)

Emission source 2: Rupture or line-break downstream of the mandatory monitoring point

A rupture or line-break failure is considered to have occurred if the rate of flow through the failure is substantial enough to be a safety hazard or off-site nuisance due to odor or noise, otherwise, the failure may be considered a fugitive emission.

When a component or pipeline that is downstream of the mandatory monitoring point and upstream of the wellhead and reservoir, suffers a rupture or line-break failure the proponent must:

- Isolate the failure; and
- Quantify the loss of CO_2 ($UD_{injection,y}$):
    - Emissions before isolation: determine the quantity of lost CO_2 by estimating the flow rate through the failure using transient flow rate calculations for compressible fluids, appropriate for the expected conditions in the pipeline or component (gaseous, dense, super-critical, etc.), based on the approximate geometry of the escaping flow and pipelines/components connected to the failure. The estimation must be made for the approximate time between when the failure occurred and when the release was stopped. If the approximate time when the failure occurred is not known, the duration of the leakage event must be estimated conservatively by assuming the leakage event existed from the last known and documented regular operation (e.g., last inspection) until the release stopped.
    - Emissions after isolation: use equations from section 6.1.1 for Scenario 2 to calculate the leaked emissions.

6.1.5 Project emissions from unintentional discharges from subsurface storage

Project emissions from unintentional discharges from the subsurface are CO_2 leaks from the geological storage complex. They are calculated according to the following equation:

$$UD_{Storage,y} = \sum Q_{LE} + Q_{Threshold,y} \quad (10)$$

Where*:*

$UD_{Storage,y}$	=	Unintentional discharges of CO_2 from subsurface storage in year y (tCO_2e)
Q_{LE}	=	Quantity of CO_2 released from a leak event from the storage reservoir in year y (tCO_2e)
$Q_{Threshold,y}$	=	Maximum undetected quantity of CO_2 that may have leaked as defined in the monitoring program document (tCO_2e)

Section 7.3 provides more guidance on determining Q_{LE} and $Q_{Threshold,y}$.

6.2 Quantification of Leakage

Equation (11) accounts for the leakage emissions in this module.

$$LE_{Sto,y} = LE_{Fuel,y} + LE_{Elec,y} \quad (11)$$

Where:

$LE_{Sto,y}$	=	Leakage emissions from storage in the year *y* (tCO_2e)
$LE_{Fuel,y}$	=	GHG emissions from upstream fuel consumption for storage processes in the year y (tCO_2e).
$LE_{Elec,y}$	=	GHG emissions from upstream electricity consumption to operate storage processes in the year y (tCO_2e).

6.2.1 Leakage emissions from fuel consumption

Upstream emissions from the production and transportation of fuel to the storage site and directly connected offsite facilities are calculated using Equation (12).

$$LE_{Fuel,y} = \sum(Q_{Fuel,i,y} \times EF_{Upstream\_Fuel,i,y}) \quad (12)$$

Where:

$LE_{Fuel,y}$	=	Leakage emissions from upstream sources related to the fuel consumed in on-site equipment in the year y (tCO_2e).
$Q_{Fuel,i,y}$	=	Quantity of fuel type i used in the storage module equipment and/or third party (for offsite energy supply) in year y (m^3 or kg or GJ)
$EF_{Upstream\_Fuel,i,y}$	=	Emission factor of upstream fuel type i used in the storage module equipment in year y (tCO_2e/m^3, tCO_2e/kg or tCO_2e/GJ) Alternatively, a default factor can be used that equals 20% of the CO_2 Emission factor from the combustion of fuel i

If power and heat are supplied from an off-site facility, $Q_{Fuel,i,y}$ must be determined as a proportion of the total fuel used to generate the total electricity and heat generated by the directly connected facility using Equation (3).

Projects where no separate information on $EF_{Fuel,i}$ and $EF_{Upstream\_Fuel,i,y}$ is available may use a combined emission factor and apply it in Equation (2) accordingly.

The emission factor for the production, processing, and transport of fuel used for storage or used by a third party to provide heat or steam to the storage facility must be accounted for using a life cycle analysis (LCA) that is consistent with the storage module boundaries (i.e., primary and secondary effects).

6.2.2 Leakage emissions from upstream electricity consumption

Project emissions from upstream electricity consumption are calculated according to the following Equation (13)

$$LE_{Elec,y} = Q_{Elec,y} \times EF_{Upstream\_Elec} \quad (13)$$

Where:

$LE_{Elec,y}$	=	Leakage emissions from consumption of electricity to operate equipment in the storage module the year y (tCO_2e).
$Q_{Elec,y}$	=	Total metered electricity usage to operate equipment in the storage module in year y (MWh/year)
$EF_{Upstream\_Elec}$	=	Emissions factor for upstream GHG sources related to electricity generation (tCO_2e/MWh).

For on-site or directly connected off-site electricity generation, the emissions related to electricity consumption must be determined based on the related fuel consumption considering project and leakage emissions as described in this module.

For grid electricity consumption, published emission factors from regional compliance market-approved tools, and/or data published by State or National government agencies must be used Project proponents must reference the sources used and provide evidence of the electricity procurement.

For directly connected wind, solar or hydropower plants that are off-grid captive plants, energy supplied is deemed to have no emissions. Project proponents must provide evidence of a direct connection.

For electricity consumption from a dedicated geothermal power plant, CO_2 emissions from the release of non-condensable gases must be considered in the emission factor.

Projects where no separate information on EF_{Elec} and $EF_{Upstream\_Elec}$ is available may use a combined emission factor and apply it in Equation (2) accordingly.

7 MONITORING

7.1 Data and Parameters Available at Validation

Additional data and parameters are defined in the respective *VM00XX Methodology for Carbon Capture and Storage* and related tools (VCS and CDM) as applicable. Please refer to Section 8.1 of *VM00XX Methodology for Carbon Capture and Storage* for the determination of CO_2 quantities.

Data / Parameter	GWP_{CH4}
Data unit	t CO_2e/t CH_4
Description	Global warming potential for CH_4
Equations	(2)
Source of data	The latest version of the VCS Standard
Value applied	See the latest version of the VCS Standard
Justification of choice of data or description of measurement methods and procedures applied	Unless otherwise directed by the VCS Program, the latest version of the VCS Standard requires that CH_4 must be converted using the 100-year global warming potential derived from the IPCC Fourth Assessment Report.
Purpose of Data	Calculation of project emissions
Comments	

Data / Parameter	GWP_{N2O}
Data unit	t CO_2e/t N_2O
Description	Global warming potential for N_2O
Equations	(2)
Source of data	The latest version of the VCS Standard
Value applied	See the latest version of the VCS Standard
Justification of choice of data or description of	Unless otherwise directed by the VCS Program, the VCS Standard requires that N_2O must be converted using the 100-year global warming potential derived from the IPCC Fourth Assessment Report.

measurement methods and procedures applied	
Purpose of Data	Calculation of project emissions
Comments	

Data / Parameter	d
Data unit	km
Description	Length of the pipeline (km)
Equations	(8)
Source of data	Manufacture specifications, part lists, measurement
Value applied	-
Justification of choice of data or description of measurement methods and procedures applied	-
Purpose of Data	Calculation of project emissions

Data / Parameter	$EF_{pipeline}$
Data unit	$kgCO_2/(hr*km)$
Description	The emission factor of pipeline
Equations	(8)
Source of data	Nationally appropriate regulations, equivalent to the US EPA reporting guideline.
Value applied	-
Justification of choice of data or description of measurement methods and procedures applied	-

Purpose of Data	Calculation of project emissions

Data / Parameter	$EF_{component}$
Data unit	$kgCO_2/(hr*km)$
Description	The emission factor of components
Equations	(9)
Source of data	Nationally appropriate regulations, equivalent to the mentioned US EPA reporting guideline.
Value applied	-
Justification of choice of data or description of measurement methods and procedures applied	-
Purpose of Data	Calculation of project emissions

7.2 Data and Parameters Monitored

Refer to Section 8.1 of *VM00XX Methodology for Carbon Capture and Storage* for the determination of CO_2 quantities.

Data / Parameter:	$Q_{Fuel,i,y}$
Data unit:	m^3, kg or GJ in a year y
Description:	Quantity of each fuel type i used in the storage module
Equations	(2) and (12)
Source of data:	Fuel receipts/invoices or flow meter readings
Description of measurement methods and procedures to be applied:	Measured from flow meters or calculated from fuel receipts/invoices.

Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Flow meters must be operated within the manufacturer's specified operating conditions at all times. Flow meters must be routinely calibrated, inspected, and maintained according to the manufacturer's specifications.
Purpose of data:	Calculation of project and leakage emissions
Calculation method:	Volumetric gas flow meter readings must be corrected for temperature and pressure.
Comments:	

Data / Parameter:	$EF_{Fuel,CO2,i}$
Data unit:	tCO_2/m^3, tCO_2/kg or tCO_2/GJ
Description:	CO_2 Emission factor from the combustion of fuel i in year y
Equations	(2)
Source of data:	The following data sources may be used: 1) Emission factor prescribed by IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press: Intergovernmental Panel on Climate Change Retrieved May 18, 2022, from https://www.ipcc.ch/report/ar6/wg1/; 2) Emission factors published by US EPA or similar source; https://www.epa.gov/climateleadership/ghg-emission-factors-hub; or 3) Data provided by the fuel supplier.
Description of measurement methods and procedures to be applied:	Use the latest data published by the above sources at the time of reporting project emissions.
Frequency of monitoring/recording:	Annual
QA/QC procedures to be applied:	N/A
Purpose of data:	Calculation of project emissions

Calculation method:	N/A
Comments:	

Data / Parameter:	$EF_{Fuel,CH4,i}$
Data unit:	tCH_4/m^3, t CH_4/kg or t CH_4/GJ
Description:	CH_4 Emission factor from the combustion of fuel i in year y
Equations	(2)
Source of data:	The following data sources may be used: 1) Emission factor prescribed by IPCC. (use latest version). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press: Intergovernmental Panel on Climate Change Retrieved May 18, 2022, from https://www.ipcc.ch/report/ar6/wg1/; 2) Emission factors published by US EPA or a similar source, https://www.epa.gov/climateleadership/ghg-emission-factors-hub; or 3) Data provided by the fuel supplier.
Description of measurement methods and procedures to be applied:	Use the latest data published by the above sources at the time of reporting project emissions.
Frequency of monitoring/recording:	Annual
QA/QC procedures to be applied:	N/A
Purpose of data:	Calculation of project emissions
Calculation method:	N/A
Comments:	

Data / Parameter:	$EF_{Fuel,N2O,i}$
Data unit:	tN_2O/m3, tN_2O/kg or tN_2O/GJ
Description:	N_2O Emission factor from the combustion of fuel i in year y

Equations	(2)
Source of data:	The following data sources may be used: 1) Emission factor prescribed by IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press: Intergovernmental Panel on Climate Change Retrieved May 18, 2022, from https://www.ipcc.ch/report/ar6/wg1/; 2) Emission factors published by US EPA or a similar source, https://www.epa.gov/climateleadership/ghg-emission-factors-hub; or 3) Data provided by the fuel supplier.
Description of measurement methods and procedures to be applied:	Use the latest data published by the above sources at the time of reporting project emissions.
Frequency of monitoring/recording:	Annual
QA/QC procedures to be applied:	N/A
Purpose of data:	Calculation of project emissions
Calculation method:	N/A
Comments:	

Data / Parameter:	$EF_{Upstream\_Fuel,i,y}$
Data unit:	tCO_2e/m^3, tCO_2e/kg or tCO_2e/GJ
Description:	The upstream emission factor of fuel type i used in the storage module equipment in year y
Equations	(12)
Source of data:	The options for satisfying this requirement are as follows: • Option 1) A qualified third-party may conduct an LCA in accordance with ISO 14040 and 14044, latest edition, that uses either primary or published and peer-reviewed data[2]; or

[2] Peer-reviewed literature means reviewed scientific literature published in reputable environmental and/or climate science journals. State or National government data on the carbon intensities of the fuels are also acceptable sources of data for determining emissions factors for fuels used by the transport facility.

	• Option 2) The embodied emission factor for each fuel type can be calculated using regional compliance market-approved methods or equivalent (e.g., CA-GREET in the California Low Carbon Fuel Standard[3] and GHGenius in the British Colombia Renewable and Low Carbon Fuel Requirements Regulation[4]; or • Option 3) Emission factors published in peer-reviewed literature[4] that are representative both temporally and geographically of the transport plant operation.
Description of measurement methods and procedures to be applied:	Use the latest data published by the sources at the time of reporting project emissions.
Frequency of monitoring/recording:	Annual
QA/QC procedures to be applied:	Use the latest data published by the above sources at the time of reporting project emissions. In the case of peer-reviewed literature, the literature must have been published within a year of reporting project emissions. It must be temporally and geographically representative of the storage facility
Purpose of data:	Calculation of leakage emissions
Calculation method:	N/A
Comments:	N/A

Data / Parameter:	$Q_{fuel\_cogen,i,y}$
Data unit:	*m*^{3}*, kg or GJ*
Description:	Quantity of fuel consumed in the Cogeneration unit
Equations	(3)

[3] CA-GREET (https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation) is adapted from the open-source Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (https://greet.es.anl.gov/) from Argonne National Laboratory (https://www.anl.gov/) based out of Lemont, Illionis in the United States.

[4] GHGenius (https://www.ghgenius.ca/index.php/modelling-resources/about-ghgenius) is an open-source LCA model developed and maintained by (S&T) Squared Consultants Inc. and can be used to analyze the emissions of many contaminants associated with the production and use of traditional and alternative transportations fuels.

Source of data:	Fuel receipts/invoices or flow meter readings, as applicable
Description of measurement methods and procedures to be applied:	Measured from flow meters or calculated from fuel receipts/invoices.
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Flow meters must be operated within the manufacturer's specified operating conditions at all times. Flow meters must be routinely calibrated, inspected, and maintained according to the manufacturer's specifications.
Purpose of data:	Calculation of project emissions
Calculation method:	See above
Comments:	Invoices and/or contracts with the third party must be in place to allow proper data collection.

Data / Parameter:	$Heat_{Sto,y}$
Data unit:	*MWh*
Description:	Quantity of useful heat consumed by the storage module
Equations	(3)
Source of data:	Utility receipts/invoices or metered data for heat usage.
Description of measurement methods and procedures to be applied:	Measured from calorimeters or calculated from receipts/invoices.
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Calorimeter must be routinely calibrated, inspected, and maintained according to manufacturer specifications.
Purpose of data:	Calculation of project emissions

Calculation method:	See above
Comments:	Invoices and/or contracts with the third party must be in place to allow proper data collection.

Data / Parameter:	$Electricity_{Sto,y}$
Data unit:	*MWh*
Description:	Quantity of electricity consumed by the storage module
Equations	(3)
Source of data:	Utility receipts/invoices or metered data for electricity use.
Description of measurement methods and procedures to be applied:	Measured from electricity meters or calculated from receipts/invoices.
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Electricity meters must be routinely calibrated, inspected, and maintained according to manufacturer specifications.
Purpose of data:	Calculation of project emissions
Calculation method:	See above
Comments:	Invoices and/or contracts with the third party must be in place to allow proper data collection.

Data / Parameter:	$Heat_{cogen,y}$
Data unit:	*MWh*
Description:	Quantity of total useful heat produced by the Cogeneration unit
Equations	(3)
Source of data:	Utility receipts/invoices or metered data for heat produced.
Description of measurement methods	Direct measurement of steam flows (or other heat transfer fluid) and characteristics at the cogeneration facility taking into consideration energy content in steam and condensate return.

and procedures to be applied:	
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Calorimeters must be routinely calibrated, inspected, and maintained according to manufacturer specifications.
Purpose of data:	Calculation of project emissions
Calculation method:	See above
Comments:	Invoices and/or contracts with the third party must be in place to allow proper data collection.

Data / Parameter:	$Electricity_{cogen,y}$
Data unit:	*MWh*
Description:	Quantity of electricity produced by the Cogeneration unit
Equations	(3)
Source of data:	Utility receipts/invoices or metered data.
Description of measurement methods and procedures to be applied:	Measured from electricity meters or calculated from receipts/invoices.
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Invoices and/or contracts with the third party
Purpose of data:	Calculation of project emissions
Calculation method:	See above
Comments:	Invoices and/or contracts with the third party must be in place to allow proper data collection.

Data / Parameter:	$Q_{Elec,y}$

Data unit:	*MWh*
Description:	Quantity of electricity consumed by the storage module
Equations	(4) and (13)
Source of data:	Utility receipts/invoices or metered data for off-grid use.
Description of measurement methods and procedures to be applied:	Measured from electricity meters or calculated from receipts/invoices. Engineering estimates based on equipment size and manufacturer efficiency estimates can be used for equipment where it can be demonstrated that the specific electricity consumption of the equipment is less than 1% of the total electricity consumption.
Frequency of monitoring/recording:	Aggregated annually
QA/QC procedures to be applied:	Electricity meters must be routinely calibrated, inspected, and maintained according to manufacturer specifications.
Purpose of data:	Calculation of project and leakage emissions
Calculation method:	See above
Comments:	

Data / Parameter:	EF_{Elec}
Data unit:	tCO_2e/MWh
Description:	Emissions factor for electricity generation including upstream emissions from electricity generation and transport
Equations	(4)
Source of data:	The following data sources may be used: 1) For grid electricity consumption, regional emission factors from compliance tools, and data published by State or National government must be used. Examples of such tools/sources are listed in Appendix I of *VMD00XX: CO_2 Capture from Air (Direct Air Capture)*. 2) Renewable energy (i.e., wind, solar, hydro) from a dedicated/off-grid captive source is deemed to have no emissions. 3) For electricity consumption from a dedicated geothermal power plant, CO_2 emissions from the release of non-condensable gases must be considered in the emission factor as provided by the operator of the geothermal power plant.
Description of measurement methods	In line with data sources used.

and procedures to be applied:	
Frequency of monitoring/recording:	Annual
QA/QC procedures to be applied:	Use the latest published data or tools by the sources at the time of reporting project emissions.
Purpose of data:	Calculation of project emissions
Calculation method:	N/A
Comments:	

Data / Parameter:	$T_{x,y}$
Data unit:	hour
Description:	Venting hours in year y
Equations	(5) and (6)
Source of data:	Measurement onsite
Description of measurement methods and procedures to be applied:	Venting time must be recorded
Frequency of monitoring/recording:	Monitored continuously
QA/QC procedures to be applied:	
Purpose of data:	Calculation of project emissions
Calculation method:	N/A
Comments:	-

Data / Parameter:	$T_{i,y}$
Data unit:	hour
Description:	Operating hours of component i in year y
Equations	(8) and (9)
Source of data:	Measurement onsite
Description of measurement methods and procedures to be applied:	The operating time of the monitored component must be recorded
Frequency of monitoring/recording:	Monitored continuously
QA/QC procedures to be applied:	
Purpose of data:	Calculation of project emissions
Calculation method:	N/A
Comments:	-

Data / Parameter:	Q_{LE}
Data unit:	tCO_2e
Description:	Quantity of CO_2 released as a result of a leak event from the storage reservoir
Equations	(10)
Source of data:	Calculated based on procedures as provided in Section 6.1.5
Description of measurement methods and procedures to be applied:	Calculated based on procedures as provided in Section 6.1.5
Frequency of monitoring/recording:	Continuously

QA/QC procedures to be applied:	Depending on the method(s) used
Purpose of data:	Calculation of project emissions
Calculation method:	Calculated based on procedures as provided in Section 6.1.5
Comments:	

Data / Parameter:	$Q_{Threshold,y}$
Data unit:	tCO2e
Description:	Maximum undetected quantity of CO_2 that may have leaked
Equations	(10)
Source of data:	Calculated based on procedures as provided in Section 5.2.6
Description of measurement methods and procedures to be applied:	Calculated based on procedures as provided in Section 5.2.6
Frequency of monitoring/recording:	Updated in line with the updated monitoring program
QA/QC procedures to be applied:	Depending on the method(s) used
Purpose of data:	Calculation of project emissions
Calculation method:	Calculated based on procedures as provided in Section 6.1.5
Comments:	

7.3 Description of the Monitoring Program

Each project must have a monitoring program. The monitoring program must support the permanent storage of CO_2 injected by ensuring the containment of the plume over time. This must include surface and subsurface equipment for continuous monitoring (e.g., pressure and temperature gauges), and a defined monitoring program (e.g., set seismic data acquisition frequencies).

A loss of conformance occurs if the injected CO_2 does not adhere to the predicted behavior based on the reservoir model but remains within the target geological storage complex and does not migrate outside of a seal(s). A loss of conformance may lead to a loss of containment.

A loss of containment occurs if the injected CO_2 migrates out of the geological storage complex and its respective seal(s). A loss of containment may occur in another zone or directly in the atmosphere. This can occur along a wellbore or natural or induced fractures for example.

A simplified representation of the subsurface is provided in Figure 3, acknowledging the complexity and heterogeneity of the subsurface, only one type of reservoir and several potential flow pathways are provided as examples.

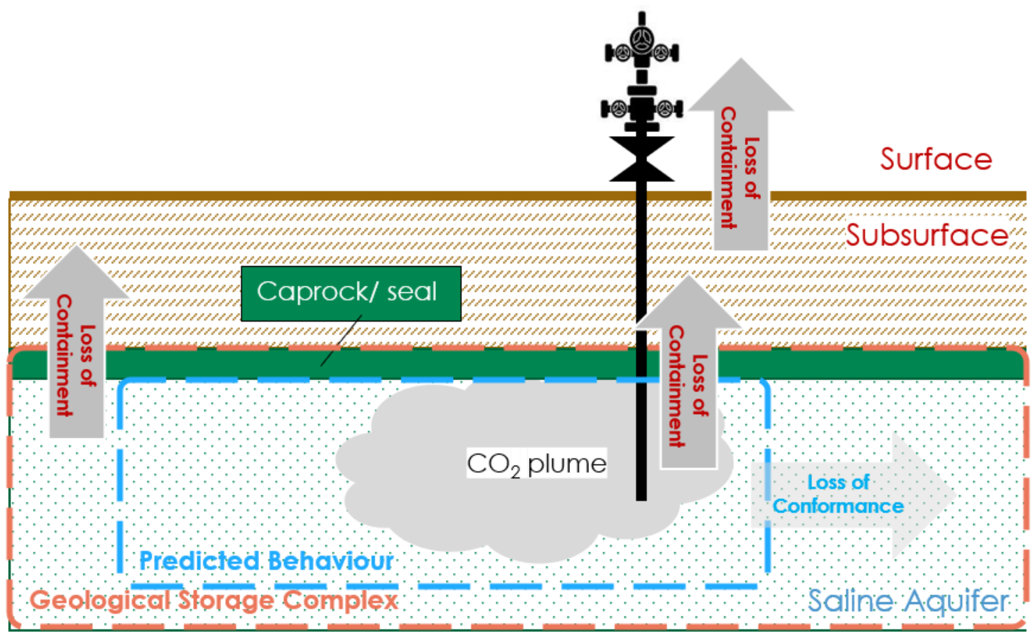

Figure 3: Simplified representation of loss of containment and conformance examples

In addition to the requirements given in the VCS Standard and the *GCS Requirements*, the monitoring program document must:

- Outline the mandatory monitoring point(s) for CO_2 injection downstream of all intermediate storage, compression, or other CO_2 conditioning. The location of the mandatory monitoring points must be as follows:
    - for onshore injection wells:
        - no farther than 300m by run-of-pipe from all injection wellhead(s), when multiple injection wellheads are served by one mandatory monitoring point: or
        - no farther than 100m by run-of-pipe for the injection wellhead, when one injection wellhead is served by one mandatory monitoring point.

  - for offshore injection wells:
    - no farther than 300m by run-of-pipe from the pipeline landfall point, when off-shore wells are connected by sub-sea pipeline to on-shore facilities; or
    - no farther than 300m by run-of-pipe from the submersion point, when off-shore wells are connected to fixed or floating platforms.
- Describe techniques used to detect, localize, and quantify subsurface CO_2 movement outside the geological storage complex of the project, including relevant parameters of each technique such as the detection threshold, probability of detection, resolution, and frequency,
- Define a specific detection threshold to detect a loss of containment (e.g., tCO_2/year or tCO_2) for each monitoring technique.
- Define the expected mean time to detect a loss of containment at the project-specific threshold for each monitoring technique used intermittently (considering the planned frequency of use). The specific detection threshold to detect a loss of containment and the expected mean time to detection must also be specified in the project description document.
- Outline how the reservoir model and monitoring approaches are used to localize and quantify the loss of containment, and
- Define the maximum undetected leak ($Q_{Threshold,y}$) by considering all the following:
  - Leak estimations for each likely pathway (based on each unique loss of containment incident) and the summation of the emissions released from each pathway, respectively (total sum);
  - For continuous monitoring approaches, the threshold for detection as defined in the monitoring program document; and
  - For discontinuous monitoring approaches the threshold for detection and the expected mean time to detect a loss of containment as defined in the monitoring program document.

Upon identification of a loss of CO_2 conformance, and prior to the next verification, the proponent must:

- Evaluate the potential for current or future release to the atmosphere;
- Identify the root cause(s) for the loss of conformance, and
- Revise the monitoring program to reflect the changed CO_2 migration.

Upon detection of a loss of containment, the project must halt injection at the affected storage site.

Upon localization and quantification of a loss of containment, the proponent must conduct an assessment to determine if the loss of containment can be repaired. The project may not resume injection at the concerned storage site until containment is fully re-established.

At the concerned storage site, the project will not generate emissions reduction or removal credits until the following conditions are resolved:

- The loss of containment is stopped, permanent storage is restored; and
- The loss of containment is quantified.

Projects are no longer eligible if the quantity of CO_2 lost is more than 10% of the total CO_2 injected quantity in the project to date.

Project proponents must follow jurisdictional regulations where the project activity occurs. The procedures of the VCS Program Documents Registration and Issuance Process and the *GCS Non-Permanence Risk Tool* apply if a loss of containment occurs.

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