

Useful chemistry: from the mole to H₂/O₂/CO₂ loops

SPACE ACADEMY | MODULE 03

USEFUL CHEMISTRY

REACTIONS, MATERIALS, AIR, WATER, AND FUELS

- 1 MIX**
Understand what reacts
- 2 SEPARATE**
Filter, purify, recover
- 3 TRANSFORM**
Electrolysis, Sabatier, metallurgy
- 4 PROTECT**
Corrosion, toxicity, compatibility
- 5 CONTROL**
Measure, verify, secure

ON MARS, CHEMISTRY LINKS WATER, OXYGEN, MATERIALS, AND FUELS.

Chemistry is material bookkeeping. On Mars it connects air, water, propellants, materials, and local resources.

A balanced equation does not specify power, , kinetics, or lifetime, so the module separates stoichiometry from industrial architecture. Quantitative reference

1. Atoms, elements, and chemical species

An element is defined by proton count. An atom can gain or lose electrons and become an ion. A molecule combines atoms in a defined structure. O₂ and O₃ are therefore different species made from the same element. Quantitative reference

Engineering balances must identify the species unambiguously. “Oxygen” can refer to element O or molecular oxygen O₂. The distinction prevents molar-mass and balancing errors.

Why this matters

Chemistry starts by separating element, isotope, molecule, ion, and chemical species. A process does not conserve vague “matter”; it conserves atoms and charge under the reaction model. Quantitative reference

CO₂ contains one carbon and two oxygen atoms per molecule. Two moles of CO₂ contain two moles of C atoms and four moles of O atoms even though gas volume depends on p and T. The calculation below is a consistency test, not a complete truth.

Counting atoms from molecular coefficients

$$n(\text{O atoms}) = 2 \cdot n(\text{CO}_2)$$

1 — Concrete question	How many moles of oxygen atoms are contained in a given amount of CO ₂ ?
2 — Intuition without symbols	Each carbon-dioxide molecule contains two oxygen atoms, so the oxygen-atom count is doubled.
3 — Quantities first	$n(\text{O atoms})$: moles of O atoms; $n(\text{CO}_2)$: moles of CO ₂ molecules; 2: oxygen atoms per molecule.
4 — Formula	$n(\text{O atoms}) = 2 \cdot n(\text{CO}_2)$
5 — Read aloud	Read the relation by naming every quantity and operation: $n(\text{O atoms}) = 2 \cdot n(\text{CO}_2)$.
6 — Symbols and meaning	The factor 2 comes directly from the chemical formula CO ₂ , not from a measurement.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Both amounts are in mol; the factor 2 is dimensionless.
9 — Convention	Distinguish moles of molecules from moles of atoms in labels.
10 — Why this operation	Each molecule contributes two O atoms, so each mole of CO ₂ contributes two moles of O atoms.
11 — Assumptions	Count atoms within correctly identified CO ₂ molecules.
12 — Unit check	$2 \times \text{mol} = \text{mol}$.
13 — Numerical case	5 mol CO ₂ contain 10 mol of O atoms.
14 — Why the calculation works	Multiplying by the atomic subscript converts molecule count to atom count for the selected element.
15 — Algebra check	$n(\text{CO}_2) = n(\text{O atoms}) / 2$.
16 — Mental estimate	Two O atoms per molecule means exactly twice as many O atoms.
17 — Interpretation	This counting underpins elemental conservation in reaction balances.
18 — What it does	It does not give mass without a molar-mass conversion.

not prove	
19 — Sensitivity or limit case	The result scales linearly with amount of CO ₂ .
20 — Guided and autonomous practice	----- Guided exercise. How many moles of O atoms are in 3 mol CO₂? Guided correction — open after attempting the exercise 2×3=6 mol. Autonomous exercise. If 14 mol of O atoms are present only in CO₂, how many mol CO₂? Autonomous correction — open after attempting the exercise 14/2=7 mol.
21 — Mission decision	Always verify atomic subscripts before converting molecular resources into elemental inventory.

Confusing molar mass with atom count breaks material balances; is a count, kilogram is mass.

2. The mole links particles and measurable mass

One mole contains exactly $6.02214076 \times 10^{23}$ specified elementary entities in the SI. Amount of substance is n in mol. Molar mass M connects measured mass with amount: $n = m/M$ when units are consistent. Quantitative reference

Water has molar mass about 18.015 g/mol. A mole is not one universal mass: one mole of water and one mole of CO₂ contain the same entity count but different masses. Quantitative reference

Physical reading

The mole makes enormous particle counts manageable. Under the redefined SI, one mole contains exactly $6.02214076 \times 10^{23}$ specified entities. Associated mass depends on the species molar mass. Quantitative reference

With $M(\text{O}_2)=32$ g/mol, 64 g O₂ is 2 mol. With $M(\text{CO}_2)=44$ g/mol, 88 g is also 2 mol, but those are not the same molecules. Quantitative reference

Amount of substance from mass

$$n = m/M$$

1 — Concrete question

How many moles are contained in a known mass of a chemical species?

2 — Intuition without symbols

A mole is a fixed amount of entities; molar mass tells how much one mole of the species weighs.

3 — Quantities first	n : amount of substance; m : mass; M : molar mass.
4 — Formula	$n = m/M$
5 — Read aloud	Read the relation by naming every quantity and operation: $n = m/M$.
6 — Symbols and meaning	Mass and molar mass must use compatible units, such as g and g/mol.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	n in mol, m in g or kg, M in g/mol or kg/mol using the same mass basis.
9 — Convention	Always associate M with the exact chemical species and formula.
10 — Why this operation	Dividing total mass by mass per mole counts how many moles are present.
11 — Assumptions	Sample identity is known and molar mass matches composition.
12 — Unit check	$\text{g}/(\text{g}/\text{mol})=\text{mol}$.
13 — Numerical case	180 g of water at $M=18 \text{ g/mol}$ gives $n=10 \text{ mol}$.
14 — Why the calculation works	Division compares available mass with the mass corresponding to one mole.
15 — Algebra check	$m=nM$ and $M=m/n$.
16 — Mental estimate	180/18 is exactly 10.
17 — Interpretation	Amount of substance connects measured masses to stoichiometric coefficients.
18 — What it does not prove	The calculation does not give purity or actual reaction conversion.
19 — Sensitivity or limit case	At fixed M , n scales with m ; at fixed mass, larger M reduces n .
20 — Guided and autonomous practice	----- Guided exercise. Find n for 44 g CO_2 with $M=44 \text{ g/mol}$. Guided correction — open after attempting the exercise $n=44/44=1 \text{ mol}$. Autonomous exercise. What mass is 3 mol O_2 at $M=32 \text{ g/mol}$? Autonomous correction — open after attempting the exercise $m=3 \times 32=96 \text{ g}$.
21 — Mission decision	Convert mass inventories to moles before checking reaction stoichiometry.

Engineering molar masses have finite precision and real products contain impurities and mixtures; stoichiometric calculation is an ideal balance.

Chemistry check for 2. The mole links particles and measurable mass. Recalculate the material balance after changing one feed composition or process. Track the change in moles before converting back to mass, and state explicitly which species becomes limiting. Then identify one impurity or side process that the ideal equation omits but a Mars plant would have to monitor.

3. Balancing a reaction conserves atoms

Water is $2 \text{H}_2\text{O} \rightarrow 2 \text{H}_2 + \text{O}_2$. Four hydrogen atoms and two oxygen atoms appear on each side. Coefficients are mole ratios, not direct kilograms. Quantitative reference

Balancing water electrolysis



1 — Concrete question	Does the water-electrolysis equation conserve H and O atoms?
2 — Intuition without symbols	A chemical reaction rearranges atoms but does not create or destroy them; coefficients must balance each element.
3 — Quantities first	$2\text{H}_2\text{O}$: two molecules or moles of water; 2H_2 : two of hydrogen; O_2 : one of oxygen.
4 — Formula	$2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$
5 — Read aloud	Read the relation by naming every quantity and operation: $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$.
6 — Symbols and meaning	Left: 4 H and 2 O. Right: 4 H in 2H_2 and 2 O in O_2 .
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Stoichiometric coefficients are dimensionless ratios between molecules or moles.
9 — Convention	Never change molecular subscripts to balance a reaction; change only coefficients before species.
10 — Why this operation	The 2:2:1 coefficients are the smallest integers that conserve both H and O.
11 — Assumptions	This represents only the ideal overall stoichiometry of electrolysis.
12 — Unit check	Two moles water produce two moles H_2 and one mole O_2 ; the atomic balance closes.
13 — Numerical case	2 mol H_2O contain 4 mol H atoms and 2 mol O atoms; products contain exactly the same amounts.
14 — Why the calculation works	Counting H and O separately on each side tests the balance unambiguously.

15 — Algebra check	Multiplying all coefficients by the same factor preserves balance but is not the minimal integer form.
16 — Mental estimate	Two waters contain four H and two O; two H ₂ plus one O ₂ visibly reproduces that count.
17 — Interpretation	A balanced equation provides molar ratios needed for mass balances.
18 — What it does not prove	It does not give real electrical energy, efficiency, kinetics or product purity.
19 — Sensitivity or limit case	Changing processed moles scales all stoichiometric amounts proportionally.
20 — Guided and autonomous practice	----- Guided exercise. For 6 mol H₂O, how many mol H₂ and O₂ ideally? Guided correction — open after attempting the exercise The 2:2:1 ratio gives 6 mol H₂ and 3 mol O₂. Autonomous exercise. How many mol H₂O are ideally required to produce 5 mol O₂? Autonomous correction — open after attempting the exercise Two moles water per mole O₂: 10 mol H₂O.
21 — Mission decision	Do not use a downstream mass balance until atomic conservation is verified.

With rounded molar masses, 36 g water corresponds ideally to 4 g hydrogen plus 32 g oxygen. The $36 = 4 + 32$ check closes the ideal mass balance. Quantitative reference

Move into calculation

Balancing a chemical equation conserves each atom type. Coefficients express molar ratios, not equal masses. They become an engineering tool when converted to kilograms.

For $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, 4 g H₂ ideally reacts with 32 g O₂ to produce 36 g water. Total mass is conserved. The teaching value is seeing units turn into a decision. Quantitative reference

Linked application

Application — Balancing water electrolysis

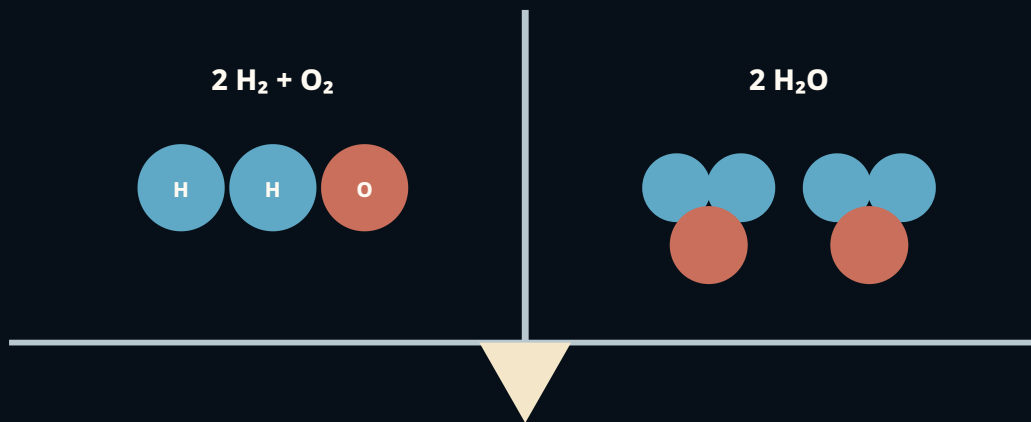
Retained worked application. Water electrolysis: $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$. Ideal mass balance: 36 g $\rightarrow$ 4 g H₂ + 32 g O₂. Method, units, assumptions and practice remain in the linked canonical mini-lesson.

Canonical lesson : open the corresponding canonical 1 $\rightarrow$ 21 mini-lesson.

A balanced equation gives no reaction rate, temperature, yield, or purity; it only fixes ideal stoichiometry. Quantitative reference

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Conservation des atomes / atom balance



Balance atoms before converting masses

Stoichiometric balance: moles to masses, then limiting reagent to real yield.

4. Limiting reagent, conversion, yield, purity

A reaction stops when a necessary reactant becomes limiting. Conversion tracks how much reactant is consumed; yield compares desired product with the theoretical amount; purity describes how much of an output stream is the desired species. Quantitative reference

These metrics answer different questions. High purity can coexist with low throughput, while high conversion can still have separation losses. One generic efficiency percentage cannot describe an industrial process.

Control point

The sets maximum production. Conversion, selectivity, yield, and purity then describe what the real process obtains relative to that limit. These concepts are not interchangeable.

If stoichiometry allows 100 kg but the process delivers only 82 kg pure product, yield relative to the maximum is 82%. If a batch is only 90% useful product, 82 kg mixture contains 73.8 kg useful material. An engineer keeps numerical result, margin, and validity domain separate.

Usable mass from feed purity

$$m_{\text{usable}} = m_{\text{batch}} \cdot w$$

1 — Concrete question

How much usable material is contained in a batch of known purity?

2 — Intuition without symbols

An impure batch provides only a fraction of total mass as the desired reactant or product.

3 — Quantities first

m_{usable} : mass of desired material; m_{batch} : total batch mass; w : mass-fraction purity.

4 — Formula	$m_{\text{usable}} = m_{\text{batch}} \cdot w$
5 — Read aloud	Read the relation by naming every quantity and operation: $m_{\text{usable}} = m_{\text{batch}} \cdot w$.
6 — Symbols and meaning	$w=0.85$ means 85% of batch mass is the desired species.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Both masses in the same unit; w dimensionless between 0 and 1.
9 — Convention	Convert percent to a decimal fraction before calculation: $85\% \rightarrow 0.85$.
10 — Why this operation	Multiplication applies the usable fraction to total mass.
11 — Assumptions	Purity is representative of the batch and defined on a mass basis.
12 — Unit check	$\text{kg} \times 1 = \text{kg}$.
13 — Numerical case	$100 \text{ kg} \times 0.85 = 85 \text{ kg}$ usable material.
14 — Why the calculation works	Multiplying by a fraction below 1 reduces total mass to the desired component.
15 — Algebra check	$m_{\text{batch}} = m_{\text{usable}} / w$.
16 — Mental estimate	85% of 100 kg is immediately 85 kg.
17 — Interpretation	This usable mass, not gross batch mass, should feed the real stoichiometric balance.
18 — What it does not prove	Purity alone does not describe chemical conversion or downstream recovery.
19 — Sensitivity or limit case	At fixed batch mass, usable mass scales linearly with w .
20 — Guided and autonomous practice	----- Guided exercise. A 250 kg batch is 92% pure. What usable mass? Guided correction — open after attempting the exercise $250 \times 0.92 = 230 \text{ kg}$. Autonomous exercise. What gross batch mass is needed for 180 kg usable at 75% purity? Autonomous correction — open after attempting the exercise $180 / 0.75 = 240 \text{ kg}$.
21 — Mission decision	Size extraction and transport on gross mass, but reaction on usable mass.

Yield above 100% usually signals an inconsistent basis, moisture, impurities, or measurement error.

5. Gas mixtures and partial pressure

In an ideal mixture, each gas contributes and the partial pressures sum to total pressure. A 70 kPa habitat atmosphere is not fully defined until O₂, CO₂, water vapor, and contaminant fractions are known. Quantitative reference

$pV = nRT$ connects amount, absolute temperature, volume, and pressure. Chemistry makes molecules; engineering must then store, circulate, purify, and measure them at defined conditions. [Quantitative reference](#)

Interpretation

In an ideal gas mixture, each gas contributes to total pressure according to mole fraction. Partial pressure links composition to physiology: the same oxygen fraction does not have the same effect at different total pressures.

At 70 kPa and 30 mol% O₂, $p_{O_2} \approx 21$ kPa. At 50 kPa total, about 42% O₂ would be needed to keep 21 kPa in this idealized calculation. The formula is useful because it makes a system dependency visible. Quantitative reference

Partial pressure in a gas mixture

$$p_i = y_i p_{\text{total}}$$

1 — Concrete question	What partial pressure does a species exert when it has a known mole fraction in a gas mixture?
2 — Intuition without symbols	In an ideal mixture, each species contributes to total pressure in proportion to its share of molecules.
3 — Quantities first	p_i : partial pressure of species i ; y_i : mole fraction; p_{total} : total pressure.
4 — Formula	$p_i = y_i p_{\text{total}}$
5 — Read aloud	Read the relation by naming every quantity and operation: $p_i = y_i p_{\text{total}}$.
6 — Symbols and meaning	Mole fractions sum to 1 and partial pressures ideally sum to total pressure.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	p_i and p_{total} in the same pressure unit; y_i dimensionless.
9 — Convention	Use mole fraction, not mass fraction, unless explicitly converted.
10 — Why this operation	Multiplication applies the species mole fraction to total mixture pressure.
11 — Assumptions	Mixture is close enough to ideal-gas behavior.
12 — Unit check	$1 \times \text{kPa} = \text{kPa}$.
13 — Numerical case	$y_i = 0.95$ and $p_{\text{total}} = 70$ kPa give $p_i = 66.5$ kPa.

14 — Why the calculation works	Multiplying by mole fraction isolates the species contribution to the total.
15 — Algebra check	$y_i = p_i / p_{\text{total}}$.
16 — Mental estimate	95% of 70 kPa should be slightly below 70, about 66.5 kPa.
17 — Interpretation	Partial pressure supports checks for breathing, condensation, reactions and safety limits.
18 — What it does not prove	It does not by itself capture nonideal effects or local composition gradients.
19 — Sensitivity or limit case	At fixed total pressure, p_i scales linearly with y_i .
20 — Guided and autonomous practice	----- Guided exercise. $y=0.21$ in a 70 kPa habitat: find p_i. Guided correction — open after attempting the exercise $0.21 \times 70 = 14.7$ kPa. Autonomous exercise. What mole fraction gives 20 kPa in an 80 kPa mixture? Autonomous correction — open after attempting the exercise $y = 20 / 80 = 0.25$.
21 — Mission decision	Verify each critical partial pressure, not total habitat pressure alone.

Real safety must also consider fire risk, humidity, CO₂, contaminants, and physiological limits; matching pO₂ alone does not define a safe atmosphere.

6. Electrolysis: material balance plus energy cost

Electrolysis separates water into H₂ and O₂ using electrical energy. Stoichiometry fixes the ideal mass relation but not electrical efficiency, cell voltage, heat rejection, drying, separation, or lifetime.

Ideal mass balance of electrolysis



1 — Concrete question	What ideal masses of hydrogen and oxygen come from 36 kg of water?
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2 — Intuition without symbols	The balanced reaction fixes molar ratios; molar masses then convert those ratios into kilograms.
3 — Quantities first	36 kg H ₂ O: reference water mass; 4 kg H ₂ and 32 kg O ₂ : ideal stoichiometric product masses.
4 — Formula	36 kg H ₂ O → 4 kg H ₂ + 32 kg O ₂
5 — Read aloud	Read the relation by naming every quantity and operation: 36 kg H ₂ O → 4 kg H ₂ + 32 kg O ₂ .
6 — Symbols and meaning	Values come from 2 mol H ₂ O = 36 g, 2 mol H ₂ = 4 g and 1 mol O ₂ = 32 g, then scale linearly.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	All masses may use g, kg or t as long as the same mass unit is used throughout.
9 — Convention	Distinguish ideal stoichiometric yield from actual electrolyzer yield.
10 — Why this operation	Product masses follow directly from molar ratios and molar masses in the balanced equation.
11 — Assumptions	Ideal complete reaction, pure products and no process losses.
12 — Unit check	4+32=36 kg: total mass is conserved.
13 — Numerical case	72 kg H ₂ O would ideally give 8 kg H ₂ + 64 kg O ₂ .
14 — Why the calculation works	Scaling all products by the same factor preserves the stoichiometric balance.
15 — Algebra check	For water mass m, ideal H ₂ = m×4/36 and O ₂ = m×32/36.
16 — Mental estimate	Oxygen is about 89% of water mass and hydrogen about 11%.
17 — Interpretation	This balance sets mass ceilings before electrical efficiency, separation and storage.
18 — What it does not prove	It does not give energy demand, purity, losses or real throughput.
19 — Sensitivity or limit case	Product masses scale linearly with water feed mass.
20 — Guided and autonomous practice	----- Guided exercise. What ideal products from 18 kg water? Guided correction — open after attempting the exercise 2 kg H₂ + 16 kg O₂. Autonomous exercise. How much water is ideally required for 24 kg O₂? Autonomous correction — open after attempting the exercise

$$24 \times 36 / 32 = 27 \text{ kg H}_2\text{O}.$$

21 — Mission decision

Then apply efficiency and storage capacity before claiming usable production.

Exercise 6

In the ideal balance, how much O_2 corresponds to 9 kg water?

Solution: 9 kg is one quarter of 36; ideal O_2 is $32/4 = 8$ kg. Quantitative reference

The mass ratio comes from water stoichiometry rather than an empirical percentage. Scaling the reference batch by one quarter preserves the ideal proportions; yield and purity are applied only after the atomic balance.

Case study — electrolyse a mass of water

The ideal equation $2 \text{H}_2\text{O} \rightarrow 2 \text{H}_2 + \text{O}_2$ gives a simple mass balance. Two moles of water are about 36 g and ideally yield about 4 g H_2 and 32 g O_2 . At the scale of 36 kg of perfectly converted water, stoichiometry becomes 4 kg hydrogen plus 32 kg oxygen. Total mass remains 36 kg because atoms, and therefore mass in this ideal closed system, are conserved. Quantitative reference

This balance says nothing about electrical demand, cell efficiency, purity, storage pressure, or electrode life. Moving from reaction to equipment requires energy, kinetics, separation, thermal management, and maintenance. Stoichiometry still sets a physical boundary: a system cannot promise 40 kg O_2 from 36 kg water without another oxygen source.

Linked application

Application — Ideal mass balance of electrolysis

Retained worked application: $36 \text{ kg H}_2\text{O} \rightarrow$ ideally $4 \text{ kg H}_2 + 32 \text{ kg O}_2$. Method, symbols, units, assumptions and practice are carried by the linked canonical mini-lesson below.

Canonical lesson : open the corresponding canonical 1 → 21 mini-lesson.

Field reasoning

Water electrolysis turns electrical energy into chemical separation. Stoichiometry fixes the H_2/O_2 ratio; real energy depends on overpotential, resistance, temperature, pressure, purity, and auxiliary equipment.

36 kg water ideally corresponds to 4 kg H_2 and 32 kg O_2 . If a teaching scenario assumes 55 kWh per kg H_2 , producing 4 kg would require 220 kWh electrical input before other auxiliaries. Quantitative reference

Linked application

Application — Balancing water electrolysis

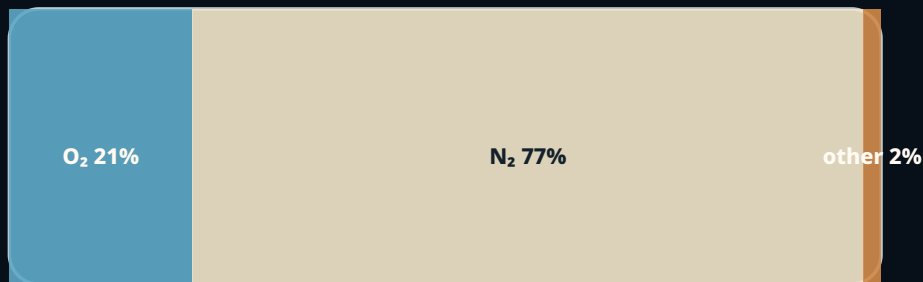
Retained worked application: $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$. Method, symbols, units, assumptions and practice are carried by the linked canonical mini-lesson below.

Canonical lesson : open the corresponding canonical 1 → 21 mini-lesson.

The selected energy figure is a scenario assumption; it must not be presented as universal electrolyzer performance.

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Pression partielle / partial pressure



$$p_i = x_i \cdot p_{\text{total}}$$

Composition × total pressure = species partial pressure

Partial pressures: connect fraction, total pressure, p_{O_2} and p_{CO_2} to operating limits.

7. Sabatier connects CO_2 , H_2 , CH_4 , and water

$\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$ converts carbon dioxide and hydrogen into methane and water. Rounded mass balance: 44 kg $\text{CO}_2 + 8 \text{ kg H}_2 \rightarrow 16 \text{ kg CH}_4 + 36 \text{ kg H}_2\text{O}$. Quantitative reference

Sabatier stoichiometric mass balance



1 — Concrete question	What ideal methane and water masses correspond to 44 kg CO_2 and 8 kg H_2 ?
2 — Intuition without symbols	A balanced equation fixes molecular proportions and, through molar masses, a closed mass balance.
3 — Quantities first	CO_2 , H_2 : reactants; CH_4 , H_2O : products; coefficients 1:4:1:2.
4 — Formula	$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} ; 44+8 \rightarrow 16+36$
5 — Read aloud	Read the relation by naming every quantity and operation: $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} ; 44+8 \rightarrow 16+36$.
6 — Symbols and meaning	One mole CO_2 (44 g) with four moles H_2 (8 g) ideally gives one mole CH_4 (16 g) and two moles H_2O (36 g).
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Molar ratios in mol; mass balance may use g, kg or t consistently.
9 — Convention	Identify the limiting reactant before applying actual conversion/yield.

10 — Why this operation	Coefficients balance C, H and O; molar masses then close 52 kg in = 52 kg out.
11 — Assumptions	Ideal overall reaction, complete conversion and no side reactions.
12 — Unit check	44+8=52 kg and 16+36=52 kg.
13 — Numerical case	With 88 kg CO ₂ and 16 kg H ₂ , ideal products are 32 kg CH ₄ + 72 kg H ₂ O.
14 — Why the calculation works	Verify molar ratio first, then scale all masses by the same factor.
15 — Algebra check	With CO ₂ limiting, ideal CH ₄ = m_CO ₂ × 16/44.
16 — Mental estimate	16/44 ≈ 0.36: 100 kg CO ₂ can give only about 36 kg ideal CH ₄ .
17 — Interpretation	The balance links CO ₂ capture, H ₂ demand, CH ₄ production and water recovery.
18 — What it does not prove	It does not give real conversion, catalyst behavior, temperature, pressure, separation or energy use.
19 — Sensitivity or limit case	Production is limited by whichever reactant is smallest relative to its stoichiometric requirement.
20 — Guided and autonomous practice	----- Guided exercise. With 22 kg CO₂ and excess H₂, what ideal CH₄ mass? Guided correction — open after attempting the exercise 22 × 16/44 = 8 kg CH₄. Autonomous exercise. How much H₂ is ideally required for 110 kg CO₂? Autonomous correction — open after attempting the exercise 110 × 8/44 = 20 kg H₂.
21 — Mission decision	Size inventories and recycle around the limiting reactant, not one nominal flow alone.

Recovered water can feed electrolysis, but integration adds compressors, catalyst, separation, storage, and common dependencies. A closed mass balance is not automatically a reliable architecture.

Case study — and partial closure

CO₂ + 4 H₂ → CH₄ + 2 H₂O gives, using rounded molar masses, 44 kg CO₂ + 8 kg H₂ → 16 kg CH₄ + 36 kg H₂O. If the water is then electrolysed ideally, 36 kg water yields 4 kg H₂ and 32 kg O₂. Only half the hydrogen fed to Sabatier therefore returns as hydrogen in this ideal sequence: 4 kg returns from the 8 kg input. Quantitative reference

The methane contains the other hydrogen. Depending on architecture it may be stored as useful product, burned as fuel, or become an output that prevents complete hydrogen-loop closure. The word “recycling” must therefore identify which species returns, with what yield, and where losses go. A chemical loop is judged by a complete material balance,

not by the fact that water appears somewhere downstream. Quantitative reference

Linked application

Application — Sabatier stoichiometric mass balance

Retained worked application: $44 \text{ CO}_2 + 8 \text{ H}_2 \rightarrow 16 \text{ CH}_4 + 36 \text{ H}_2\text{O}$; ideal electrolysis: $36 \text{ H}_2\text{O} \rightarrow 4 \text{ H}_2 + 32 \text{ O}_2$. Method, symbols, units, assumptions and practice are carried by the linked canonical mini-lesson below.

Canonical lesson : open the corresponding canonical 1 → 21 mini-lesson.

Why this matters

The Sabatier reaction couples CO_2 , hydrogen, methane, and water. In a closed architecture its value cannot be judged in isolation: it depends on hydrogen source, methane use, water recovery, and losses.

44 kg CO_2 and 8 kg H_2 ideally produce 16 kg CH_4 and 36 kg H_2O . Re-electrolyzing 36 kg water ideally returns 4 kg H_2 , only half of the 8 kg H_2 fed to Sabatier. The calculation below is a consistency test, not a complete truth.

Linked application

Application — Sabatier stoichiometric mass balance

Retained worked application: $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$. Method, symbols, units, assumptions and practice are carried by the linked canonical mini-lesson below.

Canonical lesson : open the corresponding canonical 1 → 21 mini-lesson.

Saying “the loop recycles hydrogen” without a quantified balance hides makeup demand or the need for another recovery step.

8. Methane-oxygen combustion

Ideal $\text{CH}_4 + 2 \text{ O}_2 \rightarrow \text{CO}_2 + 2 \text{ H}_2\text{O}$ gives about 16 kg methane + 64 kg oxygen → 44 kg CO_2 + 36 kg water. Both sides total 80 kg. Quantitative reference

A real engine adds mixture ratio, pressure, temperature, combustion stability, cooling, nozzle behavior, and efficiency. Chemistry gives a stoichiometric boundary, not finished propulsion hardware. Quantitative reference

Physical reading

Methane-oxygen combustion partly reverses the synthesis logic: it releases energy and produces CO_2 and water. Stoichiometric ratios support tank sizing and recycle balances.

$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$ means 16 kg CH_4 for 64 kg O_2 , ideally producing 44 kg CO_2 and 36 kg water. Quantitative reference

Stoichiometric methane combustion



1 — Concrete question

How much oxygen is ideally required to burn methane without stoichiometric deficit or excess?

2 — Intuition without symbols	One methane molecule contains one carbon and four hydrogens; enough oxygen is needed to form one CO ₂ and two waters.
3 — Quantities first	CH ₄ : methane; O ₂ : oxygen; CO ₂ : carbon dioxide; H ₂ O: water.
4 — Formula	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O
5 — Read aloud	Read the relation by naming every quantity and operation: CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O.
6 — Symbols and meaning	The coefficient 2 before O ₂ supplies four O atoms: two for CO ₂ and two for 2H ₂ O.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Coefficients are molar ratios; proportional masses follow from molar masses.
9 — Convention	Separate ideal stoichiometric ratio from the mixture ratio actually used by an engine or burner.
10 — Why this operation	Coefficients conserve one C, four H and four O atoms.
11 — Assumptions	Complete combustion to CO ₂ and H ₂ O, with no CO or intermediates.
12 — Unit check	16 g CH ₄ + 64 g O ₂ → 44 g CO ₂ + 36 g H ₂ O; 80 g on each side.
13 — Numerical case	16 kg CH ₄ ideally require 64 kg O ₂ and produce 44 kg CO ₂ + 36 kg H ₂ O.
14 — Why the calculation works	Balancing atoms fixes the molar ratio; molar masses then convert that ratio to mass.
15 — Algebra check	Ideal O ₂ = 4×m _{CH₄} on a mass basis for this reaction.
16 — Mental estimate	Oxygen mass is four times methane mass in the ideal balance.
17 — Interpretation	The ratio sets baseline O ₂ demand and CO ₂ /H ₂ O production.
18 — What it does not prove	A real engine often uses a different mixture ratio for temperature, stability and performance.
19 — Sensitivity or limit case	All masses scale linearly with methane amount while O ₂ remains available.
20 — Guided and autonomous practice	----- Guided exercise. What ideal O₂ for 5 kg CH₄? Guided correction — open after attempting the exercise 5×4=20 kg O₂. Autonomous exercise. How much CH₄ can ideally burn with 128 kg O₂? Autonomous correction — open after attempting the exercise 128/4=32 kg CH₄.

21 — Mission decision

Use the system's actual mixture ratio operationally, while keeping stoichiometry as the balance reference.

A real engine uses a mixture ratio chosen for performance, temperature, and stability; stoichiometry alone does not define operating point.

Chemistry check for 8. Methane-oxygen combustion.

9. MOXIE: Mars demonstration, not a factory

NASA reports produced 122 g total oxygen across 16 Mars runs, reaching 12 g/h and at least 98% purity at its best. Extracting O₂ from Martian CO₂ has therefore been demonstrated at small scale.

A hypothetical 1,000 kg/day requirement equals 41.7 kg/h. Compared with 0.012 kg/h demonstrated peak, the throughput ratio is above 3,400. That is a scale comparison, not a proposal to copy 3,400 identical MOXIE units. Quantitative reference

Case study — scale MOXIE toward an industrial demand

NASA reports that MOXIE produced 122 g of oxygen in total on Mars, reached up to 12 g/h, and achieved at least 98% purity at its best. Take a teaching demand of 1,000 kg O₂ per day. That is 41.7 kg/h on average, about 3,475 times the demonstrated 0.012 kg/h peak. The ratio exposes a scale change; it does not mean that 3,475 copies of the instrument form an industrial design.

A plant changes compressors, cell area, electrical supply, heat rejection, storage, controls, maintenance, spares, and availability. A nominal 50 kg/h plant available only 80% of the time averages 40 kg/h. Availability can therefore matter as much as nameplate capacity. Scientific status must remain explicit: MOXIE demonstrated the principle on Mars; industrial oxygen production remains future engineering. Quantitative reference

Convert daily throughput to hourly rate and unit count

$$\dot{m}_h = M_{\text{day}}/24 ; N = \dot{m}_h/q_{\text{unit}}$$

1 — Concrete question

How many units are needed to process a daily target at a known per-unit rate?

2 — Intuition without symbols

A daily target must first be converted to the same time basis as one machine capacity before comparing them.

3 — Quantities first

M_{day}: mass target per day; $\dot{m}_h$: required hourly rate; q_{unit}: one-unit throughput; N: ideal unit count.

4 — Formula

$$\dot{m}_h = M_{\text{day}}/24 ; N = \dot{m}_h/q_{\text{unit}}$$

5 — Read aloud

Read the relation by naming every quantity and operation: $\dot{m}_h = M_{\text{day}}/24 ; N = \dot{m}_h/q_{\text{unit}}$.

6 — Symbols and meaning

The first division converts day → hour; the second compares required rate with one-unit capacity.

7 — Pronunciation

Name every symbol, subscript and operator separately from its unit.

8 — Units	M_{day} in kg/day, $\dot{m}_h$ and q_{unit} in kg/h, N dimensionless.
9 — Convention	Use the same availability and time basis for target and units before rounding N .
10 — Why this operation	Dividing by 24 gives average hourly demand; dividing by one-unit capacity gives the ideal number of units.
11 — Assumptions	Continuous 24 h/day operation and constant per-unit throughput for this simplified calculation.
12 — Unit check	$(\text{kg/day}) / (24 \text{ h/day}) = \text{kg/h}$, then $(\text{kg/h}) / (\text{kg/h}) = 1$.
13 — Numerical case	$1,000 \text{ kg/day} \div 24 = 41.67 \text{ kg/h}$. At 0.012 kg/h per unit: $N \approx 3472.2$, so at least 3,473 ideal units before margin.
14 — Why the calculation works	Converting time bases first prevents division of rates expressed on incompatible bases.
15 — Algebra check	$M_{\text{day}} = 24 N q_{\text{unit}}$ for continuous operation.
16 — Mental estimate	42 kg/h divided by 0.012 kg/h gives a few thousand units, consistent with $\sim 3,500$.
17 — Interpretation	The result immediately shows whether a demonstration technology can be scaled directly.
18 — What it does not prove	Availability, maintenance, redundancy, ramp-up and scale effects are excluded.
19 — Sensitivity or limit case	N scales linearly with target and inversely with per-unit throughput.
20 — Guided and autonomous practice	----- Guided exercise. 500 kg/day at 0.5 kg/h per unit: how many ideal units? Guided correction — open after attempting the exercise $500/24 = 20.83 \text{ kg/h}$, then $20.83/0.5 = 41.67$: at least 42 units. Autonomous exercise. 1,000 kg/day, but unit throughput doubles to 0.024 kg/h: how many units? Autonomous correction — open after attempting the exercise $41.67/0.024 \approx 1736.1$: at least 1,737 units.
21 — Mission decision	Do not extrapolate a demonstration to a factory without availability and industrial architecture.

Move into calculation

MOXIE is a real Mars demonstration of oxygen production from atmospheric CO₂. Its importance is the process demonstrated in the actual environment, not a claim that a small instrument was already a propellant factory.

NASA reports 122 g O₂ total, up to 12 g/h, at least 98% purity. A 2 kg/h plant would theoretically make 17.52 t/year at 100% availability but 12.264 t/year at 70%. The teaching value is seeing units turn into a decision. Quantitative reference

Annual production with availability

$$M_{\text{annual}} = \dot{m} \cdot 8760 \text{ h} \cdot A$$

1 — Concrete question	What annual production follows from nominal throughput and a stated availability?
2 — Intuition without symbols	A machine does not necessarily produce all year; availability reduces nominal time to productive time.
3 — Quantities first	M_{annual} : annual mass; $\dot{m}$: hourly throughput; 8760 h: hours in a 365-day year; A: availability.
4 — Formula	$M_{\text{annual}} = \dot{m} \cdot 8760 \text{ h} \cdot A$
5 — Read aloud	Read the relation by naming every quantity and operation: $M_{\text{annual}} = \dot{m} \cdot 8760 \text{ h} \cdot A$.
6 — Symbols and meaning	$A=0.90$ means 90% of nominal time is available for production.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	$\dot{m}$ in kg/h, time in h, A dimensionless, result in kg/year.
9 — Convention	Define what counts as unavailable: maintenance, failures, cleaning, resource wait.
10 — Why this operation	Throughput multiplied by productive time gives total produced mass.
11 — Assumptions	Constant throughput while available and a standard 365-day year.
12 — Unit check	$\text{kg/h} \times \text{h} \times 1 = \text{kg}$.
13 — Numerical case	$41.7 \text{ kg/h} \times 8760 \text{ h} \times 0.90 \approx 328,763 \text{ kg/year}$, about 329 t/year.
14 — Why the calculation works	Multiply annual time by availability for productive hours; then multiply by throughput for mass.
15 — Algebra check	$\dot{m} = M_{\text{annual}} / (8760A)$.
16 — Mental estimate	42 kg/h for roughly 8,000 productive hours gives about 336 t/year, close to the precise result.
17 — Interpretation	Annual production compares industrial capacity with annual mission demand.
18 — What it does	The calculation hides seasonality, throughput degradation and long correlated outages.

not prove

19 — Sensitivity or limit case

Annual mass scales linearly with throughput and availability.

20 — Guided and autonomous practice

Guided exercise. 10 kg/h at 80% availability: annual production?

Guided correction — open after attempting the exercise

$10 \times 8760 \times 0.8 = 70,080$ kg/year.

Autonomous exercise. What throughput is needed for 100 t/year at 85% availability?

Autonomous correction — open after attempting the exercise

$100000 / (8760 \times 0.85) \approx 13.43$ kg/h.

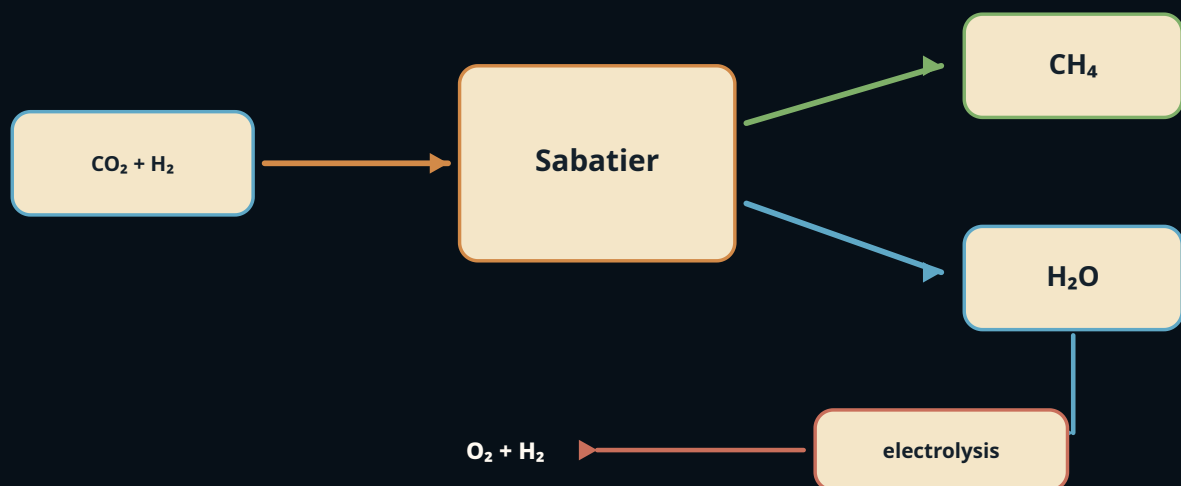
21 — Mission decision

Size capacity using demonstrated availability and credible maintenance margin.

Scaling requires compression, filtration, thermal control, power, maintenance, and storage; multiplying flow rate is not plant design.

Space Academy · 03

Boucle Sabatier-électrolyse / Sabatier-electrolysis loop



Tracking atoms reveals the hydrogen that does not return

Electrolysis–Sabatier coupling: track chemical species moving between the two processes.

10. Corrosion, materials, contamination

Surface chemistry depends on water, oxygen, salts, temperature, and material. “Stainless” does not mean is impossible. Seals, coatings, alloys, cleaning, and inspection must match a defined environment.

Perchlorate-bearing materials and Martian dust add problems requiring characterization and separation rules. “Martian soil” is not one chemically uniform substance.

Case study — contamination and acceptance criteria

A chemical product is not defined only by its name. Water containing 50 mg/L of a contaminant is not equivalent to water at 0.5 mg/L, even though both are “water.” If an 800 L tank contains 2 mg/L of a dissolved species, total mass of that species is 1,600 mg or 1.6 g. The calculation converts concentration into inventory and helps size purification or monitoring. Quantitative reference

Measurement must match a relevant limit and an analytical method capable of testing it. A sensor with insufficient sensitivity can report “not detected” without proving the concentration acceptable. Mars industrial chemistry therefore links composition, measurement method, detection limit, sampling interval, and response to exceedance. Purity is measured evidence, not a label. Quantitative reference

Contaminant mass from concentration

$$m = C \cdot V$$

1 — Concrete question	What contaminant mass corresponds to a known concentration in a given volume?
2 — Intuition without symbols	Concentration is mass per volume; multiplying by total volume reconstructs contained mass.
3 — Quantities first	m: contaminant mass; C: mass concentration; V: solution or fluid volume.
4 — Formula	$m = C \cdot V$
5 — Read aloud	Read the relation by naming every quantity and operation: $m = C \cdot V$.
6 — Symbols and meaning	The volume basis in C must match the unit used for V.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	C in mg/L, V in L, result in mg; or any consistent unit set.
9 — Convention	Convert volume or concentration before multiplication if units do not match.
10 — Why this operation	Each liter contains C milligrams; V liters therefore contain C times V.
11 — Assumptions	Uniform concentration representative of the considered volume.
12 — Unit check	$(\text{mg/L}) \times \text{L} = \text{mg}$.
13 — Numerical case	$2 \text{ mg/L} \times 800 \text{ L} = 1,600 \text{ mg} = 1.6 \text{ g}$.
14 — Why the calculation works	Multiplication implicitly sums the same mass per liter over the full volume.

15 — Algebra check	$C=m/V$ and $V=m/C$.
16 — Mental estimate	2 mg/L over 1,000 L would give 2 g; over 800 L, 1.6 g is plausible.
17 — Interpretation	Total mass helps assess filter loading, toxicity, recovery or cleanup.
18 — What it does not prove	A volume average may hide higher local contamination.
19 — Sensitivity or limit case	At fixed C , m scales with V ; at fixed V , it scales with C .
20 — Guided and autonomous practice	----- Guided exercise. 3 mg/L in 500 L: what mass? Guided correction — open after attempting the exercise 1,500 mg=1.5 g. Autonomous exercise. What concentration corresponds to 2 g in 400 L? Autonomous correction — open after attempting the exercise 2,000 mg/400 L=5 mg/L.
21 — Mission decision	Compare total mass and local concentration with filtration and health limits.

Control point

Corrosion and contamination describe surface or material changes that can alter strength, sealing, electrical contact, or cleanliness. A settlement must connect environmental chemistry, material choice, and inspection method. Quantitative reference

If a wall loses 0.05 mm/year uniformly in a simplified model, a 0.5 mm allowance corresponds to ten years. Localized pitting can penetrate much earlier despite the same average loss. An engineer keeps numerical result, margin, and validity domain separate.

Lifetime of a corrosion thickness margin

$$t_{\text{margin}} = e_{\text{margin}}/v_{\text{corrosion}}$$

1 — Concrete question	How long does extra thickness protect a component under an assumed steady corrosion rate?
2 — Intuition without symbols	If a surface loses the same thickness each year, lifetime is available margin divided by yearly loss.

3 — Quantities first	t_{margin} : covered time; e_{margin} : sacrificial thickness; $v_{\text{corrosion}}$: thickness-loss rate.
4 — Formula	$t_{\text{margin}} = e_{\text{margin}}/v_{\text{corrosion}}$
5 — Read aloud	Read the relation by naming every quantity and operation: $t_{\text{margin}} = e_{\text{margin}}/v_{\text{corrosion}}$.
6 — Symbols and meaning	Rate must use the same thickness basis as the margin, for example mm/year.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	e in mm, v in mm/year, result in years.
9 — Convention	Use a conservative rate representative of material, environment and actual protection.
10 — Why this operation	Dividing thickness reserve by thickness consumed each year gives years of coverage.
11 — Assumptions	Constant uniform corrosion rate with no accelerated pitting.
12 — Unit check	$\text{mm}/(\text{mm}/\text{year})=\text{year}$.
13 — Numerical case	$2 \text{ mm} / 0.05 \text{ mm}/\text{year} = 40 \text{ years}$.
14 — Why the calculation works	Division compares thickness inventory with its consumption rate.
15 — Algebra check	$e_{\text{margin}}=t_{\text{margin}} v_{\text{corrosion}}$.
16 — Mental estimate	0.05 mm/year means 1 mm in 20 years; 2 mm gives about 40 years.
17 — Interpretation	The result gives a scale for inspection, replacement or design margin.
18 — What it does not prove	Real corrosion may be localized, variable, galvanic or accelerated by coating damage.
19 — Sensitivity or limit case	Doubling margin doubles lifetime; doubling corrosion rate halves it.
20 — Guided and autonomous practice	----- Guided exercise. 1.5 mm margin at 0.03 mm/year: lifetime? Guided correction — open after attempting the exercise $1.5/0.03=50 \text{ years}$. Autonomous exercise. What margin is needed for 25 years at 0.08 mm/year? Autonomous correction — open after attempting the exercise $25 \times 0.08=2 \text{ mm}$.

21 — Mission decision

Combine this calculation with inspection, coupons, sensors and localized-corrosion margin.

A corrosion rate measured in one environment must not be transferred without validation to another mixture, temperature, or surface condition. Quantitative reference

11. Concentration needs units and definition

Concentration may be reported as mg/L, mol/m³, mole fraction, mass fraction, or other forms. The numerical value is incomplete without the definition and unit. Quantitative reference

Health or process limits can also depend on averaging time and sampling method. Copying the number alone discards essential specification context.

Interpretation

A concentration must state its basis: mass per volume, amount per volume, mass fraction, mole fraction, or ppm. Without the definition, numerically similar values can describe different things. Quantitative reference

Dissolving 5 g solute to a final volume of 2 L gives 2.5 g/L. If the statement means “2 L solvent plus solute” rather than final solution volume, the exact concentration can differ. The formula is useful because it makes a system dependency visible.

Mass concentration

$$C_m = m_{\text{solute}}/V_{\text{solution}}$$

1 — Concrete question	What mass concentration results from a solute mass distributed in a solution volume?
2 — Intuition without symbols	Concentration relates an amount of mass to the volume in which it is distributed.
3 — Quantities first	C_m : mass concentration; m_{solute} : solute mass; V_{solution} : final solution volume.
4 — Formula	$C_m = m_{\text{solute}}/V_{\text{solution}}$
5 — Read aloud	Read the relation by naming every quantity and operation: $C_m = m_{\text{solute}}/V_{\text{solution}}$.
6 — Symbols and meaning	Volume is the final solution volume, not necessarily initial solvent volume.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	Examples: g/L, mg/L or kg/m ³ .
9 — Convention	Keep a consistent volume basis and convert prefixes before comparing limits.
10 — Why this operation	Dividing distributed mass by volume gives mass per unit volume.

11 — Assumptions	Uniform mixture and known final volume.
12 — Unit check	g/L or equivalent mass-per-volume unit.
13 — Numerical case	$5 \text{ g} / 2 \text{ L} = 2.5 \text{ g/L}$.
14 — Why the calculation works	Division normalizes mass by volume size.
15 — Algebra check	$m_{\text{solute}} = C_m V_{\text{solution}}$.
16 — Mental estimate	5 g in roughly 2 L should give a few g/L, here 2.5.
17 — Interpretation	This concentration can be compared with process, health or quality specifications.
18 — What it does not prove	An average concentration does not guarantee local uniformity or absence of precipitation.
19 — Sensitivity or limit case	At fixed mass, doubling volume halves C_m .
20 — Guided and autonomous practice	----- Guided exercise. 12 g in 3 L: concentration? Guided correction — open after attempting the exercise 4 g/L. Autonomous exercise. What mass is needed for 1.5 g/L in 8 L? Autonomous correction — open after attempting the exercise $1.5 \times 8 = 12 \text{ g}$.
21 — Mission decision	Use actual measured concentration to decide filtration, dosing or rejection.

ppm is not universally mg/L; the approximate equivalence depends on density and definition.

Chemistry check for 11. Concentration needs units and definition.

12. Combined loop: identify what does not return

Ideal Sabatier uses 44 kg CO₂ and 8 kg H₂ to make 36 kg H₂O. Ideal electrolysis of that water returns about 4 kg H₂ and 32 kg O₂. Only half of the 8 kg hydrogen used returns through the water.

The cycle therefore needs additional hydrogen or a different architecture. Atom bookkeeping prevents circular diagrams from creating material by implication.

Guided project — follow atoms through an oxygen-methane-water loop

Build an ideal batch from 88 kg CO₂ and 16 kg H₂. The ratio is twice the Sabatier equation, yielding ideally 32 kg CH₄ and 72 kg H₂O. Total input is 104 kg and total output is 104 kg. If all water is electrolysed, 72 kg ideally yields 8 kg H₂ and 64 kg O₂. Only 8 kg of the original 16 kg hydrogen feed therefore returns as hydrogen; the other half is bound into methane.

Now assume a 90% overall Sabatier conversion for the exercise, without modelling side reactions. You cannot simply multiply every output by 0.90 and make the rest disappear: the unconverted 10% remains as reactants or other species that must appear in the balance. A teaching approximation is to treat 90% of the batch as ideally converted and 10% as unreacted. That gives 28.8 kg CH₄ and 64.8 kg H₂O while about 8.8 kg CO₂ and 1.6 kg H₂ remain for separation, recycle, or purge. Quantitative reference

Ideal electrolysis of 64.8 kg water would yield 7.2 kg H₂ and 57.6 kg O₂. If electrolysis converts only 95% of water per pass, instantaneous streams differ again. Recycle loops return unconverted material but add separators, pumps, sensors, and energy. '90% efficiency' is incomplete language unless it says chemical conversion, energy efficiency, material recovery, or product purity.

Add quality next: oxygen for a habitable atmosphere and oxygen for propulsion can have different pressure, purity, contamination, and storage requirements. A flow measurement of 10 kg/h proves nothing about composition. Conversely, 99.9% purity does not prove adequate throughput. Industrial processes track flow, composition, temperature, pressure, energy, availability, and equipment condition simultaneously. Quantitative reference

Finish with a boundary balance: which species enter from Mars or inventory, which return to the loop, which are consumed, and which losses require makeup? That table matters more than a slogan about a 'closed cycle.' Closure exists only for a defined boundary, time period, and set of species.

Sabatier–electrolysis loop: net balance



1 — Concrete question	What is actually recovered and consumed when ideal Sabatier and electrolysis are chained?
2 — Intuition without symbols	Chaining two reactions reveals which species return to the loop and which leave as net products.
3 — Quantities first	88 CO ₂ and 16 H ₂ : Sabatier feed; 32 CH ₄ and 72 H ₂ O: products; water electrolysis: 8 H ₂ recyclable and 64 O ₂ .
4 — Formula	$88 \text{ CO}_2 + 16 \text{ H}_2 \rightarrow 32 \text{ CH}_4 + 72 \text{ H}_2\text{O} \rightarrow 8 \text{ H}_2 + 64 \text{ O}_2$
5 — Read aloud	Read the relation by naming every quantity and operation: 88 CO ₂ + 16 H ₂ → 32 CH ₄ + 72 H ₂ O → 8 H ₂ + 64 O ₂ .
6 — Symbols and meaning	After ideal recycle of 8 kg H ₂ , external net H ₂ demand falls from 16 kg to 8 kg for this batch, while CH ₄ and O ₂ are net products.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	All mass-balance values use the same unit, here kg.
9 — Convention	Distinguish internal recycle streams from external consumed or produced streams.
10 — Why this operation	Adding steps then canceling recycled species reveals the net loop balance.
11 — Assumptions	Ideal reactions, complete water/H ₂ recovery, no purge or loss.

12 — Unit check	Sabatier: 104 kg in =104 kg out. Electrolysis: 72 kg H ₂ O =8+64 kg. Recycle redistributes without creating mass.
13 — Numerical case	The batch ideally gives 32 kg CH ₄ and 64 kg O ₂ , recycles 8 kg H ₂ and therefore needs 8 kg net external H ₂ .
14 — Why the calculation works	Writing each reaction separately then identifying the stream returned to feed avoids double-counting recycle.
15 — Algebra check	With ideal recycle, net external H ₂ = Sabatier H ₂ demand – H ₂ recovered by electrolysis.
16 — Mental estimate	Electrolysis of 72 kg water recovers 8 kg H ₂ , half of the initial 16 kg demand.
17 — Interpretation	The loop reduces net imported hydrogen demand while co-producing oxygen and methane.
18 — What it does not prove	Real efficiencies, purge, separation, compression and energy use reduce effective loop closure.
19 — Sensitivity or limit case	H ₂ recovery below 100% directly increases external makeup demand.
20 — Guided and autonomous practice	----- Guided exercise. If only 75% of the 8 kg produced H₂ is recovered, what net external makeup is needed? Guided correction — open after attempting the exercise Recycled H₂ = 6 kg; net makeup = 16–6=10 kg. Autonomous exercise. At 50% H₂ recovery, what net external makeup? Autonomous correction — open after attempting the exercise Recycle 4 kg; net makeup 12 kg.
21 — Mission decision	Size storage and imports using demonstrated recycle efficiency, not the ideal loop.

13. End-of-module check

- I know what a mole measures.
- I balance a simple reaction.
- I distinguish conversion, yield, and purity.
- I check electrolysis/Sabatier/combustion balances.
- I distinguish MOXIE demonstration from industrial plant.

- I keep concentration definition and units.

Corrected drill set — independent check

1. How many moles are in 36 g water with $M \approx 18$ g/mol? Quantitative reference

$n = m/M = 36/18 = 2$ mol. The mole converts measurable mass into amount of substance without counting individual molecules. Quantitative reference

2. Why balance an equation before calculating masses?

Balanced coefficients express conservation of atoms. Mass calculations on an unbalanced equation create an impossible material balance.

3. 44 kg CO₂ but only 4 kg H₂ for Sabatier: limiting reactant?

The ideal equation needs 8 kg H₂ for 44 kg CO₂. With only 4 kg H₂, hydrogen limits and only about half the CO₂ can react in the ideal model.

4. A 50 kg product is 98% pure. Impurity mass? Quantitative reference

Impure fraction is 2%, so $50 \times 0.02 = 1$ kg. The calculation does not identify impurity species or whether they are acceptable. Quantitative reference

5. Why does 95% recycling not automatically close a loop?

A 5% loss per pass still requires makeup and can accumulate over time. Species, purge streams, contaminants, and immobilized inventories also matter. Quantitative reference

Deep practice workshop

Treat each chemistry exercise as a material balance. Balance the species first, convert masses or gas quantities to moles when needed, identify the limiting reagent, and apply yield or purity only at the end. The solutions explicitly separate ideal stoichiometry, measured process performance, and engineering assumptions.

1. Moles

How many moles are in 96 g O₂?

Reasoned solution: $96/32 = 3$ mol. Quantitative reference

2. Balancing

Balance $\text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O}$. Quantitative reference

Reasoned solution: $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$. Quantitative reference

3. Limiting reagent

4 mol H₂ and 1 mol O₂: which limits? Quantitative reference

Reasoned solution: 1 mol O₂ needs 2 mol H₂. O₂ limits and 2 mol H₂ remains. Quantitative reference

The limiting reagent is the species exhausted first according to the balanced coefficients. Here one mole of O₂ can consume only two moles of H₂, so the remaining two moles must remain in the balance.

4. Purity

50 kg mixture at 92% useful product.

Reasoned solution: 46 kg useful product.

5. Partial pressure

25% O₂ at 80 kPa. Quantitative reference

Reasoned solution: pO₂=20 kPa. Quantitative reference

A 25% mole fraction gives 20 kPa only because total pressure is 80 kPa. Changing total pressure would change partial pressure even if composition stayed identical. Quantitative reference

6. Sabatier

88 kg CO₂ with enough H₂: ideal CH₄?

Reasoned solution: 44 kg CO₂ → 16 kg CH₄, so 88 → 32 kg CH₄. Quantitative reference

The 44 kg CO₂ to 16 kg CH₄ relation is ideal Sabatier stoichiometry with sufficient hydrogen. A real unit must also state conversion, selectivity, methane purity, and unreacted recycle streams. Quantitative reference

7. Combustion

How much ideal O₂ for 32 kg CH₄?

Reasoned solution: Ratio 16:64, so 128 kg O₂.

8. Loop capstone

A Sabatier unit receives 44 kg CO₂ and 8 kg H₂, then all produced water is electrolyzed. What ideal H₂/O₂ balance remains? Quantitative reference

Reasoned solution: Sabatier makes 36 kg H₂O and 16 kg CH₄. Electrolyzing 36 kg water returns 4 kg H₂ and 32 kg O₂. Only half the original H₂ returns, so 4 kg H₂ makeup or another recovery path is still required.

The capstone exposes the open hydrogen loop: electrolysis returns only 4 kg H₂ from the 8 kg initially injected. The missing 4 kg remains bound in methane unless another recovery route is added.

Additional advanced problems

1. Electrolyzed water

18 kg H₂O ideally gives how much H₂ and O₂?

Reasoned solution: Half the 36 kg balance: 2 kg H₂ and 16 kg O₂.

Half the water batch gives half the ideal products because this stoichiometric scaling is linear. That linearity should not be assumed for real machine efficiency at partial load.

2. Mole fraction

2 mol O₂ + 8 mol N₂, O₂ fraction? Quantitative reference

Reasoned solution: $2/10=0.20=20\%$. Quantitative reference

3. Yield

Maximum 250 kg, actual 210 kg.

Reasoned solution: 84%.

4. MOXIE mini-project

At 12 g/h for 10 h, production? Why not scale directly to a factory?

Reasoned solution: 120 g. A factory adds availability, power, compression, thermal control, filtration, maintenance, and storage; flow alone is not architecture. Quantitative reference

The 120 g is cumulative production at a fixed demonstrated rate for ten hours. It does not turn MOXIE into a plant; an industrial system also needs availability, compression, thermal control, filtration, storage, and maintenance.

Chemistry laboratory — track atoms, purity and process losses

This parity extension deepens the operational reasoning of the English curriculum without replacing the existing lesson. It is designed to make the learner explain assumptions, verify a calculation or chain, and convert the result into a decision.

Start with the chemical inventory, not the equipment

A process diagram is easier to reason about when every stream has a defined chemical composition, flow basis and purity. The learner should track atoms through reactions before discussing compressors, reactors or separators. Stoichiometry tells what is theoretically required; equipment performance tells how closely the real process approaches that limit. Confusing those two levels leads to impossible mass balances and hidden makeup requirements. Quantitative reference

Use the mole to connect microscopic chemistry and plant-scale mass

The mole lets chemical equations become quantitative. Coefficients in a balanced reaction describe molar ratios, not directly kilograms. Converting between moles and mass requires molar mass. This distinction is essential when comparing oxygen, hydrogen, carbon dioxide and methane streams because equal numbers of moles do not have equal masses. Every worked reaction should therefore show at least one explicit conversion between amount of substance and mass.

Close electrolysis and Sabatier as coupled loops

Water electrolysis can provide oxygen and hydrogen; the Sabatier reaction can combine hydrogen with carbon dioxide to produce methane and water. Coupling the processes creates useful recirculation, but it does not create a perfectly closed loop. Separation losses, purge streams, maintenance, contamination and the intended export of oxygen or methane all change the inventory. The correct engineering question is which atoms leave the defined boundary and at what rate.

Separate reaction yield from product purity

A reactor may convert a high fraction of the limiting reactant while still producing a stream that requires substantial purification. Yield, conversion, selectivity and purity answer different questions. For life-support or propellant use, downstream specifications may matter more than the reactor headline number. A robust design therefore includes sampling points, off-spec storage or recycle routes and a decision rule for when product is acceptable for its intended use. Quantitative reference

Treat contamination as chemistry plus operations

Corrosion products, lubricants, dust, cleaning agents and microbial films can alter process chemistry even when the nominal reaction is correct. Materials compatibility and cleanliness control belong in the chemical flowsheet. A maintenance action that opens a clean line to the workshop environment may create more risk than a small change in reaction efficiency. The process boundary must therefore include interfaces where contamination can enter. Quantitative reference

Use demonstration results at the correct scale

A successful technology demonstration establishes that a principle can operate under defined conditions; it does not automatically establish settlement-scale capacity, reliability or maintainability. Scaling requires throughput, duty cycle, energy, thermal rejection, feed variability, spare parts and quality control to be closed together. The learner should state clearly whether a cited result is a laboratory result, a flight demonstration or an operational production requirement.

Progressive mastery drills — eight linked checks

Drill 1 — Mole and molar mass

Convert between amount of substance and mass without treating one mole of different gases as equal mass.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 2 — Balanced reaction

Use coefficients in a balanced reaction to define theoretical reactant ratios before applying real conversion efficiency.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 3 — Gas composition

Explain why percent composition must state whether it is molar, mass or another basis.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 4 — Electrolysis

List the electrical, water-quality and gas-separation information needed to turn electrolysis chemistry into a plant balance.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 5 — Sabatier loop

Trace carbon and hydrogen atoms through carbon dioxide, hydrogen, methane and water, including what leaves the boundary.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 6 — Combustion

Separate stoichiometric requirement from operational mixture ratio and explain why excess reactant changes exhaust composition.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 7 — Purity and yield

Describe a case where reactor conversion is high but product cannot yet be released for use.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Drill 8 — Contamination control

Explain how maintenance materials or dust can enter a chemical process and which acceptance check should catch the problem.

Expected reasoning. Show the physical meaning, units or evidence path, state at least one assumption, and explain what operational decision would change if the result or evidence were different.

Integrated exercise — Audit a simplified oxygen-production chain

A training process receives a carbon-dioxide-rich feed, separates the required fraction, converts part of it to oxygen and stores product only after a purity check. List at least six quantities that must be recorded to close the material and quality balance. Do not assume the reactor conversion alone is sufficient. Quantitative reference

Reasoned solution. A defensible list includes feed mass or molar flow, feed composition, accepted inlet fraction, reactor conversion, product oxygen flow, off-gas flow, water or other co-products where relevant, product purity, rejected/off-spec product, recycle flow, operating time and uncertainty. The exact list depends on the chosen process boundary, which must be stated. Quantitative reference

Primary-source bridge for this extension. [Official source 1](#) [Official source 2](#) [Official source 3](#). These links are evidence anchors already present in the French reference module; values and limits must still be checked against the source version applicable to the mission.

Sources and references

The sources separate chemical laws, constants, and demonstrated technology. Plant-scale flows used for scaling exercises are teaching scenarios, not announced capabilities.

- [NIST — SI Units: Amount of Substance](#) — Exact definition of the mole and Avogadro constant.
- [NASA Glenn — Equation of State](#) — Ideal-gas relation and state variables.
- [NASA — Environmental Control and Life Support System](#) — Operational ISS life-support architecture.

- [NASA/JPL — MOXIE completes Mars mission](#) — 122 g total O₂, up to 12 g/h, at least 98% purity.
- [NASA TechPort — MARS-C](#) — Primary or institutional source used for definitions, technology status, or module data.

First Man chemistry closure dossier — balances, purity and process evidence

Chemistry in a Mars system is operational accounting of matter. Atoms do not disappear because a process is convenient. Feed composition, conversion, selectivity, purity, contaminants, storage and analytical evidence all have to close before a product can be released for use.

Moles connect microscopic composition to engineering quantities

The mole is the bridge between particle count and measurable mass. [NIST — SI units: amount of substance](#) defines amount of substance in the SI framework. In practical process work, molar relationships tell us how much reactant is theoretically required and how much product could be formed if the reaction and separation were ideal.

Beginners should keep three layers separate: chemical equation, amount of substance and mass. Balancing the equation gives stoichiometric ratios in moles; molar masses then convert those amounts to grams or kilograms. Skipping directly from coefficients to kilograms is a common error.

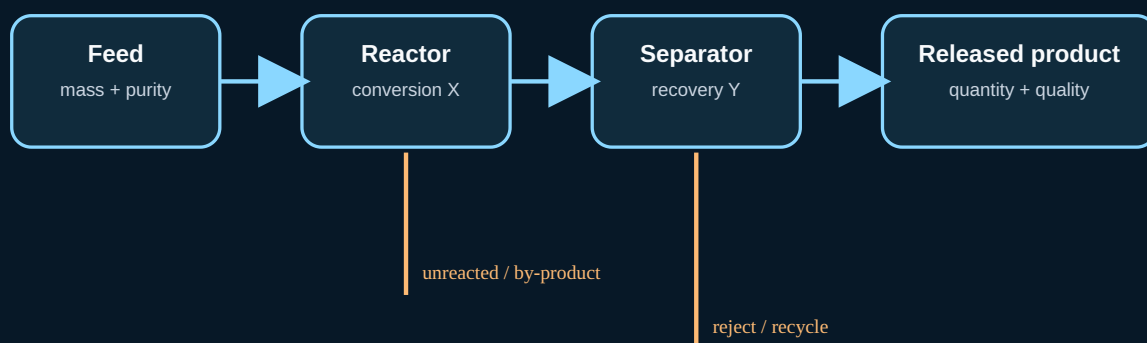
A process balance distinguishes feed, reacted material and released product

Real systems have losses. The feed may contain impurities, only part of the usable feed may react, side reactions may consume material, and the separation train may fail to recover all desired product. A single 'efficiency' number can hide these mechanisms. It is better to write a chain: feed mass → usable fraction → converted fraction → recovered on-spec product. Quantitative reference

This chain also exposes where evidence belongs. Feed purity comes from incoming material characterization; conversion may come from reactor measurements; recovered mass comes from the separator; final product quality comes from analytical verification. A process is not qualified merely because the mass balance looks plausible. Quantitative reference

Chemical process mass balance

Feed, impurities, conversion, recovery, analysis and release.



Delta-Sierra pedagogical synthesis · schematic, not to scale

Feed, impurities, conversion, recovery, analysis and release. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Gas chemistry is a mixture problem as well as a pressure problem

A habitat atmosphere contains multiple gases. The total pressure is the sum of partial pressures, while physiological and flammability concerns often depend on individual constituents. Carbon dioxide control, oxygen addition and inert-gas inventory therefore require composition measurements, not just one pressure gauge. Quantitative reference

Life-support systems combine chemistry, adsorption, catalysis, phase change and fluid handling. The [NASA — Environmental Control and Life Support System](#) provides mission-system context. When teaching a reaction or sorbent model, always state whether the number is a stoichiometric ideal, an observed performance value or a design assumption.

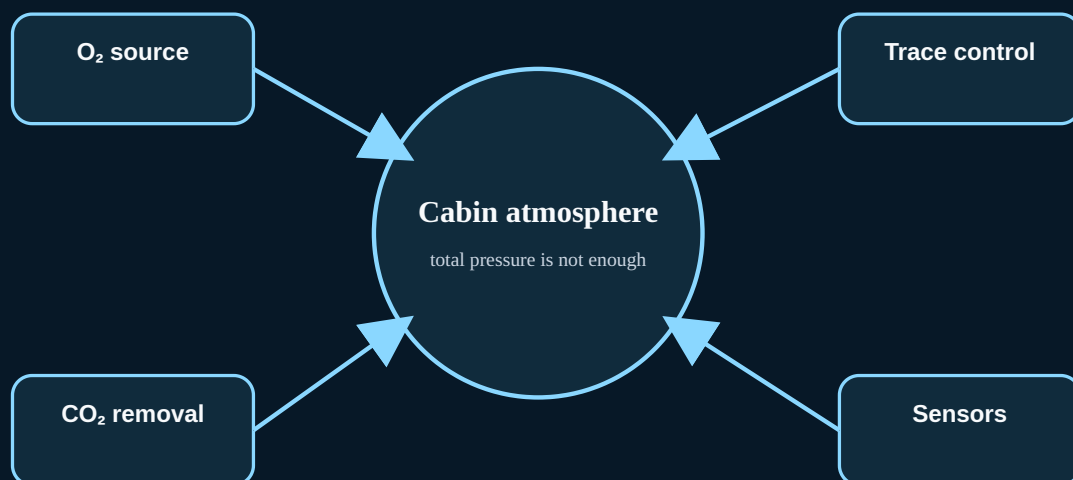
ISRU turns local material into a qualified process stream

MOXIE demonstrated oxygen production from the Martian atmosphere, providing a concrete example of in-situ resource utilization. The [NASA/JPL — MOXIE completes Mars mission](#) describes the experiment. The correct lesson is not that oxygen production is 'solved'; it is that a process chain can be demonstrated, measured and progressively scaled while tracking power, throughput, purity, thermal conditions and degradation.

Scale-up introduces new questions: feed conditioning, dust tolerance, heat rejection, maintenance access, spare parts, quality control and storage. A chemistry module must therefore connect reaction equations to plant behaviour rather than stopping after stoichiometry.

Atmosphere chemistry boundary map

Oxygen, carbon dioxide, trace contaminants and verification paths.



Delta-Sierra pedagogical synthesis · schematic, not to scale

Oxygen, carbon dioxide, trace contaminants and verification paths. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Release criteria turn a chemical batch into usable inventory

A product becomes mission inventory only after its identity and quality are demonstrated. NASA technology work such as [NASA TechPort — MARS-C](#) illustrates how local-resource concepts must be integrated into broader systems. In a settlement, an oxygen stream, cleaning fluid or construction reagent may have different allowable impurity limits depending on use. Quantitative reference

A strong release record states the specification, sample method, instrument, calibration status, result, uncertainty and disposition. Material that is chemically close to target but outside a critical impurity limit may be reprocessed, downgraded to another use or rejected rather than silently mixed into good stock. Quantitative reference

Worked process dossier — oxygen production is more than reaction yield

Imagine a local oxygen-production plant receives a carbon-dioxide-rich feed. The chemistry may suggest a theoretical oxygen yield, but the plant review must also account for feed composition, compressor performance, reactor conversion, separator losses, product purity, storage, sensor calibration and contaminants. Each stage has a different failure mode. A mass balance that closes does not prove that the oxygen meets a breathing, propulsion or industrial specification. Quantitative reference

The operator should therefore maintain two ledgers. The quantity ledger follows mass through feed, reaction, recycle, reject and storage. The quality ledger follows composition, water content, trace species, sampling method and release status. Material can exist physically in a tank while remaining unavailable to the mission because its quality has not been verified. Conversely, a high-purity batch may be too small to satisfy the required reserve. Quantity and quality are independent gates.

Stage	Evidence	Possible disposition
Feed	Composition / pressure / dust control	Accept, condition, reject
Reaction	Temperature / conversion / stability	Continue, derate, stop

Stage	Evidence	Possible disposition
Separation	Recovery / contaminant carryover	Recycle or reprocess
Product	Identity / purity / quantity	Release, downgrade, quarantine

Chemical release scenario — a batch that is almost right

A batch meets its required oxygen quantity but one impurity exceeds the limit. The wrong response is to average the result with a previous good batch unless the procedure explicitly allows blending and the resulting mixture can be verified. The defensible response is to quarantine the batch, confirm the analytical result, investigate the process step that could create the impurity and decide whether the material can be reprocessed or used for a less demanding function. Quantitative reference

This scenario teaches a broad principle: specifications are not suggestions. If several limits apply, passing four of five does not create an 80% pass. Some criteria are hard gates because failure creates a hazard or invalidates downstream assumptions. The student should learn to distinguish a continuous performance metric from a binary release criterion.

Review drills — move from explanation to operational judgement

- 1. Stoichiometry drill.** Balance a simple reaction before converting coefficients into masses.
- 2. Purity drill.** Explain why 100 kg of 80% feed is not equivalent to 100 kg pure reactant.
- 3. Atmosphere drill.** Describe why total pressure can remain stable while CO₂ concentration becomes unacceptable.
- 4. Release drill.** Write a disposition for an oxygen batch that meets quantity but misses a purity requirement.

Real product mass with purity, conversion and recovery

$$m_P = m_{\text{feed}} \cdot w \cdot X \cdot (v_P/v_R) \cdot (M_P/M_R) \cdot Y$$

1 — Concrete question	How much recoverable product results when feed is impure, conversion incomplete and recovery imperfect?
2 — Intuition without symbols	Stoichiometry sets an ideal ceiling; each real-world imperfection successively reduces recoverable product.
3 — Quantities first	m_P : recovered product mass; m_{feed} : gross feed mass; w : purity; X : conversion; v_P/v_R : stoichiometric molar ratio; M_P/M_R : mole-to-mass factor; Y : final recovery.
4 — Formula	$m_P = m_{\text{feed}} \cdot w \cdot X \cdot (v_P/v_R) \cdot (M_P/M_R) \cdot Y$
5 — Read aloud	Read the relation by naming every quantity and operation: $m_P = m_{\text{feed}} \cdot w \cdot X \cdot (v_P/v_R) \cdot (M_P/M_R) \cdot Y$.
6 — Symbols and meaning	Factors w , X and Y lie between 0 and 1; stoichiometric and molar-mass ratios encode reaction chemistry.
7 — Pronunciation	Name every symbol, subscript and operator separately from its unit.
8 — Units	m_{feed} and m_P use the same mass unit; all other factors are compatible ratios.
9 — Convention	Apply factors traceably and do not confuse chemical conversion with physical product recovery.

10 — Why this operation	Each multiplication removes an unavailable fraction or converts reactant to product through stoichiometry.
11 — Assumptions	One reference reactant limits production and all factors represent the same batch.
12 — Unit check	Fractions and ratios are dimensionless, so the result retains the feed mass unit.
13 — Numerical case	For 1,000 kg gross CO ₂ at w=0.90, X=0.80, CH ₄ /CO ₂ mass ratio 16/44 and Y=0.95: m _{CH₄} ≈248.7 kg.
14 — Why the calculation works	Purity isolates available reactant, X applies converted fraction, the mass ratio gives product ceiling, and Y keeps the recovered fraction.
15 — Algebra check	Overall yield relative to gross feed is the product of all multiplicative factors.
16 — Mental estimate	The 16/44 ratio is about 0.36; with three factors below 1, final product must be well below 360 kg per gross tonne.
17 — Interpretation	This relation links resource quality, reactor performance and separation directly to recoverable production.
18 — What it does not prove	It does not replace a multi-reactant balance, kinetics, or a full energy/recycle model.
19 — Sensitivity or limit case	A 10% relative decrease in w, X or Y causes a 10% relative product decrease if other factors stay fixed.
20 — Guided and autonomous practice	----- Guided exercise. 500 kg gross CO₂, w=0.8, X=0.9, Y=1: recoverable CH₄ at 16/44? Guided correction — open after attempting the exercise 500×0.8×0.9×16/44≈130.9 kg. Autonomous exercise. Repeat the 1,000 kg case with Y=0.80. What CH₄ mass? Autonomous correction — open after attempting the exercise 1000×0.9×0.8×16/44×0.8≈209.5 kg.
21 — Mission decision	Use recoverable production, not the stoichiometric ceiling, to close mission demand.

The mass-basis method is tied to a named reaction rather than a generic retained fraction. See [NIST on amount of substance](#) for the mole basis and [NASA MOXIE mission context](#) for Mars oxygen-production relevance.

Final chemistry review — quantity, identity and quality must all close

- Is the chemical equation balanced before mass conversion?
- Are feed purity, conversion and recovery treated separately?
- Are percentages entered as fractions in calculations?
- Does atmosphere analysis distinguish total pressure from composition?
- Is a product batch quarantined until its release evidence is complete?

- Can reject, recycle and off-spec material be traced?

The strongest habit in process chemistry is refusing to call material usable merely because it exists. A tank can contain enough mass and still fail identity or purity. Conversely, excellent purity does not satisfy an inventory requirement if the quantity is too small. The release decision must close both ledgers. Quantitative reference

Primary-source bridges used in this closure dossier

- NIST — SI units: amount of substance
- NASA — Environmental Control and Life Support System
- NASA/JPL — MOXIE completes Mars mission
- NASA TechPort — MARS-C

Closure rule. A chemical batch is mission-usable only when quantity and quality gates both close with traceable analytical evidence.

FR ↔ EN competency matrix

This matrix verifies FR ↔ EN intellectual coverage competency by competency across the canonical mini-lessons.

Competency	French	English	Status
01	Quantité de matière à partir de la masse	Amount of substance from mass	PASS
02	Compter les atomes par coefficient moléculaire	Counting atoms from molecular coefficients	PASS
03	Équilibrer l'électrolyse de l'eau	Balancing water electrolysis	PASS
04	Masse utile à partir de la pureté	Usable mass from feed purity	PASS
05	Pression partielle dans un mélange gazeux	Partial pressure in a gas mixture	PASS
06	Bilan massique idéal de l'électrolyse	Ideal mass balance of electrolysis	PASS
07	Bilan stœchiométrique de Sabatier	Sabatier stoichiometric mass balance	PASS
08	Combustion stœchiométrique du méthane	Stoichiometric methane combustion	PASS
09	Passer d'un débit journalier à un débit horaire et à un nombre d'unités	Convert daily throughput to hourly rate and unit count	PASS
10	Production annuelle avec disponibilité	Annual production with availability	PASS
11	Masse de contaminant à partir d'une concentration	Contaminant mass from concentration	PASS
12	Autonomie d'une marge d'épaisseur face à la corrosion	Lifetime of a corrosion thickness margin	PASS
13	Concentration massique	Mass concentration	PASS
14	Boucle Sabatier–électrolyse : bilan net	Sabatier–electrolysis loop: net balance	PASS
15	Masse de produit réelle avec pureté, conversion et récupération	Real product mass with purity, conversion and recovery	PASS