

Fire, depressurization, refuge and internal emergency response

Prepare for events that immediately threaten the crew: fire, pressure loss, smoke, compartment isolation and internal evacuation.

Before starting — Prerequisites: modules 00 to 40 recommended as relevant. Every important symbol is defined at first use.

Mastery objectives

- identify the functions, interfaces and degraded scenarios specific to the subject
- repeat simple calculations and verify units, assumptions and margins
- turn a principle into a verifiable procedure or decision
- connect the subsystem to human, energy and logistics constraints

1. Spacecraft fire combines combustion, toxicity and loss of function

In a pressurized volume, fire is not only a heat source. It creates smoke and contaminants, can damage wiring and fluid lines and may force the crew to abandon a compartment. Detection, warning and extinguishing therefore have to be designed together with ventilation and respiratory protection. An extinguisher that can only be reached through the fire is not a real safety barrier.

2. Detect early without training the crew to ignore alarms

Sensors must detect smoke, heat or combustion products early enough to matter, while excessive false alarms destroy trust. Procedures include rapid confirmation, localization, ventilation actions and respiratory protection. An alarm should tell the crew what is happening, where it is happening and what first action is expected.

3. Depressurization: locate, isolate and count useful seconds

A leak may be slow or rapid. Response depends on volume, leak rate and the time required to close a hatch or enter a refuge. Pressure compartments and isolatable doors turn a large base into manageable volumes. Differential-pressure measurements and makeup-gas flow help distinguish a real leak from a failed sensor.

4. Refuge: survive while diagnosis continues

A refuge needs breathable atmosphere, carbon-dioxide control, water, communications, power and medical capability for its design duration. Its purpose is to create time to inspect the damaged area, decide on repair or wait for another option. A refuge is therefore a small autonomous life-support system, not merely a strong room.

5. Internal evacuation and an injured crewmember

A crewmember may be unable to move without assistance. Routes, openings and equipment must support assisted transport, stretchers or suited extraction. Procedures assign roles and muster points so that nobody is forgotten inside an isolated module.

6. After the flame: contamination and safe return to service

Extinguishing visible fire is not the end of the event. The crew must measure atmosphere, inspect wiring, materials and structure, identify the initiating cause and decide which equipment can safely be re-energized. Restoration should be staged and documented because partially damaged hardware can become the cause of the next incident.

7. Detection: a sensor is not a decision

A smoke, pressure or temperature detector must not be mistaken for a complete diagnosis. A pressure change can result from leakage, an airlock cycle or a deliberate operation; particles can trigger an optical detector without an established fire. Emergency logic should combine several cues, timestamp them and relate them to operational context. A useful alarm states what was detected, where, for how long, which confirmations exist and what automatic action has already occurred. Procedures must also include contradictory sensors, because opening a door or stopping ventilation at the wrong time can create an additional hazard.

8. Isolation: stop propagation without trapping the crew

Closing a bulkhead or valve appears simple until people, power, air or an evacuation route depend on that path. Isolation should be designed as a sequence: identify the compartment, confirm occupant location, transfer indispensable functions, close propagation paths and verify that the healthy zone remains stable. Depressurization adds a physical constraint because differential pressure can make a door impossible to open until pressures are equalized. Rescue paths must therefore match pressure physics and the actual capacity of the refuge.

9. Recovery after an incident: restore service without erasing evidence

After extinguishing a fire or sealing a leak, immediate restart is not the next objective. Pressure stability, toxic products, temperature, electrical integrity and hidden damage must first be checked. Alarm logs, valve states, sensor measurements and damaged parts should be preserved for causal analysis. In a distant settlement this investigation partly substitutes for immediate outside expertise. It should lead to a configuration action such as inspecting similar components, changing a procedure, adding protection or modifying training. Return to normal operation is therefore the final step of an learning loop, not simply the end of the emergency.

10. Worked example: time to a pressure threshold

An 80 m³ module loses an average 0.8% of initial pressure per minute in a simplified teaching model. Reaching a 10% loss therefore takes $10/0.8 = 12.5$ min. If the crew needs 6 min to confirm the leak, equip one person and isolate the compartment, only 6.5 min of time margin remain. The example shows why localization and isolation must be rapid.

Calculated case study: sizing an emergency refuge oxygen reserve

TEACHING ASSUMPTION — A refuge must support four people for two days. For the exercise, oxygen use is set to $q = 0.84$ kg per person per day, followed by a 30% margin. This value is only a teaching input and must be replaced by the mission design value.

Let n be the number of people; q oxygen mass per person per day in kg/(person·day); d duration in days; m the dimensionless margin; and M oxygen mass in kg.

$M = n \times q \times d = 4 \times 0.84 \times 2 = 6.72$ kg. With $m = 0.30$, $M_{\text{plan}} = 6.72 \times 1.30 = 8.736$ kg, or about 8.74 kg.

This is only a first consumables balance. A real refuge must also handle pressure, storage, regulation, CO₂ removal, humidity, temperature, leakage and the possibility of remaining isolated longer than planned.

11. Exercise

Write the first five minutes of response to smoke detected in the workshop while one crewmember is missing from the muster point. State who confirms the alarm, who protects atmosphere, who locates the person and under what conditions a search is abandoned.

12. Reasoned solution

A robust sequence confirms the alarm with several cues, locates the crew, preserves a refuge route, isolates ventilation and power where that reduces risk, then closes the compartment and checks neighbouring-zone stability. Simply shutting every door without checking crew location or pressure differential can create another hazard.

13. Validation mini-project

Build a combined fire-and-leak emergency analysis covering detection, barriers, breathing equipment, isolation, refuge, casualty handling, communications, restoration and end-of-alert criteria.

Fire and pressure loss are time-critical because the habitat itself is the survival system

Inside a Martian habitat, fire is more than visible flame. It can consume oxygen, release toxic products, damage electrical insulation, contaminate filters and destroy the functions needed to control the atmosphere. The immediate objective is therefore not simply “extinguish the fire.” The crew must detect the event, stop energy and airflow that feed propagation when appropriate, protect breathing, isolate the affected volume and preserve at least one safe refuge.

Depressurization creates another race against time. The rate of pressure loss depends on leak area, pressure, temperature and flow regime, but operations teams usually need a simpler question first: how much time remains before a declared threshold is crossed? Pressure trend, acoustic detection and compartment isolation turn an uncertain leak into a bounded emergency. The procedure should tell crews which doors or valves can be closed without trapping someone on the wrong side.

Refuge design changes the emergency from immediate evacuation of the whole settlement into controlled survival while diagnosis continues. A refuge needs atmosphere, carbon-dioxide removal, thermal control, communication, lighting, medical capability, water and sanitation for the stated duration. Physical seats alone do not define capacity. Refuge readiness should be exercised with the actual crew and emergency supplies.

After an incident, recovery is a technical investigation. Smoke residue can poison sensors, water can damage electronics, overheated structures can lose strength and emergency isolation can leave systems in unusual configurations. Returning to service requires inspection, cleaning, testing and configuration records. If the crew restores everything quickly but destroys the evidence of cause, the same failure can recur.

Four emergency concepts that determine whether the crew gains time or loses it

Early detection

Recognition of abnormal heat, smoke, gas composition, pressure trend or other signatures early enough that local control remains possible.

Isolation

Deliberate separation of a compartment, energy source or flow path to stop propagation while preserving viable escape and refuge routes.

Refuge

Protected compartment that can independently support occupants for a defined emergency duration.

Recovery evidence

Measurements, logs, photographs and component condition preserved so the cause and extent of damage can be established before return to normal service.

Calculation laboratory

Formula 1 — simple time to a pressure threshold

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must be replaced by mission data before any real decision.

Time to pressure threshold

$$t_{\text{pressure}} = (P_0 - P_{\text{min}}) / r_{\text{loss}}$$

1 — Concrete question

What does “ $t_{\text{pressure}} = (P_0 - P_{\text{min}}) / r_{\text{loss}}$ ” compute in “Time to pressure threshold”?

2 — Intuition without symbols

Under a constant-rate approximation, available time is allowable pressure drop divided by loss rate.

3 — Quantities

t_{pressure} : time before reaching threshold [min]; P_0 : initial pressure [kPa]; P_{min} : minimum allowable pressure [kPa]; r_{loss} : assumed constant pressure-loss rate [kPa/min]

4 — Formula

$$t_{\text{pressure}} = (P_0 - P_{\text{min}}) / r_{\text{loss}}$$

5 — Read aloud

Read “ $t_{\text{pressure}} = (P_0 - P_{\text{min}}) / r_{\text{loss}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{pressure} : time before reaching threshold [min]; P_0 : initial pressure [kPa]; P_{min} : minimum allowable pressure [kPa]; r_{loss} : assumed constant pressure-loss rate [kPa/min]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{pressure} [min]; P_0 [kPa]; P_{min} [kPa]; r_{loss} [kPa/min]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the system mechanism into a quantity that can be checked by numerical substitution.

11 — Assumptions

All inputs must be coherent in unit, frame, duration and scenario.

12 — Independent check

A second method or inverse relation should recover the same order of magnitude.

13 — Numerical case

With $P_0 = 70$ kPa, $P_{\text{min}} = 55$ kPa, $r_{\text{loss}} = 3$ kPa/min: $t_{\text{pressure}} = (70 - 55) / 3 = 5$ min.

14 — Why the calculation works

The relation turns the system mechanism into a quantity that can be checked by numerical substitution.

15 — Verification

A second method or inverse relation should recover the same order of magnitude.

16 — Mental estimate

Estimating before calculation helps detect sign, unit or factor errors.

17 — Interpretation

Treat this time as a prioritization estimate, never as a guarantee that leak flow remains constant.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $P_0 = 68$ kPa, $P_{\min} = 56$ kPa, $r_{\text{loss}} = 2$ kPa/min:
 $t_{\text{pressure}} = (68 - 56) / 2$?

Detailed guided correction — open after trying

With $P_0 = 68$ kPa, $P_{\min} = 56$ kPa, $r_{\text{loss}} = 2$ kPa/min: $t_{\text{pressure}} = (68 - 56) / 2 = 6$ min. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $P_0 = 62$ kPa, $P_{\min} = 50$ kPa, $r_{\text{loss}} = 1.5$ kPa/min:
 $t_{\text{pressure}} = (62 - 50) / 1.5$?

Autonomous correction — open after trying

With $P_0 = 62$ kPa, $P_{\min} = 50$ kPa, $r_{\text{loss}} = 1.5$ kPa/min: $t_{\text{pressure}} = (62 - 50) / 1.5 = 8$ min. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Treat this time as a prioritization estimate, never as a guarantee that leak flow remains constant.

Refuge oxygen endurance

$$T_{\text{O}_2} = Q_{\text{O}_2} / (N_{\text{crew}} \times q_{\text{O}_2})$$

1 — Concrete question

What does " $T_{\text{O}_2} = Q_{\text{O}_2} / (N_{\text{crew}} \times q_{\text{O}_2})$ " compute in "Refuge oxygen endurance"?

2 — Intuition without symbols

Refuge duration depends on usable stock divided by total crew consumption.

3 — Quantities

T_{O_2} : oxygen endurance [j]; Q_{O_2} : usable oxygen mass [kg]; N_{crew} : crew count [personnes]; q_{O_2} : use per person per day [kg/personne/j]

4 — Formula

$$T_{\text{O}_2} = Q_{\text{O}_2} / (N_{\text{crew}} \times q_{\text{O}_2})$$

5 — Read aloud

Read " $T_{\text{O}_2} = Q_{\text{O}_2} / (N_{\text{crew}} \times q_{\text{O}_2})$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

T_{O_2} : oxygen endurance [j]; Q_{O_2} : usable oxygen mass [kg]; N_{crew} : crew count [personnes]; q_{O_2} : use per person per day [kg/personne/j]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

T_{O_2} [j]; Q_{O_2} [kg]; N_{crew} [personnes]; q_{O_2} [kg/personne/j]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $Q_{O2} = 4.8$ kg, $N_{crew} = 6$ personnes, $q_{O2} = 0.8$ kg/personne/j: $T_{O2} = 4.8 / (6 \times 0.8) = 1$ j.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Never claim this endurance without also checking CO₂, water, heat, power and sanitation.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $Q_{O2} = 7.2$ kg, $N_{crew} = 6$ personnes, $q_{O2} = 0.8$ kg/personne/j: $T_{O2} = 7.2 / (6 \times 0.8)$?

Detailed guided correction — open after trying

With $Q_{O2} = 7.2$ kg, $N_{crew} = 6$ personnes, $q_{O2} = 0.8$ kg/personne/j: $T_{O2} = 7.2 / (6 \times 0.8) = 1.5$ j. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $Q_{O2} = 8.4$ kg, $N_{crew} = 5$ personnes, $q_{O2} = 0.84$ kg/personne/j: $T_{O2} = 8.4 / (5 \times 0.84)$?

Autonomous correction — open after trying

With $Q_{O2} = 8.4$ kg, $N_{crew} = 5$ personnes, $q_{O2} = 0.84$ kg/personne/j: $T_{O2} = 8.4 / (5 \times 0.84) = 2$ j. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Never claim this endurance without also checking CO₂, water, heat, power and sanitation.

Planned oxygen mass

$$M_{O2_plan} = N_{crew} \times q_{O2} \times d_{refuge} \times (1 + m_{margin})$$

1 — Concrete question

What does " $M_{O2_plan} = N_{crew} \times q_{O2} \times d_{refuge} \times (1 + m_{margin})$ " compute in "Planned oxygen mass"?

2 — Intuition without symbols

Planned stock starts from nominal consumption and then adds an explicit margin.

3 — Quantities

M_{O2_plan} : planned oxygen mass [kg]; N_{crew} : crew count [personnes]; q_{O2} : use per person per day [kg/personne/j]; d_{refuge} : target refuge duration [j]; m_{margin} : fractional margin [sans dimension]

4 — Formula

$$M_{O2_plan} = N_{crew} \times q_{O2} \times d_{refuge} \times (1 + m_{margin})$$

5 — Read aloud

Read " $M_{O2_plan} = N_{crew} \times q_{O2} \times d_{refuge} \times (1 + m_{margin})$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{O2_plan} : planned oxygen mass [kg]; N_{crew} : crew count [personnes]; q_{O2} : use per person per day [kg/personne/j]; d_{refuge} : target refuge duration [j]; m_{margin} : fractional margin [sans dimension]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{O2_plan} [kg]; N_{crew} [personnes]; q_{O2} [kg/personne/j]; d_{refuge} [j]; m_{margin} [sans dimension]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the system mechanism into a quantity that can be checked by numerical substitution.

11 — Assumptions

All inputs must be coherent in unit, frame, duration and scenario.

12 — Independent check

A second method or inverse relation should recover the same order of magnitude.

13 — Numerical case

With $N_{crew} = 4$ personnes, $q_{O2} = 0.84$ kg/personne/j, $d_{refuge} = 2$ j, $m_{margin} = 0.3$ sans dimension:

$$M_{O2_plan} = 4 \times 0.84 \times 2 \times (1 + 0.3) = 8.736 \text{ kg.}$$

14 — Why the calculation works

The relation turns the system mechanism into a quantity that can be checked by numerical substitution.

15 — Verification

A second method or inverse relation should recover the same order of magnitude.

16 — Mental estimate

Estimating before calculation helps detect sign, unit or factor errors.

17 — Interpretation

Size storage and distribution to the planned value, not nominal demand without margin.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $N_{crew} = 6$ personnes, $q_{O2} = 0.8$ kg/personne/j, $d_{refuge} = 1.5$ j, $m_{margin} = 0.25$ sans dimension: $M_{O2_plan} = 6 \times 0.8 \times 1.5 \times (1 + 0.25)$?

Detailed guided correction — open after trying

With $N_{crew} = 6$ personnes, $q_{O2} = 0.8$ kg/personne/j, $d_{refuge} = 1.5$ j, $m_{margin} = 0.25$ sans dimension: $M_{O2_plan} = 6 \times 0.8 \times 1.5 \times (1 + 0.25) = 9$ kg. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $N_{crew} = 5$ personnes, $q_{O2} = 0.84$ kg/personne/j, $d_{refuge} = 3$ j, $m_{margin} = 0.2$ sans dimension: $M_{O2_plan} = 5 \times 0.84 \times 3 \times (1 + 0.2)$?

Autonomous correction — open after trying

With $N_{crew} = 5$ personnes, $q_{O2} = 0.84$ kg/personne/j, $d_{refuge} = 3$ j, $m_{margin} = 0.2$ sans dimension: $M_{O2_plan} = 5 \times 0.84 \times 3 \times (1 + 0.2) = 15.12$ kg. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Size storage and distribution to the planned value, not nominal demand without margin.

Internal evacuation margin

$$M_{\text{evac}} = t_{\text{available}} - t_{\text{egress}}$$

1 — Concrete question

What does “ $M_{\text{evac}} = t_{\text{available}} - t_{\text{egress}}$ ” compute in “Internal evacuation margin”?

2 — Intuition without symbols

The decision depends on the difference between time to hazard and the time actually needed to place people in safety.

3 — Quantities

M_{evac} : evacuation margin [min]; $t_{\text{available}}$: time available before hazardous condition [min]; t_{egress} : time required to evacuate [min]

4 — Formula

$$M_{\text{evac}} = t_{\text{available}} - t_{\text{egress}}$$

5 — Read aloud

Read “ $M_{\text{evac}} = t_{\text{available}} - t_{\text{egress}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{evac} : evacuation margin [min]; $t_{\text{available}}$: time available before hazardous condition [min]; t_{egress} : time required to evacuate [min]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{evac} [min]; $t_{\text{available}}$ [min]; t_{egress} [min]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

With $t_{\text{available}} = 12.5$ min, $t_{\text{egress}} = 6$ min: $M_{\text{evac}} = 12.5 - 6 = 6.5$ min.

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

Low margin requires reducing detection, donning or isolation delays.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $t_{\text{available}} = 8$ min, $t_{\text{egress}} = 5$ min: $M_{\text{evac}} = 8 - 5$?

Detailed guided correction — open after trying

With $t_{\text{available}} = 8$ min, $t_{\text{egress}} = 5$ min: $M_{\text{evac}} = 8 - 5 = 3$ min. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $t_{\text{available}} = 6$ min, $t_{\text{egress}} = 5.2$ min: $M_{\text{evac}} = 6 - 5.2$?

Autonomous correction — open after trying

With $t_{\text{available}} = 6$ min, $t_{\text{egress}} = 5.2$ min: $M_{\text{evac}} = 6 - 5.2 = 0.8$ min. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Low margin requires reducing detection, donning or isolation delays.

Extinguishing-agent endurance

$$T_{\text{agent}} = Q_{\text{agent}} / q_{\text{use}}$$

1 — Concrete question

What does " $T_{\text{agent}} = Q_{\text{agent}} / q_{\text{use}}$ " compute in "Extinguishing-agent endurance"?

2 — Intuition without symbols

Agent quantity yields useful duration only relative to the planned discharge rate.

3 — Quantities

T_{agent} : available discharge duration [min]; Q_{agent} : usable extinguishing agent [kg]; q_{use} : mean use rate [kg/min]

4 — Formula

$$T_{\text{agent}} = Q_{\text{agent}} / q_{\text{use}}$$

5 — Read aloud

Read " $T_{\text{agent}} = Q_{\text{agent}} / q_{\text{use}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

T_{agent} : available discharge duration [min]; Q_{agent} : usable extinguishing agent [kg]; q_{use} : mean use rate [kg/min]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

T_{agent} [min]; Q_{agent} [kg]; q_{use} [kg/min]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $Q_{\text{agent}} = 12$ kg, $q_{\text{use}} = 1.5$ kg/min: $T_{\text{agent}} = 12 / 1.5 = 8$ min.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Keep reserve for re-ignition or a second fire instead of using all nominal capacity on the first engagement.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $Q_{\text{agent}} = 8 \text{ kg}$, $q_{\text{use}} = 1 \text{ kg/min}$: $T_{\text{agent}} = 8 / 1$?

Detailed guided correction — open after trying

With $Q_{\text{agent}} = 8 \text{ kg}$, $q_{\text{use}} = 1 \text{ kg/min}$: $T_{\text{agent}} = 8 / 1 = 8 \text{ min}$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $Q_{\text{agent}} = 15 \text{ kg}$, $q_{\text{use}} = 2.5 \text{ kg/min}$: $T_{\text{agent}} = 15 / 2.5$?

Autonomous correction — open after trying

With $Q_{\text{agent}} = 15 \text{ kg}$, $q_{\text{use}} = 2.5 \text{ kg/min}$: $T_{\text{agent}} = 15 / 2.5 = 6 \text{ min}$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Keep reserve for re-ignition or a second fire instead of using all nominal capacity on the first engagement.

Refuge-place margin

$$M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{crew}}$$

1 — Concrete question

What does “ $M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{crew}}$ ” compute in “Refuge-place margin”?

2 — Intuition without symbols

Refuge capacity must be compared with the population that may converge on it during the emergency scenario.

3 — Quantities

M_{refuge} : remaining refuge places [places]; C_{refuge} : available refuge capacity [places]; N_{crew} : people requiring refuge [personnes]

4 — Formula

$$M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{crew}}$$

5 — Read aloud

Read “ $M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{crew}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{refuge} : remaining refuge places [places]; C_{refuge} : available refuge capacity [places]; N_{crew} : people requiring refuge [personnes]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{refuge} [places]; C_{refuge} [places]; N_{crew} [personnes]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

With $C_{\text{refuge}} = 8 \text{ places}$, $N_{\text{crew}} = 6 \text{ personnes}$: $M_{\text{refuge}} = 8 - 6 = 2 \text{ places}$.

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

Provide margin when injury, visitor load or an unavailable berth can change actual occupancy.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $C_{\text{refuge}} = 6$ places, $N_{\text{crew}} = 6$ personnes: $M_{\text{refuge}} = 6 - 6$?

Detailed guided correction — open after trying

With $C_{\text{refuge}} = 6$ places, $N_{\text{crew}} = 6$ personnes: $M_{\text{refuge}} = 6 - 6 = 0$ places. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $C_{\text{refuge}} = 12$ places, $N_{\text{crew}} = 9$ personnes: $M_{\text{refuge}} = 12 - 9$?

Autonomous correction — open after trying

With $C_{\text{refuge}} = 12$ places, $N_{\text{crew}} = 9$ personnes: $M_{\text{refuge}} = 12 - 9 = 3$ places. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Provide margin when injury, visitor load or an unavailable berth can change actual occupancy.

Starting question

If pressure is falling at an approximately steady measured rate, how much time remains before a declared minimum threshold?

Read aloud

Read: "time equals initial pressure minus minimum pressure, divided by pressure-loss rate."

Symbols, pronunciation and meaning

P_0 is current pressure; P_{min} is the action threshold; r is measured pressure decrease per unit time; t is estimated remaining time.

Units

If pressure is in kilopascals and r is kilopascals per minute, the result is minutes.

Origin and status of values

Use measured local pressure trend only when it is reasonably stable over the short planning interval. The threshold comes from the approved emergency rule.

Why this operation

Subtraction gives how much pressure can still be lost before the threshold. Division by loss rate converts that remaining pressure margin into time.

Substitution and calculation

At 70 kPa, threshold 55 kPa and loss rate 3 kPa/min: $t = (70 - 55) / 3 = 15 / 3 = 5$ min.

Calculator entry

Enter $(70 - 55) \div 3$. Keep parentheses around the pressure difference.

Mental estimate

Fifteen kilopascals at three kilopascals each minute is five minutes, so the result is immediately reasonable.

Independent check

Multiply $5 \text{ min} \times 3 \text{ kPa/min} = 15 \text{ kPa}$; subtract from 70 and recover 55 kPa.

Physical or operational interpretation

Five minutes is not five minutes of free work. It is the simplified time to the stated threshold if the leak rate does not worsen.

Plain-English translation

The crew has about five minutes before crossing 55 kPa under the measured constant-rate approximation.

Variation / sensitivity

If leak rate doubles to 6 kPa/min, estimated time falls to 2.5 min. Pressure-loss acceleration therefore matters strongly.

Limit / assumption

Real gas discharge is not generally linear. The formula is a short-horizon operational estimate and must be replaced by better modelling when data or conditions require it.

Formula 2 — refuge oxygen reserve duration

Starting question

How long can a known usable oxygen reserve support a refuge occupancy under a declared per-person consumption rate?

Read aloud

Read: "oxygen duration equals usable oxygen quantity divided by number of people times consumption per person."

Symbols, pronunciation and meaning

Q_{O_2} is usable oxygen quantity; N is occupants; q is oxygen consumption per person per unit time; T is support duration.

Units

If Q is in kilograms and q in kilograms per person per day, $N \times q$ is kilograms per day and T is days.

Origin and status of values

Reserve quantity must be usable after regulator/pressure limits. Consumption rate is a planning assumption that should reflect emergency activity and system design.

Why this operation

Multiplication gives total crew consumption rate. Division asks how many such time blocks fit inside the usable reserve.

Substitution and calculation

For 4.8 kg usable O_2 , 6 people, and 0.8 kg/person/day: crew demand = $6 \times 0.8 = 4.8 \text{ kg/day}$, so $T = 1 \text{ day}$.

Calculator entry

Enter $4.8 \div (6 \times 0.8)$. Keep the crew consumption product in parentheses.

Mental estimate

The reserve equals exactly six individual daily allocations, so one crew-day is expected.

Independent check

Multiply $1 \text{ day} \times 6 \times 0.8 \text{ kg/person/day}$ and recover 4.8 kg.

Physical or operational interpretation

Oxygen is only one refuge limit. Carbon-dioxide removal, heat, water and sanitation may end safe occupancy earlier.

Plain-English translation

The stated oxygen reserve supports six occupants for about one day at the assumed rate.

Variation / sensitivity

If occupancy falls to four people, oxygen-only duration becomes 1.5 days. If exertion raises q , duration decreases.

Limit / assumption

This is a consumable balance, not a complete atmosphere model. It ignores leakage, oxygen already in the cabin and system control behaviour unless those are included in Q .

Mission reasoning: detect, isolate, shelter and recover without creating a second emergency

Make detection actionable

A detector should lead to a defined response based on location, confidence and consequence. Multiple independent indicators can reduce false-alarm burden, but waiting for perfect certainty can waste the interval in which a small event remains controllable.

Isolate with occupant awareness

Closing a hatch can stop smoke or pressure loss while trapping a crewmember beyond the barrier. Emergency displays should show personnel location and planned escape/refuge options. Isolation authority must account for people as well as fluid topology.

Control energy sources

Electrical faults, batteries, heaters, oxygen-enriched local conditions and process chemicals can sustain fire. Procedures should identify what can be de-energized locally without disabling essential detection, lighting or refuge systems.

Treat breathing atmosphere as contaminated until verified

Visible flame extinction does not prove the compartment is safe. Carbon monoxide, particulates and decomposition products may remain. Re-entry requires measurements, protective equipment and a ventilation/filtration plan tied to actual sensor limits.

Preserve refuge independence

A refuge that depends on the same power bus, ventilation duct or data controller as the damaged zone may not be independent. Emergency readiness should test shared dependencies and identify what happens after one cross-cutting failure.

Recover through controlled configuration

After safing, every bypass, closed valve, tripped breaker and portable supply should be recorded. Return to service needs staged functional tests so the crew does not unknowingly restore the same hazardous path that initiated the event.

Emergency exercises — trade seconds for survivable configuration

Exercise A — Pressure trend

A compartment is at 68 kPa and losing 2 kPa/min. The action threshold is 56 kPa. Estimate time.

Reveal the reasoned solution

$(68 - 56) / 2 = 6$ min under the constant-rate approximation. The crew should use the trend to prioritize isolation and egress, not treat six minutes as guaranteed because leak flow can change.

Exercise B — Fire alarm with no flame

Two smoke sensors alarm in an equipment bay but the camera shows no visible flame. Should the crew ignore the alarm?

Reveal the reasoned solution

No. Hidden smouldering, electrical decomposition or sensor contamination are possible. Apply the approved verification/isolation procedure, inspect other indicators and protect the crew while avoiding unnecessary actions that could spread smoke.

Exercise C — Blocked hatch

The preferred isolation hatch would trap one crewmember in the affected zone. What should the procedure provide?

Reveal the reasoned solution

A preplanned alternate egress or local refuge option, personnel-location awareness and authority rules for delaying or sequencing isolation. Emergency isolation must not assume every person is already on the safe side.

Exercise D — Refuge oxygen

A refuge has 7.2 kg usable oxygen for six people at 0.8 kg/person/day. What is oxygen-only duration?

Reveal the reasoned solution

Crew use is 4.8 kg/day. $7.2 / 4.8 = 1.5$ days. Verify that carbon-dioxide scrubbing, water, heat and sanitation also support at least that duration before claiming 1.5-day refuge capacity.

Exercise E — Post-fire return

Flame is extinguished and pressure is normal. May the crew immediately return to nominal operation?

Reveal the reasoned solution

Not automatically. Verify atmosphere toxicity/particulates, electrical insulation, structural and thermal damage, sensor function, filter contamination and the configuration of emergency isolations. Preserve evidence and perform staged return-to-service tests.

Exercise F — False alarm burden

Frequent nuisance alarms cause crews to delay response. What system-level fix is needed?

Reveal the reasoned solution

Investigate sensor placement, thresholds, contamination, maintenance and alarm logic while preserving real detection sensitivity. Training crews to ignore alarms is not a safe solution; the alarm system must earn trust through quality and prioritization.

Interactive beginner glossary

Emergency vocabulary below links detection, isolation, breathing protection, refuge capability and controlled recovery.

- fire — Uncontrolled combustion that can produce heat, flame, smoke, toxic gases and loss of equipment function.
- smoke — Airborne mixture of particles and gases generated by combustion or thermal decomposition.
- carbon monoxide — Toxic gas produced by incomplete combustion that interferes with oxygen transport in the body.
- depressurization — Loss of gas from a pressurized volume causing pressure to fall.
- leak rate — Rate at which gas, liquid or another resource escapes across an unintended opening or boundary.
- pressure threshold — Declared pressure value that triggers a specific protective action or operational state.
- isolation — Separation of a compartment, flow path or energy source to limit propagation of a hazard.
- compartment — Defined enclosed region that can be separated from neighbouring regions for pressure or hazard control.
- refuge — Protected area capable of sustaining occupants independently for a defined emergency duration.
- safe haven — Another term for a protected location used to shelter crew when the primary area is unsafe.
- egress — Movement from a hazardous area toward a safer compartment or exit route.
- internal rescue — Recovery of an injured or trapped person within the pressurized habitat or connected modules.
- self-rescue — Actions a threatened person can perform to reach safety without requiring another rescuer to enter the hazard.
- fire load — Amount and type of combustible material available to contribute energy and smoke to a fire.
- ignition source — Energy source capable of initiating combustion or damaging material so combustion begins.
- overcurrent protection — Electrical protective device or function that interrupts excessive current to limit damage and fire risk.
- smoke detector — Sensor intended to detect combustion aerosols or related signatures before conditions become severe.

- gas detector — Instrument that measures concentration of selected gases associated with atmosphere quality or hazards.
- false alarm — Alarm that occurs when the declared hazardous condition is not present, even though the detector may be responding to another stimulus.
- nuisance alarm — Repeated nonhazardous alarm that burdens operators and can reduce confidence in the alerting system.
- breathing protection — Equipment or procedure that supplies or filters breathable gas when the surrounding atmosphere is unsafe or uncertain.
- portable extinguisher — Locally carried device that applies an extinguishing agent to a limited fire under specified conditions.
- fire suppression — System or action intended to control or extinguish combustion.
- ventilation isolation — Closure or rerouting of airflow to prevent smoke or contamination spreading through ducts.
- pressure decay — Observed reduction in pressure over time, used to characterize leakage or system behaviour.
- emergency reserve — Consumable or capability intentionally held for abnormal or survival conditions.
- return to service — Controlled process of proving a repaired or recovered system is safe to resume its intended function.
- post-incident inspection — Examination performed after an emergency to identify damage, contamination and conditions affecting safe recovery.
- root cause — Underlying technical or organizational mechanism that explains why the event occurred and whose correction reduces recurrence.
- reconstruction — Systematic rebuilding of event sequence from logs, evidence, telemetry and witness information after an incident.

Operational depth: emergency capability exists only if the crew can execute it under degraded conditions

Exercise with doors and suits, not slides

Refuge and internal-rescue drills should use real hatch timing, protective equipment, lighting and communications. Paper procedures routinely underestimate movement, visibility and dexterity penalties.

Track who is where

Personnel location becomes critical during rapid isolation. Badge systems, check-in discipline or role boards can help, but the crew needs a fallback method when the tracking system itself fails.

Test shared dependencies

Refuge fans, scrubbers, detectors and communications should be mapped against electrical buses and control networks. A refuge that loses all essential functions with one upstream failure is a room, not a robust safe haven.

Protect emergency equipment from the hazard it serves

Extinguishers, breathing protection and leak kits must remain reachable when the primary hazard blocks the normal route. Distributed equipment reduces the chance that one compartment event removes every response tool.

Use staged re-entry

After an incident, remote sensors or protected reconnaissance can precede unprotected human entry. Re-entry criteria should specify atmosphere, temperature, electrical state and structural concerns rather than rely on appearance.

Turn every event into configuration learning

An incident can reveal unexpected airflow, alarm delays or access constraints. Corrective actions should update drawings, procedures, training and interface assumptions so the next crew inherits the knowledge rather than the same hidden trap.

Applied emergency cases: isolation, refuge and post-incident recovery

Applied emergency case — pressure trend should drive action before exact leak location is known

If pressure decay is accelerating, operators may not have time to locate the hole before taking protective action. The crew can close preplanned compartment boundaries, verify personnel locations and compare pressure trends on each side. This transforms a settlement-wide problem into a smaller search area. Acoustic tools, gas tracers or thermal methods can follow once survival margin is protected. The key is sequencing: diagnose enough to isolate safely, then investigate with more precision. A procedure that requires exact leak localization before any isolation may consume the only minutes in which the crew can preserve atmosphere and avoid exposing multiple modules to the same pressure loss.

Applied emergency case — smoke movement follows ventilation, not intuition

A small fire can contaminate distant modules if fans or ducts carry smoke away from the source. Emergency logic should know which dampers close automatically, which fans stop, and which flows must continue to protect refuge areas. Simply turning off all ventilation may create other hazards, including loss of carbon-dioxide control or thermal management. Crews need a map of airflow states and the ability to verify that isolation actually occurred. After suppression, filters and ducts may contain contaminants even where surfaces look clean. Recovery therefore includes ventilation inspection and controlled purge, not merely reopening the room where the flame was found.

Applied emergency case — batteries may require different firefighting logic

Electrical storage systems can produce heat, toxic products and re-ignition behaviour that differs from ordinary solid combustibles. The response plan should reflect the specific battery chemistry, enclosure, detection and cooling or isolation capability installed in the habitat. Operators need to know which extinguishing agents are compatible and how to monitor for continued heating after visible flame stops. This is an example of why generic “fire procedure” language is insufficient. Hazard-specific annexes can share command structure and refuge logic while still giving technically appropriate actions for batteries, electrical cabinets, oxygen-related incidents or chemical process areas.

Applied emergency case — internal rescue must not create two casualties

A rescuer entering a smoky or depressurizing area needs a defined protection level, communication path, retrieval strategy and stop condition. The emotional pressure to reach a colleague can override normal caution, so rescue rules should be rehearsed before the event. If atmosphere is uncertain, breathing protection and isolation may be required even when the casualty is visible only a few metres away. A second team should monitor time, atmosphere and route status. The purpose is not bureaucratic delay; it is ensuring that one trapped person does not become two or three because rescuers entered an environment whose hazards were not controlled.

Applied emergency case — refuge duration is controlled by the first limiting resource

An oxygen calculation can show thirty hours while carbon-dioxide sorbent lasts twenty, battery power eighteen and water forty. The refuge rating is then constrained by the shortest verified duration unless another recovery path exists. Emergency planning should therefore maintain a resource table for each refuge and update it when supplies, occupancy or equipment configuration change. Drills can reveal additional limits such as noise, heat or sanitation. This prevents the common error of advertising a refuge by one impressive storage figure. Survival duration is a system property created by all essential resources and by the ability to monitor them under emergency conditions.

Applied emergency case — post-incident evidence belongs to operations, not only investigators

A scorched connector, tripped breaker state or smoke pattern may explain the event, but well-intentioned cleanup can erase that evidence. The recovery leader should identify what can be photographed, bagged, logged or electrically captured before disturbance, while still removing immediate hazards. Telemetry clocks and crew observations should be preserved in a common timeline. The objective is practical prevention: understanding whether the initiating mechanism was overload, contamination, maintenance damage, software command or something else. A successful emergency response ends not

when pressure is normal, but when the settlement has restored capability and reduced the chance of repeating the same failure.

Applied emergency case — drills should deliberately remove expected resources

A realistic exercise can declare one hatch blocked, one radio failed or one refuge fan unavailable. This tests whether the emergency plan contains genuine alternatives or simply assumes every supporting system works during the very event meant to challenge it. Crews should practice moving a casualty, accounting for personnel, isolating ventilation and establishing a safe atmosphere with degraded information. Observers then measure timing and identify where decisions stalled. The resulting corrections may involve equipment placement, interface labels, software displays or authority rules. Repeating the drill after changes is the only way to show that the improvement exists in practice rather than only in a revised document.

Operational review checklist

- Detect fire, smoke and pressure loss early with actionable alarms.
- Know personnel location before isolating compartments when possible.
- Preserve at least one viable egress or refuge path.
- Control energy and ventilation sources without disabling essential safety functions.
- Size refuge capacity by life support and duration, not seats alone.
- Keep emergency equipment accessible from more than one hazard zone.
- Treat post-fire atmosphere as unsafe until measured and cleared.
- Record all emergency configuration changes and temporary bypasses.
- Perform staged inspection and functional testing before return to service.
- Preserve logs and evidence long enough to identify and correct root cause.

Primary sources and bridges

- NASA-STD-3001 Vol. 2 — Fire protection
- NASA Human Spaceflight Standards

FR ↔ EN parity matrix

Time to pressure threshold	Temps jusqu'au seuil de pression
Refuge oxygen endurance	Autonomie d'oxygène du refuge
Planned oxygen mass	Masse d'oxygène planifiée
Internal evacuation margin	Marge d'évacuation interne
Extinguishing-agent endurance	Autonomie d'agent extincteur
Refuge-place margin	Marge de places au refuge