

ISRU, local resources and first Mars industry

This course develops a capability that was still missing from the core curriculum. It starts from concepts and units, builds the necessary calculations, then connects each method to real Mars engineering decisions.

Before starting — Prerequisites: modules 00 to 22 as relevant. Every important symbol is defined at first use.

Mastery objectives

- explain quantities, units and assumptions
- repeat at least one calculation by hand
- identify uncertainty, limits and failure modes
- turn the result into a decision for a Mars architecture

1. ISRU replaces cargo with a process chain

In-situ resource utilisation can reduce launch mass, but oxygen from Mars CO_2 still requires compression, reaction, power, purification, storage and maintenance.

Every kilogram not launched from Earth becomes an industrial obligation on Mars.

Engineering reflex. Identify what is measured, assumed and calculated, then state what would change the decision.

2. MOXIE proved a principle, not a settlement plant

MOXIE demonstrated small-scale oxygen production from the Martian atmosphere under varied conditions. It validated technology, not human-mission propellant capacity.

Scaling from grams per hour to tonnes changes power, compression, thermal control, lifetime and cryogenic storage.

3. Water is a resource only when extraction is defined

Ice may support drinking, oxygen and hydrogen production, but extraction depends on depth, concentration, temperature and surrounding material.

Base-site selection therefore trades landing safety, energy, science and resources.

4. Regolith to materials

Regolith can be sorted, compacted, heated or used as process feedstock, but properties vary and contaminants may require treatment.

Industry begins with characterisation: grain size, mineralogy, volatiles and mechanical behaviour.

5. The first factory must be repairable

A plant that saves cargo but needs one unique Earth-made part every few months does not create durable autonomy.

Performance must track energy per kilogram, availability, purity, maintenance burden and imported dependencies.

6. From resource to product: ISRU is a process chain

Saying that a resource exists in regolith or atmosphere is not enough. It must be acquired, conditioned, fed into a reactor, separated, purified, stored and accompanied by waste handling. Throughput of the complete chain is limited by its slowest step. An ISRU architecture therefore reports efficiency and losses at each stage rather than only the central chemical reaction.

7. Energy is often the real production-rate limit

Excavation, heating, compression, electrolysis and liquefaction consume energy. The operational question is how many useful kilograms are produced per available kilowatt-hour and for how many hours per sol the process can run. During a degraded power mode, ISRU may be a flexible load, but interrupting a furnace or thermal cycle at the wrong point can damage the process. Flexibility has to be designed rather than assumed.

8. Start before the crew: turn production into verified inventory

A robust strategy may operate robotic ISRU before crew arrival and accumulate oxygen, water or propellant. Stored mass is useful only if product quality, tank condition and transfer capability are verified. A crew-departure criterion can therefore depend on measured inventory rather than promised nominal capacity. This turns ISRU from an aspiration into a testable mission condition.

Industrial case: the entire chain must close

An ISRU plant can have an excellent electrolyser and remain unusable if excavation, drying, purification, compression or storage limits throughput. Engineers follow matter and energy from feedstock to stored product. Every step has efficiency, capacity, maintenance downtime and consumables. Overall output is limited by the bottleneck, not by the most spectacular component.

9. Worked example step by step

A teaching production example combines nominal oxygen throughput, operating power, daily run time, campaign duration and availability. The canonical “Verified ISRU campaign production” mini-lesson below carries the arithmetic. Here the operational point is that nominal throughput and real campaign delivery are different quantities, and availability must be applied before production can be credited.

10. Progressive exercise

Size a campaign that must accumulate 10 tonnes of oxygen before crew arrival. Choose hourly production, operating hours per sol, availability and storage margin. Calculate required sols and total energy.

11. Reasoned solution

A second campaign example reaches the same conclusion from a required daily oxygen target and a long operating season. Energy, uptime, storage and qualification must all be reconciled before the campaign can claim delivered inventory; the full calculation belongs in the canonical production mini-lesson rather than in compressed prose.

12. Validation mini-project

Design a complete ISRU chain from feedstock acquisition to storage: equipment, yields, energy, maintenance, quality control, reserves, waste, crew-departure threshold and post-failure strategy.

ISRU industrialization laboratory — prove the complete chain, not one machine

This ISRU-operations extension connects resource variability, feed preparation, process availability, product quality, storage and qualification so mission inventory is based on delivered usable output rather than nameplate production.

Define the resource with variability and accessibility

A resource estimate must include concentration, spatial variability, depth, physical state and the effort required to reach it. Water that exists but cannot be excavated reliably with available machines is not yet an operational resource. Prospecting therefore reduces industrial uncertainty and should be connected directly to plant sizing and site selection.

Separate extraction, preparation and conversion

Mining or collection produces a raw stream. Preparation removes unwanted material or conditions the feed. Conversion produces the desired chemical or construction product. Each stage has throughput, recovery, purity, energy and maintenance requirements. A bottleneck in any stage limits the whole chain, so quoting only reactor capacity is misleading.

Treat energy as part of the product cost

Many ISRU processes are energy intensive. The relevant question is not only whether a reaction is possible but how much electrical or thermal energy is required per usable kilogram at the actual duty cycle. Energy storage and generation must cover startup, standby, freeze protection, compression and purification as well as the headline process step.

Design the first plant for repairability

Early Mars industry has limited spare parts and specialist labour. Equipment should expose wear items, allow isolation, support condition monitoring and use common components where practical. A highly efficient machine that requires an unavailable factory repair can be less useful than a slightly less efficient design that the settlement can diagnose and restore locally.

Build verified inventory before crew dependence

If production can start robotically before crew arrival, the mission gains evidence as well as stock. Accumulated product demonstrates sustained throughput, storage integrity and control-system stability. The acceptance criterion should be a verified inventory with known quality, not simply a machine that once produced a sample.

Choose first products by dependency reduction

The best early local product is not necessarily the one with the largest mass. Prioritize products that remove critical resupply dependencies or enable many other repairs: oxygen, water, simple construction materials, shielding fill, selected chemicals and standardized feedstock are examples depending on architecture. The choice should be justified through avoided imported mass, energy cost, reliability and crew workload.

Progressive mastery drills — eight linked checks

Define the number and distribution of measurements needed before a local resource estimate is trusted.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Separate machine nameplate capacity from sustained delivered feed.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Track rejected material and explain why it affects total recovery.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Trace water from excavation through purification to storage or downstream reaction.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Separate demonstration chemistry from sustained production, storage and quality assurance.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Define a product property that must be tested before a material is allowed into a pressure or load-bearing application.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Include maintenance, spares and mean repair effort in the usable production rate.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Show why high conversion can coexist with off-spec product and require downstream separation.

Expected reasoning. State the evidence, the assumption, the uncertainty and the operational consequence. A label or definition alone is not a complete answer.

Build a chain for prospecting/variability, raw extraction, preparation/separation, water handling, oxygen or propellant production, regolith-derived construction material, machine availability and product yield/purity. At each step, identify the measurement that proves the stage is ready to feed the next one.

Reasoned solution. A strong answer treats the plant as a sequence of acceptance gates. If one stage cannot prove quantity and quality, downstream nominal capacity is irrelevant. The final record should also identify stored inventory, energy consumption, maintenance burden and the fallback if local production stops.

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.

Primary sources and bridges

- [NASA JSC — In-Situ Resource Utilization](#)
- [NASA MOXIE](#)

- [NASA — MOXIE](#)
- [NASA — ISRU](#)

First Man ISRU industrialization dossier — from resource claim to qualified inventory

In-situ resource utilization becomes mission infrastructure only when a complete industrial chain works repeatedly: resource characterization, access, excavation, preparation, conversion, product qualification, storage, maintenance and restart. This dossier turns “we can make it on Mars” into an auditable production claim.

Define the resource before designing the plant

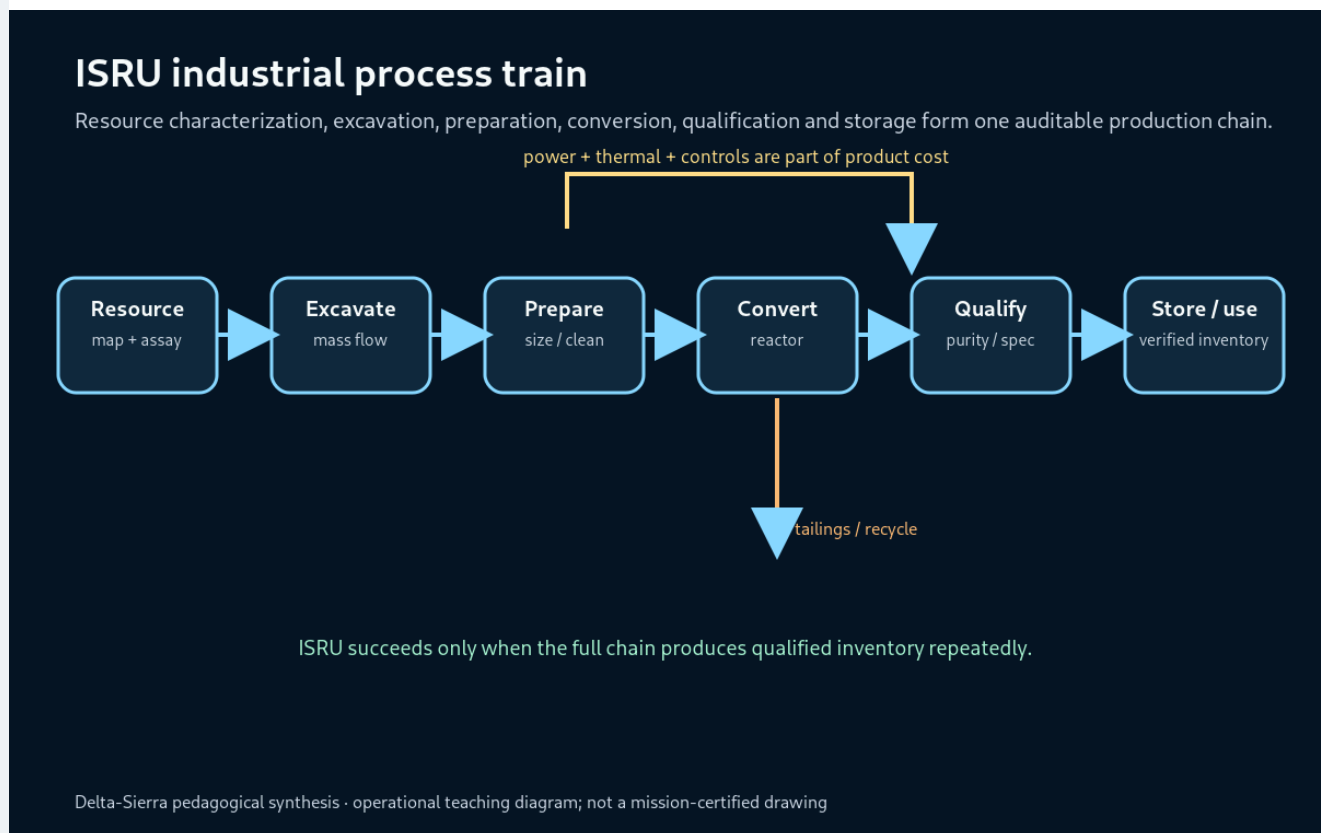
[NASA JSC — In-Situ Resource Utilization](#) frames ISRU as a set of technologies for using local resources. A resource is not simply “water” or “CO₂.” The plant designer needs concentration, spatial variability, physical form, depth or accessibility, contaminants and the sampling evidence behind those estimates.

Resource uncertainty propagates into equipment size, energy demand and campaign schedule. A process optimized for one soil distribution can fail when feed changes. The first industrial requirement is therefore a resource envelope, not a point estimate.

Separate excavation, preparation and conversion

Digging material is not the same as delivering reactor feed. Excavation creates particle-size, dust and wear challenges; preparation can include crushing, sieving, drying or gas compression; conversion imposes temperature, pressure, catalyst, electrochemistry or other process conditions.

Each stage has its own reject and recycle streams. Drawing them prevents the plant from claiming that every kilogram excavated becomes usable product.



Resource mapping, excavation, preparation, conversion, qualification and storage form one industrial chain. Pedagogical synthesis by Delta-Sierra from the primary sources cited at the point of use; not a mission-certified drawing.

Close the energy and thermal balance with production

The [NASA STMD — In-Situ Resource Utilization](#) provides program context for ISRU technology development. Production rate must be tied to the power and heat-rejection states that make the rate possible. A process may achieve impressive laboratory throughput under power conditions unavailable during a dust season or settlement peak load.

Report product energy cost alongside mass rate when it helps compare architectures. If a unit produces more kilograms per hour but forces another critical load offline, nameplate throughput is not the mission objective.

Qualify the product before counting inventory

MOXIE demonstrated oxygen production from the Martian atmosphere; see [NASA — MOXIE](#) and the [NASA STMD — MOXIE technology demonstration](#) for mission context. A demonstration proves specific functions under specific conditions. A settlement plant still needs

release criteria for purity, moisture, pressure, contamination, container integrity and the intended downstream use.

Off-spec product is not automatically waste: it may be reprocessed or downgraded to a different use. But the inventory system must never count it as qualified propellant, breathing oxygen or process reagent until the applicable gate closes.

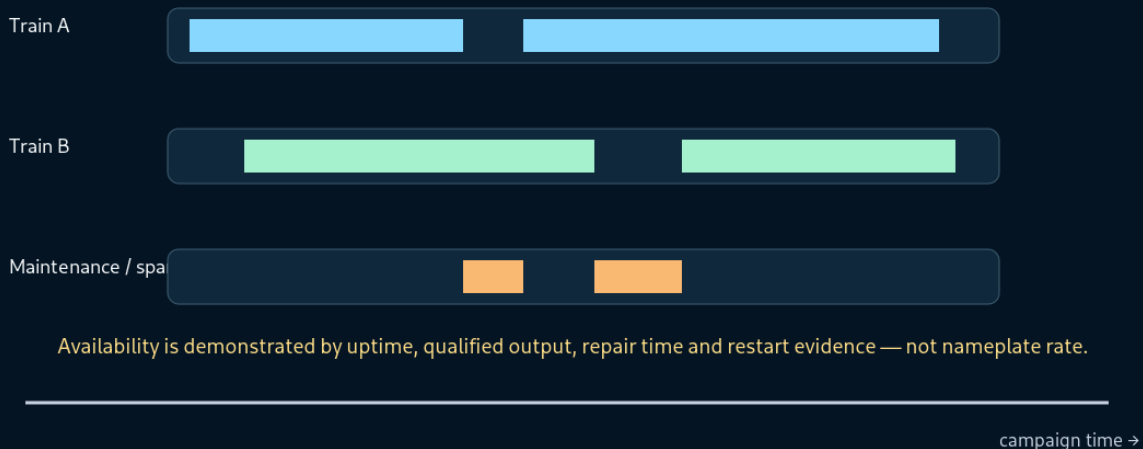
Treat availability and maintainability as production variables

Industrial output is a campaign result, not a nameplate label. Availability falls when maintenance, cleaning, feed interruptions, calibration and repair consume time. The formula below converts rated production into verified campaign inventory using measured availability and qualified-output fraction.

Design for repair from the first plant: access, lifting, connectors, dust management, inspection points, replaceable wear parts, software rollback and metrology. A plant that cannot be restored with local tools is a demonstration, not mature settlement infrastructure.

ISRU campaign availability and maintenance

Two production trains show operating windows, maintenance interruptions and the difference between nameplate capacity and campaign output.



Delta-Sierra pedagogical synthesis · operational teaching diagram; not a mission-certified drawing

Parallel production trains and repair windows show why nameplate rate is not campaign output. Pedagogical synthesis by Delta-Sierra from the primary sources cited at the point of use; not a mission-certified drawing.

Commission before crew dependence

Predeploy the plant early enough to experience starts, stops, maintenance, feed variability and storage operations before the crew depends on its output. Commissioning should accumulate verified inventory and failure history, not merely one successful production run.

A crew launch gate can therefore require both a minimum stored product and evidence that the plant can recover from representative faults. This converts ISRU from promised future capability into an already-observed logistics asset.

Choose first products by dependency reduction, not novelty

Early products should attack expensive or mission-critical dependencies. Water, oxygen, shielding material, construction feedstock or propellant may have very different value depending on mission architecture. Rank them by avoided imported mass, criticality, energy demand, equipment complexity, storage and cross-use.

The “best” product can change as the settlement matures. A product that is transformative for a small outpost may become less valuable than spare-part materials or construction feedstock once basic consumables are stable.

Board scenario — high nameplate output, poor campaign delivery

A reactor meets its rated 2 kg/h during test windows, but dust cleaning, compressor maintenance and off-spec batches reduce available hours and qualified fraction. The project still advertises nameplate production and schedules the crew around it.

A defensible review reconstructs the campaign: operating hours, downtime causes, quality yield, storage, maintenance labor, spare consumption and restart evidence. If verified output is below the mission need, the decision is to change the architecture or build inventory earlier — not to hope that nameplate rate will become real.

Operational review drills — explain the evidence, not only the answer

1. **Resource envelope.** List four resource properties that must be measured before plant sizing.

2. **Flow-sheet drill.** Draw excavation, preparation, conversion, reject, recycle and qualified product as separate streams.
3. **Energy drill.** State how a production-rate claim changes when settlement power is constrained.
4. **Quality drill.** Write release criteria for one ISRU product without assuming quantity proves purity.
5. **Availability drill.** Explain why 90% nameplate output during operating hours can coexist with poor campaign production.
6. **Commissioning drill.** Define evidence required before crew launch if the settlement depends on the plant.

Qualification notebook — prove an ISRU plant as infrastructure, not a demonstration

A settlement cannot eat, breathe or launch on a laboratory success. These cases force the learner to connect resource variability, availability, qualified yield, maintenance, power and inventory before declaring local production operational.

Review-board ledger

- Resource envelope / assay
- Nameplate rate
- Campaign availability
- Qualified fraction
- Verified inventory
- Power / thermal demand
- Maintenance hours / spares
- Restart evidence / crew-dependence gate

Situation. A prospecting campaign finds one high-grade ice-bearing location. The industrial team sizes the excavator and dryer as though the concentration represents the whole production zone.

Reasoned disposition. Treat the rich point as one sample, not the resource model. Map spatial variability and uncertainty, determine how grade changes excavation and energy per kilogram of product, and size stockpiles or blending if necessary. A plant can be technically

excellent and still fail because the feed envelope was defined from a lucky spot.

Situation. The reactor produces 2 kg/h when operating. Mission planning multiplies 2 kg/h by calendar time, even though cleaning, compressor maintenance and calibration leave only 65% availability.

Reasoned disposition. Use campaign availability in the production model and track causes of downtime. If demand requires more verified mass than the demonstrated campaign can deliver, add capacity, improve maintenance, start earlier or reduce dependency. The answer is not to keep the nameplate rate and assume downtime will disappear after crew arrival.

Situation. A campaign produces more oxygen mass than required, but a fraction of batches falls outside the release specification. Storage personnel propose blending off-spec gas into the qualified inventory to recover schedule.

Reasoned disposition. Do not blend without a controlled, validated disposition. Keep off-spec material quarantined, identify whether it can be reprocessed or assigned to a lower-grade use, and count only released product in the mission inventory. Quantity and quality are independent gates.

Situation. Dust reduces generation. The ISRU plant can maintain its target output only by taking power from habitat processing and battery recharge. The product is important for a future mission phase but not immediately life-critical.

Reasoned disposition. Prioritize functions by current criticality and protected reserve. Curtail or reschedule ISRU, preserve life-support and recovery margins, and update the future inventory forecast. Local production is valuable precisely because it reduces dependency; it should not create a new immediate dependency on power needed for survival.

Situation. The predeployed plant completed one long production run and built substantial inventory. After a planned shutdown, a valve fault makes restart uncertain. Crew launch is approaching.

Reasoned disposition. The commissioning claim is incomplete because recoverability is part of operational capability. Exercise the repair path, replace the faulted component, verify restart, product quality and stable operation, and record spare consumption. A stockpile may buy time, but crew dependence should be based on both inventory and demonstrated restoration capability.

Verified ISRU campaign production

$$m_{\text{verified}} = \dot{m}_{\text{nameplate}} \times A \times q \times t$$

1 – Concrete question

How much qualified product can an ISRU plant actually place into verified inventory over a campaign?

2 – Intuition without symbols

Nameplate rate assumes perfect operation. Reduce it by the fraction of campaign time the plant is actually available and by the fraction of output that passes the product specification, then multiply by campaign duration.

3 – Quantities first

$\dot{m}_{\text{nameplate}}$ is rated production mass per hour; A is operational availability from 0 to 1; q is qualified-output fraction from 0 to 1; t is campaign time; m_{verified} is qualified inventory produced.

4 – Formula

$$m_{\text{verified}} = \dot{m}_{\text{nameplate}} \times A \times q \times t$$

5 – Read aloud

“ m verified equals m -dot nameplate times A times q times t .”

6 – Symbols

$\dot{m}$ is mass flow rate; A is availability; q is qualified fraction; t is time; m_{verified} is the product mass that can enter mission inventory.

7 – Pronunciation

$\dot{m}$ is read “ m -dot”. A is availability. q is read “ q ”.

8 – Units

$$\text{kg/h} \times 1 \times 1 \times \text{h} = \text{kg}.$$

9 – Convention

Availability must include downtime inside the chosen campaign boundary. Qualified fraction is not the same as process conversion: it represents output that passes the relevant release criteria.

10 – Why this operation

Rated flow multiplied by time gives ideal production.

Availability discounts downtime. Qualified fraction discounts off-spec or quarantined output. The product of all four terms estimates what reaches verified inventory.

11 – Assumptions

Rate is treated as constant while operating, A and q summarize the campaign without hiding startup transients, and storage is available for qualified product.

12 – Unit check

Hours cancel, leaving kilograms of verified product.

13 – Numerical case

Nameplate rate $\dot{m}_{\text{nameplate}} = 2.0 \text{ kg/h}$.

Campaign time $t = 100 \text{ h}$.

Measured operational availability $A = 0.75$.

Qualified-output fraction $q = 0.90$.

Ideal nameplate production $= 2.0 \times 100 = 200 \text{ kg}$.

Availability-adjusted output $= 200 \times 0.75 = 150 \text{ kg}$.

Verified product $= 150 \times 0.90 = 135 \text{ kg}$.

14 – Why each operation

Calculate the ideal nameplate mass, reduce it for downtime, then reduce it again for output that does not pass specification. Keeping the stages visible prevents nameplate rate from masquerading as delivered inventory.

15 – Algebra check

If a target verified mass is required, campaign time is $t = m_{\text{verified}}/(\dot{m}_{\text{nameplate}} A q)$, provided all factors are positive and representative.

16 – Mental estimate

Two kilograms per hour for one hundred hours is two hundred kilograms; three-quarters availability gives one hundred fifty; ninety percent quality gives about one hundred thirty-five.

17 – Interpretation

The teaching plant contributes 135 kg of qualified inventory over the 100-hour campaign.

18 – What it does not prove

It does not prove feedstock is available, power is sufficient, spare parts exist, startup is safe, storage is qualified or the chosen averages will persist over a longer campaign.

19 – Sensitivity or limit case

If availability falls from 0.75 to 0.50 while all else stays fixed, verified output falls from 135 to 90 kg. Improving nameplate rate cannot compensate for chronic downtime if reliability is the real bottleneck.

20 – Practice

Guided exercise. A plant rated at 1.5 kg/h runs a 120 h campaign with $A = 0.80$ and $q = 0.95$. Find verified production.

Detailed guided correction.

1. Ideal production = $1.5 \times 120 = 180$ kg.
2. Availability-adjusted = $180 \times 0.80 = 144$ kg.
3. Verified production = $144 \times 0.95 = 136.8$ kg.

Autonomous exercise. A mission needs 300 kg verified product. One plant is rated 2.5 kg/h, demonstrated $A = 0.70$ and $q = 0.92$. Estimate the campaign hours, then explain why the schedule should include margin.

One defensible worked solution.

1. Effective verified rate = $2.5 \times 0.70 \times 0.92 = 1.61$ kg/h.
2. Required time = $300 / 1.61 \approx 186.3$ h.
3. The schedule needs margin for uncertainty, maintenance clustering, startup/restart, feed variability and storage constraints; 186.3 h is not a dispatch promise.

21 – Mission decision

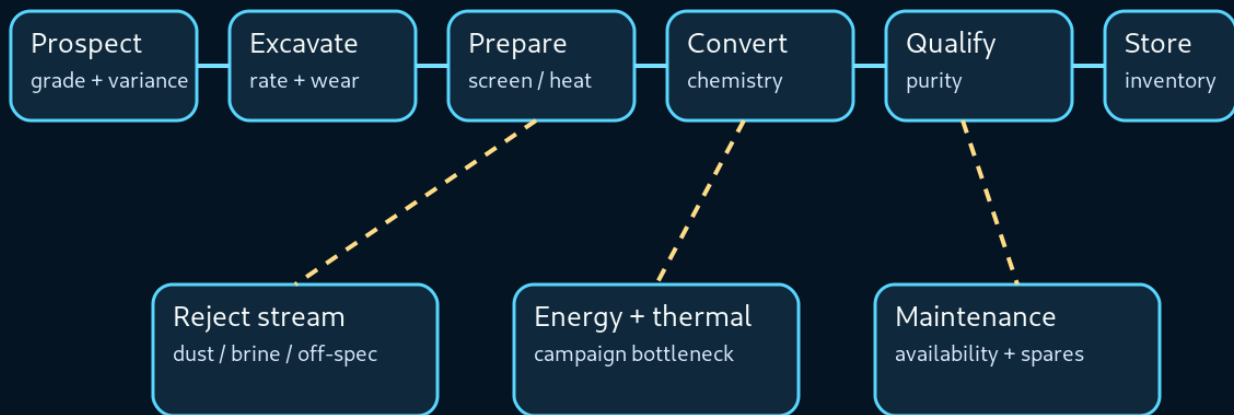
Plan from demonstrated verified output rather than nameplate rate. Before crew dependence, accumulate qualified inventory and prove restart, maintenance and spare-part performance over representative campaigns.

Closure rule. The learner should be able to reconstruct the model, challenge its assumptions, preserve the relevant safety or quality margin and state what additional evidence a real mission would require. This course does not confer operational certification.

ISRU industrialization casebook — prove a resource chain from deposit to qualified inventory

ISRU becomes settlement infrastructure only when a resource claim survives prospecting, excavation, preparation, conversion, quality control, maintenance and storage. A demonstration that makes product once is not the same as a plant the crew can depend on. The current course develops the industrial reasoning that connects the geology of the feedstock to verified mission inventory.

ISRU chain from deposit to qualified inventory



Resource prospecting flows through excavation, preparation, conversion, qualification and storage with rejects, energy and maintenance shown. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this dossier; not a mission-certified drawing.

Define the resource in engineering terms

Primary-source bridge: [NASA JSC — In-Situ Resource Utilization](#).

‘Water exists here’ is not a process specification. The plant needs concentration, depth, particle size, variability, contaminants, temperature, mechanical properties and the spatial scale of the deposit. Prospecting must therefore produce a resource model with uncertainty rather than a single optimistic grade.

The first industrial decision is often whether the deposit is consistent enough to design around. High average grade with extreme local variability can be harder to operate than a lower but predictable resource.

Excavation is part of the process, not a logistics footnote

Excavation rate depends on material strength, cohesion, particle size, slope, traction, tool wear and thermal conditions. A conversion reactor with high nameplate output is irrelevant if feed cannot be delivered at the required rate.

Industrial availability should therefore include excavation and transport. The plant is only as productive as its slowest essential stage over the campaign.

Preparation and beneficiation can determine downstream efficiency

Screening, crushing, heating, separation or concentration may improve conversion efficiency but consume energy, hardware life and crew attention. A good process design asks whether each preparation step increases total campaign value rather than simply producing a cleaner feed.

Reject streams also need a destination. Dust, fines, brines or depleted regolith can become contamination or traffic hazards if the process flow ends at the product tank and ignores waste handling.

Product quality matters before inventory credit

Primary-source bridge: [NASA](#) — [MOXIE](#).

Oxygen, water, fuels and construction feedstocks need acceptance criteria. A mass of product that fails purity, moisture, composition or mechanical-property requirements is not mission inventory for the intended use.

Quality control therefore sits inside the production chain. The plant report should distinguish gross output, sampled output, accepted output, quarantined output and rejected material.

Campaign production waterfall — normalized example

$100 \text{ nameplate units/day} \times \text{feed} \times \text{power} \times \text{uptime} \times \text{quality acceptance} = \text{qualified inventory rate}$



Delta-Sierra pedagogical synthesis · qualified campaign output is what survives every verified loss factor

A production waterfall shows how feed, power, downtime and quality reduce nameplate output to qualified inventory. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this dossier; not a mission-certified drawing.

Energy and heat flows can become the true bottleneck

Extraction and conversion can require substantial electrical and thermal energy. Power availability varies with generation architecture, storage state, weather and competing habitat loads. Thermal rejection can also limit throughput when the electrical system appears adequate.

The industrial schedule should therefore be co-planned with the microgrid and thermal system. Nameplate tonnes per day are meaningless if the plant only receives full power for a fraction of the campaign.

Availability and maintainability turn demonstrations into infrastructure

A plant that operates at high efficiency for one test but requires frequent specialist intervention may deliver poor campaign production. Track operating time, planned maintenance, unplanned downtime, spares consumption and restart effort.

The settlement should know which failures stop the whole chain and which can be bypassed. Maintainability, access and diagnostic evidence belong in the architecture from the start.

Commission before crew dependence

Primary-source bridge: [NASA STMD — In-Situ Resource Utilization](#).

Precursor operation can build verified inventory and expose early-life failures before people arrive. The commissioning plan should include startup, endurance, restart after outage, quality excursions, reduced-power operation and remote maintenance.

Crew arrival should depend on stored qualified product and proven operating evidence rather than an assumption that the plant will immediately reach nominal throughput after landing.

Choose first products by dependency reduction

A product is strategically valuable when it reduces a difficult imported dependency with acceptable complexity. The first industrial priorities may therefore be water, oxygen, shielding material or simple construction feedstocks rather than the most technologically ambitious chemistry.

The trade should compare imported mass avoided, energy, equipment mass, maintenance burden, quality risk, storage and the consequence of failure. ISRU is an architecture choice, not a slogan about using local resources.

Qualification casebook — six board decisions

1. **1. Prospecting finds a high-grade pocket with poor continuity.** A lower-grade layer is widespread and uniform.

Compare campaign reliability, not peak grade. The uniform deposit may support a more predictable mine plan and simpler quality control.

2. **2. The reactor meets nameplate output but excavation lags.** Stockpiles fall each day.

Treat the whole chain as capacity-limited by feed delivery. Improve excavation/transport or reduce claimed sustainable output.

3. **3. A purification stage raises purity but cuts throughput in half.** The product just meets a less demanding secondary use without it.

Separate product grades and allocate accepted material by use instead of forcing every kilogram through the highest-cost route.

4. **4. Power is adequate at noon but not overnight.** The plant is thermally slow to restart.

Schedule around microgrid and thermal constraints, evaluate storage or continuous low-power operation and report campaign output rather than instantaneous output.

5. **5. A key filter has one spare and long replacement time.** The plant otherwise has redundant reactors.

The filter is a single-point logistics dependency. Add spares, alternate filtration or operating limits before claiming redundant production.

- 6. 6. Crew arrival is scheduled immediately after first successful product.** Only twelve hours of operation exist.

HOLD dependence. Build verified inventory, endurance evidence and restart history before people rely on the plant for a critical commodity.

Mastery studio — four extended review problems

Use these industrial problems to follow material from uncertain deposit to qualified inventory and identify which bottleneck actually limits campaign delivery.

- 1. 1. Variable deposit grade.** Prospecting shows average resource grade is adequate, but local samples vary by a factor of three across the planned excavation zone.

Convert the geologic uncertainty into an operating plan. Define additional sampling, blending or selective mining needed to keep feed within the preparation and conversion envelope. Model the campaign using a range of grades rather than the average alone. If low-grade zones would starve the plant or increase energy beyond available margin, the mine plan must include alternate faces or stockpiles. The resource model is an operational input, not a marketing average.

- 2. 2. Nameplate versus campaign output.** A reactor reaches full output during tests but experiences frequent short shutdowns for feed jams and filter replacement.

Calculate delivered qualified inventory over the campaign, including uptime, restart time, rejected product and maintenance. Then identify the dominant loss mechanism. Raising reactor efficiency may produce less benefit than improving feed preparation or filter maintainability. Report sustainable production and confidence bounds rather than

quoting the best one-hour run. Infrastructure is judged by what it delivers repeatedly.

3. **3. Off-spec oxygen.** The plant produces the expected oxygen mass, but purity is below the requirement for the intended storage system.

Do not credit the batch as mission inventory for that use. Determine whether it can be reprocessed, downgraded to another acceptable use or safely stored separately. Trace the cause through feed, conversion and purification, and verify instrumentation before changing operating conditions. The case demonstrates why gross product mass and qualified inventory must remain separate in every production dashboard.

4. **4. Crew dependence before endurance proof.** The ISRU plant has accumulated one week of qualified output but has never restarted after a cold-soak power outage.

Treat the missing restart evidence as a real dependency risk. Either perform the restart qualification before crew dependence, carry sufficient verified imported reserve to survive a failed restart, or change the mission gate. The correct decision depends on how long stored inventory protects the crew and how quickly repair or alternate production can be established. Commissioning closes scenarios, not just steady-state throughput.

ISRU campaign handover — prove what the plant can deliver repeatedly

An industrial campaign should hand over a production history, not a best-case demonstration. The evidence package should distinguish feed processed, gross product, qualified product, quarantined or rejected product, operating hours, planned maintenance, unplanned downtime, restart duration, energy consumed and the state of critical spares. These records allow the next team to calculate sustainable output and understand why the plant missed or exceeded its plan.

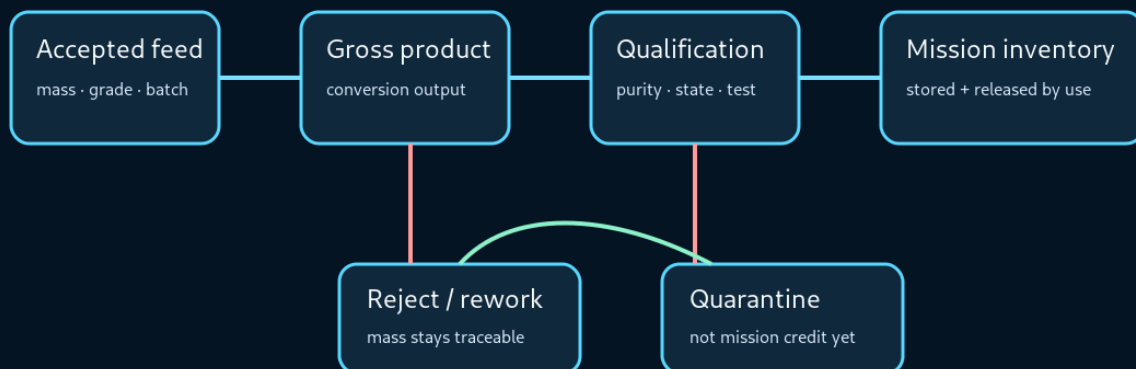
Resource uncertainty belongs in the same package. Record which excavation faces supplied the feed, how grade and physical properties varied, what blending or preparation was required and whether low-grade or contaminated material changed energy use or product quality. If the plant depends on a narrow resource assumption, the settlement needs to know when the mine plan is approaching the edge of that envelope before the process begins to fail.

Finally, connect production to mission dependency. State how many days of qualified inventory exist, which imported commodity the plant is replacing, what reserve protects a prolonged outage and what evidence is still required before the crew may reduce imported backup. This is the difference between a technology demonstration and infrastructure: the settlement can explain, with records, what the plant will probably deliver next month and what it will do when one stage fails.

ISRU production accounting — separate gross output from qualified mission inventory

An industrial plant can look productive while delivering little usable inventory. The current course closes that gap by treating every kilogram as a traceable batch that moves from feed acceptance through processing, qualification, quarantine and release. The objective is to make mission dependency auditable rather than to celebrate the highest instantaneous production rate.

ISRU inventory accounting — count only material that survives qualification



Required ledger: batch ID · origin · energy · downtime · test result · disposition · release authority · inventory balance.

Decision atlas — ISRU production accounting — separate gross output from qualified mission inventory. Pedagogical synthesis by Delta-Sierra; use the full-size link for fine labels.

Every campaign factor must be named before multiplying it

The corrected waterfall now uses a normalized example: nameplate output is reduced by feed availability, power availability, uptime and quality acceptance. These are successive capacity factors, not four material streams. The product of the factors estimates qualified campaign output under the stated assumptions.

A useful review keeps each factor independently measurable. If ‘availability’ already includes power outages and then a separate power factor is multiplied again, the model double-counts the same loss. Definitions matter as much as arithmetic.

Batch accounting preserves the link between resource and product

A batch record should connect excavation face or feed stockpile, preparation conditions, conversion run, energy used, downtime, quality tests and final disposition. This makes it possible to learn whether a purity problem came from geology, beneficiation, process control or storage.

Without that lineage, the plant may repeatedly reproduce the same defect while operators blame whichever stage is most visible.

Quarantine is inventory physically present but not yet mission credit

A tank can contain product that has not passed purity, pressure, dryness or contamination checks required for its intended use. Counting that material as mission inventory before qualification hides risk. Quarantine should therefore be visible in the production dashboard as a separate state.

If a batch fails one use but meets another, the disposition can downgrade it rather than discard it. The mission gains value without pretending every kilogram is interchangeable.

Energy and thermal integration can dominate the plant schedule

The same reactor can have very different campaign output depending on when power is available, how long thermal startup takes and whether waste heat can be rejected. A daily average power budget may hide an overnight bottleneck or a restart penalty.

The production plan should therefore align batch timing with microgrid and thermal constraints.

[NASA JSC ISRU material](#) provides a primary bridge for resource-utilization technologies; the accounting model here is a Delta-Sierra pedagogical framework.

Mission dependency should be earned by evidence

Crew plans should not reduce imported reserve because the plant achieved one successful run. Dependence is justified when the campaign has demonstrated qualified output, restart, maintenance recovery, feed variability tolerance and sufficient stored inventory for credible outages.

The acceptance board states exactly which failure modes have been demonstrated and which remain assumptions. [NASA MOXIE](#) is an important primary demonstration bridge, while a settlement-scale plant would require a much broader industrial qualification program.

Operational review board — five decisions to defend

1. **1. Nameplate 100, qualified 67.** The plant meets its reactor specification but campaign factors reduce usable output.

Plan logistics on qualified campaign output and attack the dominant loss factor instead of quoting nameplate capacity.

2. **2. Off-spec batch fills storage.** The tank is physically full.

Do not credit mission inventory until disposition/qualification is complete; quarantine must remain visible.

3. **3. Feed grade changes after moving excavation face.** Energy use and purity drift.

Trace the batch to source, update blending/beneficiation and reassess the production factor assumptions.

4. **4. Restart after cold outage has never been demonstrated.** Stored inventory covers ten days.

Keep imported/alternate reserve until restart evidence and endurance margin justify dependence.

5. 5. Product fits secondary use, not primary use. Quality misses the strictest specification.

Grade the product honestly and allocate it to an approved lower-demand use if compatible, preserving mission value without falsifying qualification.

Mission rehearsal notebook — reason through evidence before revealing the disposition

Industrial drill — high yield hides poor availability

A conversion reactor demonstrates excellent chemical yield whenever it runs, yet feed jams and maintenance limit uptime. Campaign output remains low. The engineering team separates process yield from plant availability and decides whether resources should go to chemistry improvement or feed handling. The correct answer can be to leave the reactor chemistry unchanged and redesign a mundane upstream subsystem.

Industrial drill — product is chemically correct but operationally unusable

A batch meets purity requirements but leaves the process at a pressure or thermal state incompatible with storage. The product is not yet mission inventory. Qualification includes the interfaces needed to store, transfer and use the commodity safely. This prevents a narrow laboratory specification from masquerading as end-to-end industrial readiness.

Industrial drill — dependency reduction beats production prestige

Two candidate ISRU expansions are available: one produces a glamorous structural material, the other replaces a small but frequently imported consumable that repeatedly constrains operations. The board evaluates launch mass avoided, outage risk, feed certainty, energy, spares and qualification burden. The best first expansion may be the less dramatic process if it removes a fragile supply dependency with higher confidence.

Primary-source bridges used in this operational rehearsal

- [NASA JSC — ISRU](#)
- [NASA — MOXIE](#)

Closure standard. The learner can explain the evidence chain, identify the limiting uncertainty or dependency, defend a degraded-state decision and state what a real mission would still need to verify.

Closure review — an ISRU plant earns mission credit only through qualified campaign delivery

An industrial process is not mission infrastructure because one reactor reached a good yield. Mission credit begins with a characterized resource and ends with a product that is qualified, storable, transferable and repeatedly available under the real constraints of feed preparation, energy, heat rejection, maintenance, spares and crew time.

Resource characterization belongs upstream of the plant design

The team needs variability, depth/accessibility, contaminants, particle/physical properties and the sampling uncertainty that supports the feed specification. If feed quality varies outside the demonstrated process envelope, nameplate production has little operational meaning.

Availability and quality multiply the campaign result

The corrected waterfall now shows this explicitly as successive capacity factors. Feed availability, power availability, uptime and quality acceptance reduce the amount of nameplate production that becomes qualified inventory. The factors are not four material streams. They are four different reasons a campaign can fail to deliver what a mission plan counted.

Inventory credit requires interfaces, not chemistry alone

A product can meet chemical purity while remaining unusable because its pressure, temperature, packaging, storage interface or transfer connection is incompatible with the consumer. Acceptance criteria therefore extend to the system boundary at which the mission can actually use the product.

First products should reduce fragile dependencies

The most strategically useful process is not necessarily the most impressive material. A modest local consumable can be more valuable if it repeatedly constrains operations and can be produced with high confidence. The board compares launch mass avoided, outage consequence, resource certainty, energy/thermal cost, quality burden, maintenance and spare dependence before choosing expansion. Scaling an identical reactor does not remove a shared pump, seal, technician or diagnostic bottleneck; spares, maintenance access and fault isolation must scale with production too.

Separate chemistry from availability. If jams, maintenance or power scheduling dominate lost production, improve those constraints before changing a reactor that already performs well. Campaign delivery, not isolated yield, is the mission metric.

Closure drill — qualification should follow the batch to its consumer

An ISRU batch record links resource location, feed preparation, process configuration, energy/thermal history, measured product properties, quarantine/rework disposition and the final storage/consumer interface. If a later failure is discovered, the mission can trace which inventory was produced under the same conditions.

R75 MODULE 28 PEDAGOGICAL SUPPLEMENT — PAGINATION CORRECTED

Quantitative parity laboratory — close an ISRU campaign from feed variability to time

These ten mini-lessons reproduce the FR calculation competencies for feed variability, extraction, material yield, water and oxygen production, manufacturing, useful throughput, specific energy and campaign duration; the existing verified campaign-production lesson remains as an additional integrative calculation.

Coefficient of variation — compare spread with the mean

$$CV = \sigma / \mu$$

1 — Concrete question

For **Coefficient of variation — compare spread with the mean**, how does $CV = \sigma / \mu$ inform quantifying relative variability of a feedstock or process measurement and the operational choice “Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed.”?

2 — Intuition without symbols

Intuition. Variability is easier to compare when spread is judged relative to the mean. A process with a large spread compared with its average is less predictable than one whose spread is small relative to that average.

3 — Quantities first

σ is standard deviation; μ is nonzero mean; CV is relative spread.

4 — Formula

$$CV = \sigma / \mu$$

5 — Read aloud

“C V equals sigma divided by mu.”

6 — Symbols

Symbol map for Coefficient of variation — compare spread with the mean. σ is standard deviation; μ is nonzero mean; CV is relative spread.

7 — Pronunciation

Pronunciation. Say $CV = \sigma / \mu$. For *Coefficient of variation — compare spread with the mean*, use the step-three names tied to quantifying relative variability of a feedstock or process measurement. Speak each *Coefficient of variation — compare spread with the mean* unit with the quantity it measures.

8 — Units

same unit / same unit = dimensionless

9 — Convention

Convention. For *Coefficient of variation — compare spread with the mean*, keep quantifying relative variability of a feedstock or process measurement on one declared boundary. Apply $CV = \sigma / \mu$ under that convention. CV is unstable or undefined when the mean is near zero and does not describe multimodal distributions by itself.

10 — Why this operation

Why this operation. $CV = \sigma / \mu$ answers the *Coefficient of variation — compare spread with the mean* question because it represents quantifying relative variability of a feedstock or process measurement. In this case it yields: The standard deviation is 10% of the mean magnitude.

11 — Assumptions

Assumptions. Treat the *Coefficient of variation — compare spread with the mean* values as one teaching case. For quantifying relative variability of a feedstock or process measurement, keep a single physical or operational boundary. CV is unstable or undefined when the mean is near zero and does not describe multimodal distributions by itself.

12 — Unit check

Unit check. Reduce $CV = \sigma / \mu$ for *Coefficient of variation — compare spread with the mean*. The required dimension is $\text{same unit} / \text{same unit} = \text{dimensionless}$. A different dimension invalidates “The standard deviation is 10% of the mean magnitude.”.

13 — Numerical case

$$\mu = 6.0\%$$

$$\sigma = 0.6 \text{ percentage points}$$

$$CV = 0.6/6.0 = 0.10 = 10\%$$

14 — Why each operation

Why each operation. For *Coefficient of variation — compare spread with the mean*, substitute $\mu = 6.0\%$; $\sigma = 0.6$ percentage points; $CV = 0.6/6.0 = 0.10 = 10\%$ into $CV = \sigma / \mu$. Then verify the independent statement “ $0.10 \times 6.0 = 0.6$ ”.

15 — Algebra check

Algebra check. Reverse $CV = \sigma / \mu$ for *Coefficient of variation — compare spread with the mean* using “ $0.10 \times 6.0 = 0.6$ ”. The recovered input should follow “At fixed sigma, halving the mean doubles CV.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Coefficient of variation — compare spread with the mean*. Compare that rough scale with “The standard deviation is 10% of the mean magnitude.”. If they diverge sharply, inspect $CV = \sigma / \mu$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Coefficient of variation — compare spread with the mean*, The standard deviation is 10% of the mean magnitude. Operationally: Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed. The interpretation remains limited by “CV is unstable or undefined when the mean is near zero and does not describe multimodal distributions by itself.”.

18 — What it does not prove

What it does not prove. *Coefficient of variation — compare spread with the mean* cannot support claims outside quantifying relative variability of a feedstock or process measurement. CV is unstable or undefined when the mean is near zero and does not describe multimodal distributions by itself. Use the result only to justify: Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed.

19 — Sensitivity or limit case

At fixed sigma, halving the mean doubles CV.

20 — Practice

Guided exercise — Coefficient of variation — compare spread with the mean. $\mu=12$ kg/t, $\sigma=1.8$ kg/t. Find CV.

Guided correction — Coefficient of variation — compare spread with the mean

1. $CV=1.8/12=0.15=15\%$.
2. Inspect the distribution shape before using one summary statistic.

Autonomous exercise — Coefficient of variation — compare spread with the mean. Build a second case from “At fixed sigma, halving the mean doubles CV.”. Re-evaluate $CV = \sigma / \mu$. Name the changed input. Decide whether “Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed.” still follows.

Autonomous correction — Coefficient of variation — compare spread with the mean

For *Coefficient of variation — compare spread with the mean*, state the altered case. Preserve **same unit / same unit = dimensionless**. Match the direction in “At fixed sigma, halving the mean doubles CV.”. Respect “CV is unstable or undefined when the mean is near zero and does not describe multimodal distributions by itself.”. Finish by retaining or revising: Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed.

21 — Mission decision

Use CV to decide whether blending, denser sampling or process control is needed before promising a stable feed.

Extraction throughput — mass extracted per unit operating time

$$Q_{\text{ext}} = m_{\text{ext}} / t$$

1 — Concrete question

For **Extraction throughput — mass extracted per unit operating time**, how does

$Q_{\text{ext}} = m_{\text{ext}} / t$ inform measuring excavation or mining production rate over a defined interval and the operational choice “Use verified productive throughput, not nameplate capacity, when closing campaign duration.”?

2 — Intuition without symbols

Intuition. Throughput tells how quickly material is actually extracted. Producing the same mass in less operating time means a higher rate, while downtime lowers the achieved campaign rate.

3 — Quantities first

m_{ext} is extracted mass; t operating time; Q_{ext} average extraction throughput.

4 — Formula

$$Q_{\text{ext}} = m_{\text{ext}} / t$$

5 — Read aloud

“Q extraction equals m extracted divided by t.”

6 — Symbols

Symbol map for Extraction throughput — mass extracted per unit operating time. m_{ext} is extracted mass; t operating time; Q_{ext} average extraction throughput.

7 — Pronunciation

Pronunciation. Say $Q_{\text{ext}} = m_{\text{ext}} / t$. For *Extraction throughput — mass extracted per unit operating time*, use the step-three names tied to measuring excavation or mining production rate over a defined interval. Speak each *Extraction throughput — mass extracted per unit operating time* unit with the quantity it measures.

8 — Units

kg/h

9 — Convention

Convention. For *Extraction throughput — mass extracted per unit operating time*, keep measuring excavation or mining production rate over a defined interval on one declared boundary. Apply $Q_{\text{ext}} = m_{\text{ext}} / t$ under that convention. Average throughput hides downtime and transients; define whether t is clock time, powered time or productive tool time.

10 — Why this operation

Why this operation. $Q_{\text{ext}} = m_{\text{ext}} / t$ answers the *Extraction throughput — mass extracted per unit operating time* question because it represents measuring excavation or mining production rate over a defined interval. In this case it yields: Average extraction throughput is 60 kg/h.

11 — Assumptions

Assumptions. Treat the *Extraction throughput — mass extracted per unit operating time* values as one teaching case. For measuring excavation or mining production rate over a defined interval, keep a single physical or operational boundary. Average throughput hides downtime and transients; define whether t is clock time, powered time or productive tool time.

12 — Unit check

Unit check. Reduce $Q_{\text{ext}} = m_{\text{ext}} / t$ for *Extraction throughput — mass extracted per unit operating time*. The required dimension is kg/h. A different dimension invalidates “Average extraction throughput is 60 kg/h.”.

13 — Numerical case

$$m_{\text{ext}} = 480 \text{ kg}$$

$$t = 8.0 \text{ h}$$

$$Q_{\text{ext}} = 480/8.0 = 60 \text{ kg/h}$$

14 — Why each operation

Why each operation. For *Extraction throughput — mass extracted per unit operating time*, substitute $m_{\text{ext}} = 480 \text{ kg}$; $t = 8.0 \text{ h}$; $Q_{\text{ext}} = 480/8.0 = 60 \text{ kg/h}$ into $Q_{\text{ext}} = m_{\text{ext}} / t$. Then verify the independent statement “ $60 \times 8 = 480 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $Q_{\text{ext}} = m_{\text{ext}} / t$ for *Extraction throughput — mass extracted per unit operating time* using “ $60 \times 8 = 480 \text{ kg}$ ”. The recovered input should follow “At constant mass target, a 20% lower throughput increases required operating time by 25%.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Extraction throughput — mass extracted per unit operating time*. Compare that rough scale with “Average extraction throughput is 60 kg/h.”. If they diverge sharply, inspect $Q_{\text{ext}} = m_{\text{ext}} / t$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Extraction throughput — mass extracted per unit operating time*, Average extraction throughput is 60 kg/h. Operationally: Use verified productive throughput, not nameplate capacity, when closing campaign duration. The interpretation remains limited by “Average throughput hides downtime and transients; define whether t is clock time, powered time or productive tool time.”.

18 — What it does not prove

What it does not prove. *Extraction throughput — mass extracted per unit operating time* cannot support claims outside measuring excavation or mining production rate over a defined interval. Average throughput hides downtime and transients; define whether t is clock time, powered time or productive tool time. Use the result only to justify: Use verified productive throughput, not nameplate capacity, when closing campaign duration.

19 — Sensitivity or limit case

At constant mass target, a 20% lower throughput increases required operating time by 25%.

20 — Practice

Guided exercise — Extraction throughput — mass extracted per unit operating time. 900 kg are extracted in 15 h. Find average rate.

Guided correction — Extraction throughput — mass extracted per unit operating time

1. $Q = 900/15 = 60$ kg/h.
2. State the denominator definition with the result.

Autonomous exercise — Extraction throughput — mass extracted per unit operating time. Build a second case from “At constant mass target, a 20% lower throughput increases required operating time by 25%.”. Re-evaluate $Q_{\text{ext}} = m_{\text{ext}} / t$. Name the changed input. Decide whether “Use verified productive throughput, not nameplate capacity, when closing campaign duration.” still follows.

Autonomous correction — Extraction throughput — mass extracted per unit operating time

For *Extraction throughput — mass extracted per unit operating time*, state the altered case. Preserve kg/h. Match the direction in “At constant mass target, a 20% lower throughput increases required operating time by 25%.”. Respect “Average throughput hides downtime and transients; define whether t is clock time, powered time or productive tool time.”. Finish by retaining or revising: Use verified productive throughput, not nameplate capacity, when closing campaign duration.

21 — Mission decision

Use verified productive throughput, not nameplate capacity, when closing campaign duration.

Recovered product from feed grade and process recovery

$$M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$$

1 — Concrete question

For **Recovered product from feed grade and process recovery**, how does $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$ inform estimating useful product from feed mass, target fraction and recovery efficiency and the operational choice “Close production against conservative feed variability and demonstrated recovery, not best-case assay values.”?

2 — Intuition without symbols

Intuition. Useful product depends on both how much target material exists in the feed and how much of that target the process can recover. Good feed can still produce little if recovery is poor.

3 — Quantities first

M_{feed} is feed mass; x target mass fraction in feed; η recovery fraction; M_{prod} recovered product mass.

4 — Formula

$$M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$$

5 — Read aloud

“M product equals M feed times x times eta.”

6 — Symbols

Symbol map for Recovered product from feed grade and process recovery. M_{feed} is feed mass; x target mass fraction in feed; η recovery fraction; M_{prod} recovered product mass.

7 — Pronunciation

Pronunciation. Say $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$. For *Recovered product from feed grade and process recovery*, use the step-three names tied to estimating useful product from feed mass, target fraction and recovery efficiency. Speak each *Recovered product from feed grade and process recovery* unit with the quantity it measures.

8 — Units

$\text{kg} \times \text{dimensionless} \times \text{dimensionless} = \text{kg}$

9 — Convention

Convention. For *Recovered product from feed grade and process recovery*, keep estimating useful product from feed mass, target fraction and recovery efficiency on one declared boundary. Apply

$M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$ under that convention. Grade and recovery can vary together; do not use one laboratory sample as a campaign-wide constant.

10 — Why this operation

Why this operation. $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$ answers the *Recovered product from feed grade and process recovery* question because it represents estimating useful product from feed mass, target fraction and recovery efficiency. In this case it yields: The teaching process recovers 90 kg of target product.

11 — Assumptions

Assumptions. Treat the *Recovered product from feed grade and process recovery* values as one teaching case. For estimating useful product from feed mass, target fraction and recovery efficiency, keep a single physical or operational boundary. Grade and recovery can vary together; do not use one laboratory sample as a campaign-wide constant.

12 — Unit check

Unit check. Reduce $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$ for *Recovered product from feed grade and process recovery*. The required dimension is $\text{kg} \times \text{dimensionless} \times \text{dimensionless} = \text{kg}$. A different dimension invalidates “The teaching process recovers 90 kg of target product.”.

13 — Numerical case

$$M_{\text{feed}} = 1,000 \text{ kg}$$

$$x = 0.12$$

$$\eta = 0.75$$

$$M_{\text{prod}} = 1000 \times 0.12 \times 0.75 = 90 \text{ kg}$$

14 — Why each operation

Why each operation. For *Recovered product from feed grade and process recovery*, substitute $M_{\text{feed}} = 1,000 \text{ kg}$; $x = 0.12$; $\eta = 0.75$; $M_{\text{prod}} = 1000 \times 0.12 \times 0.75 = 90 \text{ kg}$ into $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$. Then verify the independent statement “Feed contains 120 kg target; 75% recovery gives 90 kg.”.

15 — Algebra check

Algebra check. Reverse $M_{\text{prod}} = M_{\text{feed}} \times x \times \text{eta}$ for *Recovered product from feed grade and process recovery* using “Feed contains 120 kg target; 75% recovery gives 90 kg.”. The recovered input should follow “A 10-point recovery increase from 75% to 85% raises product from 90 to 102 kg at the same feed and grade.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Recovered product from feed grade and process recovery*. Compare that rough scale with “The teaching process recovers 90 kg of target product.”. If they diverge sharply, inspect $M_{\text{prod}} = M_{\text{feed}} \times x \times \text{eta}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Recovered product from feed grade and process recovery*, The teaching process recovers 90 kg of target product. Operationally: Close production against conservative feed variability and demonstrated recovery, not best-case assay values. The interpretation remains limited by “Grade and recovery can vary together; do not use one laboratory sample as a campaign-wide constant.”.

18 — What it does not prove

What it does not prove. *Recovered product from feed grade and process recovery* cannot support claims outside estimating useful product from feed mass, target fraction and recovery efficiency. Grade and recovery can vary together; do not use one laboratory sample as a campaign-wide constant. Use the result only to justify: Close production against conservative feed variability and demonstrated recovery, not best-case assay values.

19 — Sensitivity or limit case

A 10-point recovery increase from 75% to 85% raises product from 90 to 102 kg at the same feed and grade.

20 — Practice

Guided exercise — Recovered product from feed grade and process recovery. Feed=800 kg, $x=0.10$, $\eta=0.80$. Find product.

Guided correction — Recovered product from feed grade and process recovery

1. $M=800 \times 0.10 \times 0.80=64$ kg.
2. Separate unrecovered target from barren feed in the mass balance.

Autonomous exercise — Recovered product from feed grade and process recovery. Build a second case from “A 10-point recovery increase from 75% to 85% raises product from 90 to 102 kg at the same feed and grade.”. Re-evaluate $M_{\text{prod}} = M_{\text{feed}} \times x \times \eta$. Name the changed input. Decide whether “Close production against conservative feed variability and demonstrated recovery, not best-case assay values.” still follows.

Autonomous correction — Recovered product from feed grade and process recovery

For *Recovered product from feed grade and process recovery*, state the altered case. Preserve $\text{kg} \times \text{dimensionless} \times \text{dimensionless} = \text{kg}$. Match the direction in “A 10-point recovery increase from 75% to 85% raises product from 90 to 102 kg at the same feed and grade.”. Respect “Grade and recovery can vary together; do not use one laboratory sample as a campaign-wide constant.”. Finish by retaining or revising: Close production against conservative feed variability and demonstrated recovery, not best-case assay values.

21 — Mission decision

Close production against conservative feed variability and demonstrated recovery, not best-case assay values.

Water recovered from hydrated or icy feedstock

$$m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$$

1 — Concrete question

For **Water recovered from hydrated or icy feedstock**, how does $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ inform screening a regolith-water extraction campaign and the operational choice “Protect water-production commitments with conservative grade, recovery and availability assumptions.”?

2 — Intuition without symbols

Intuition. Water recovery from regolith begins with how much water the feed contains and continues with how much the process can actually liberate and collect. Dry feed or poor recovery reduces the product mass.

3 — Quantities first

x_{water} is recoverable water mass fraction in feed; m_{reg} processed regolith; η process recovery; m_{water} collected water.

4 — Formula

$$m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$$

5 — Read aloud

"m water equals x water times m regolith times eta."

6 — Symbols

Symbol map for Water recovered from hydrated or icy feedstock. x_{water} is recoverable water mass fraction in feed; m_{reg} processed regolith; η process recovery; m_{water} collected water.

7 — Pronunciation

Pronunciation. Say $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$. For *Water recovered from hydrated or icy feedstock*, use the step-three names tied to screening a regolith-water extraction campaign. Speak each *Water recovered from hydrated or icy feedstock* unit with the quantity it measures.

8 — Units

$$\text{dimensionless} \times \text{kg} \times \text{dimensionless} = \text{kg}$$

9 — Convention

Convention. For *Water recovered from hydrated or icy feedstock*, keep screening a regolith-water extraction campaign on one declared boundary. Apply $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ under that convention. Actual extractable water depends on mineralogy/ice state, temperature, excavation losses and site heterogeneity.

10 — Why this operation

Why this operation. $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ answers the *Water recovered from hydrated or icy feedstock* question because it represents screening a regolith-water extraction campaign. In this case it yields: The teaching case collects 28 kg of water.

11 — Assumptions

Assumptions. Treat the *Water recovered from hydrated or icy feedstock* values as one teaching case. For screening a regolith-water extraction campaign, keep a single physical or operational boundary. Actual extractable water depends on mineralogy/ice state, temperature, excavation losses and site heterogeneity.

12 — Unit check

Unit check. Reduce $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ for *Water recovered from hydrated or icy feedstock*. The required dimension is $\text{dimensionless} \times \text{kg} \times \text{dimensionless} = \text{kg}$. A different dimension invalidates “The teaching case collects 28 kg of water.”.

13 — Numerical case

$$x_{\text{water}} = 0.08$$

$$m_{\text{reg}} = 500 \text{ kg}$$

$$\eta = 0.70$$

$$m_{\text{water}} = 0.08 \times 500 \times 0.70 = 28 \text{ kg}$$

14 — Why each operation

Why each operation. For *Water recovered from hydrated or icy feedstock*, substitute $x_{\text{water}} = 0.08$; $m_{\text{reg}} = 500 \text{ kg}$; $\eta = 0.70$; $m_{\text{water}} = 0.08 \times 500 \times 0.70 = 28 \text{ kg}$ into $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$. Then verify the independent statement “500 kg feed contains 40 kg water-equivalent; 70% recovery gives 28 kg.”.

15 — Algebra check

Algebra check. Reverse $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ for *Water recovered from hydrated or icy feedstock* using “500 kg feed contains 40 kg water-equivalent; 70% recovery gives 28 kg.”. The recovered input should follow “If grade falls from 8% to 5%, product falls proportionally to 17.5 kg at the same mass and recovery.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Water recovered from hydrated or icy feedstock*. Compare that rough scale with “The teaching case collects 28 kg of water.”. If they diverge sharply, inspect $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Water recovered from hydrated or icy feedstock*, The teaching case collects 28 kg of water. Operationally: Protect water-production commitments with conservative grade, recovery and availability assumptions. The interpretation remains limited by “Actual extractable water depends on mineralogy/ice state, temperature, excavation losses and site heterogeneity.”.

18 — What it does not prove

What it does not prove. *Water recovered from hydrated or icy feedstock* cannot support claims outside screening a regolith-water extraction campaign. Actual extractable water depends on mineralogy/ice state, temperature, excavation losses and site heterogeneity. Use the result only to justify: Protect water-production commitments with conservative grade, recovery and availability assumptions.

19 — Sensitivity or limit case

If grade falls from 8% to 5%, product falls proportionally to 17.5 kg at the same mass and recovery.

20 — Practice

Guided exercise — Water recovered from hydrated or icy feedstock. $x=0.06$, $m_{\text{reg}}=1,200$ kg, $\eta=0.75$. Find water.

Guided correction — Water recovered from hydrated or icy feedstock

1. $m=0.06 \times 1200 \times 0.75=54$ kg.
2. Use a grade distribution for campaign planning, not one point estimate.

Autonomous exercise — Water recovered from hydrated or icy feedstock. Build a second case from “If grade falls from 8% to 5%, product falls proportionally to 17.5 kg at the same mass and recovery.”. Re-evaluate $m_{\text{water}} = x_{\text{water}} \times m_{\text{reg}} \times \eta$. Name the changed input. Decide whether “Protect water-production commitments with conservative grade, recovery and availability assumptions.” still follows.

Autonomous correction — Water recovered from hydrated or icy feedstock

For *Water recovered from hydrated or icy feedstock*, state the altered case. Preserve $\text{dimensionless} \times \text{kg} \times \text{dimensionless} = \text{kg}$. Match the direction in “If grade falls from 8% to 5%, product falls proportionally to 17.5 kg at the same mass and recovery.”. Respect “Actual extractable water depends on mineralogy/ice state, temperature, excavation losses and site heterogeneity.”. Finish by retaining or revising: Protect water-production commitments with conservative grade, recovery and availability assumptions.

21 — Mission decision

Protect water-production commitments with conservative grade, recovery and availability assumptions.

Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency

$$m_{\text{O}_2} = \eta \times (16/44) \times m_{\text{CO}_2}$$

1 — Concrete question

For **Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency**, how does $m_{\text{O}_2} = \eta \times (16/44) \times m_{\text{CO}_2}$ inform estimating oxygen mass obtained when one oxygen atom per CO_2 molecule becomes product O_2 -equivalent mass in a specified process model and the operational choice “Use stoichiometry to catch impossible production claims before energy and hardware trades proceed.”?

2 — Intuition without symbols

Intuition. Carbon dioxide contains oxygen that can be released by processing, but chemistry sets an upper bound before hardware losses are considered. Efficiency determines how much of that theoretical oxygen becomes usable product.

3 — Quantities first

m_{CO_2} is processed CO_2 mass; $16/44$ is the oxygen-product mass fraction for the chosen net reaction basis; η overall product recovery; m_{O_2} product.

4 — Formula

$$m_{O_2} = \eta \times (16/44) \times m_{CO_2}$$

5 — Read aloud

“m O two equals eta times sixteen over forty-four times m C O two.”

6 — Symbols

Symbol map for Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency. m_{CO_2} is processed CO_2 mass; $16/44$ is the oxygen-product mass fraction for the chosen net reaction basis; η overall product recovery; m_{O_2} product.

7 — Pronunciation

Pronunciation. Say $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$. For *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*, use the step-three names tied to estimating oxygen mass obtained when one oxygen atom per CO_2 molecule becomes product O_2 -equivalent mass in a specified process model. Speak each *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency* unit with the quantity it measures.

8 — Units

$$\text{dimensionless} \times \text{dimensionless} \times \text{kg} = \text{kg}$$

9 — Convention

Convention. For *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*, keep estimating oxygen mass obtained when one oxygen atom per CO_2 molecule becomes product O_2 -equivalent mass in a specified process model on one declared boundary. Apply $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$ under that convention. The stoichiometric factor depends on the actual chemical pathway and accounting boundary; energy and coproducts must be closed separately.

10 — Why this operation

Why this operation. $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$ answers the *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency* question because it represents estimating oxygen mass obtained when one oxygen atom per CO₂ molecule becomes product O₂-equivalent mass in a specified process model. In this case it yields: The illustrative product is about 32.7 kg O₂ for this reaction basis and efficiency.

11 — Assumptions

Assumptions. Treat the *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency* values as one teaching case. For estimating oxygen mass obtained when one oxygen atom per CO₂ molecule becomes product O₂-equivalent mass in a specified process model, keep a single physical or operational boundary. The stoichiometric factor depends on the actual chemical pathway and accounting boundary; energy and coproducts must be closed separately.

12 — Unit check

Unit check. Reduce $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$ for *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*. The required dimension is $\text{dimensionless} \times \text{dimensionless} \times \text{kg} = \text{kg}$. A different dimension invalidates “The illustrative product is about 32.7 kg O₂ for this reaction basis and efficiency.”.

13 — Numerical case

$$m_{CO_2} = 100 \text{ kg}$$

$$\eta = 0.90$$

$$m_{O_2} = 0.90 \times (16/44) \times 100 \approx 32.7 \text{ kg}$$

14 — Why each operation

Why each operation. For *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*, substitute $m_{CO_2} = 100 \text{ kg}$; $\eta = 0.90$; $m_{O_2} = 0.90 \times (16/44) \times 100 \approx 32.7 \text{ kg}$ into

$m_{O_2} = \eta \times (16/44) \times m_{CO_2}$. Then verify the independent statement “The theoretical basis gives 36.36 kg; 90% is 32.73 kg.”.

15 — Algebra check

Algebra check. Reverse $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$ for *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency* using “The theoretical basis gives 36.36 kg; 90% is 32.73 kg.”. The recovered input should follow “At fixed feed, product scales linearly with η in this simplified model.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*. Compare that rough scale with “The illustrative product is about 32.7 kg O₂ for this reaction basis and efficiency.”. If they diverge sharply, inspect $m_{O_2} = \eta \times (16/44) \times m_{CO_2}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*, The illustrative product is about 32.7 kg O₂ for this reaction basis and efficiency. Operationally: Use stoichiometry to catch impossible production claims before energy and hardware trades proceed. The interpretation remains limited by “The stoichiometric factor depends on the actual chemical pathway and accounting boundary; energy and coproducts must be closed separately.”.

18 — What it does not prove

What it does not prove. *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency* cannot support claims outside estimating oxygen mass obtained when one oxygen atom per CO₂ molecule becomes product O₂-equivalent mass in a specified process model. The stoichiometric factor depends on the actual chemical pathway and accounting boundary; energy and coproducts must be closed separately. Use the result only to justify: Use stoichiometry to catch impossible production claims before energy and hardware trades proceed.

19 — Sensitivity or limit case

At fixed feed, product scales linearly with η in this simplified model.

20 — Practice

Guided exercise — Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency. Process 220 kg CO₂ at $\eta=0.85$ on the same basis.

Guided correction — Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency

1. theoretical = $220 \times 16/44 = 80.0$ kg; product = 68.0 kg.
2. State the reaction basis explicitly.

Autonomous exercise — Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency. Build a second case from “At fixed feed, product scales linearly with η in this simplified model.”. Re-evaluate $m_{O2} = \eta \times (16/44) \times m_{CO2}$. Name the changed input. Decide whether “Use stoichiometry to catch impossible production claims before energy and hardware trades proceed.” still follows.

Autonomous correction — Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency

For *Oxygen from processed carbon dioxide — stoichiometric upper bound with efficiency*, state the altered case. Preserve $\text{dimensionless} \times \text{dimensionless} \times \text{kg} = \text{kg}$. Match the direction in “At fixed feed, product scales linearly with η in this simplified model.”. Respect “The stoichiometric factor depends on the actual chemical pathway and accounting boundary; energy and coproducts must be closed separately.”. Finish by retaining or revising: Use stoichiometry to catch impossible production claims before energy and hardware trades proceed.

21 — Mission decision

Use stoichiometry to catch impossible production claims before energy and hardware trades proceed.

Manufactured part mass from material density and finished volume

$$m_{\text{part}} = \rho \times V$$

1 — Concrete question

For **Manufactured part mass from material density and finished volume**, how does $m_{\text{part}} = \rho \times V$ inform estimating feedstock mass for a solid component before allowances and the operational choice “Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity.”?

2 — Intuition without symbols

Intuition. A manufactured part becomes heavier when it occupies more finished volume or uses denser material. Geometry and material choice therefore determine the mass that production, handling and logistics must support.

3 — Quantities first

ρ is material density; V finished solid volume; m_{part} ideal finished mass.

4 — Formula

$$m_{\text{part}} = \rho \times V$$

5 — Read aloud

"m part equals rho times V."

6 — Symbols

Symbol map for Manufactured part mass from material density and finished volume. ρ is material density; V finished solid volume; m_{part} ideal finished mass.

7 — Pronunciation

Pronunciation. Say $m_{\text{part}} = \rho \times V$. For *Manufactured part mass from material density and finished volume*, use the step-three names tied to estimating feedstock mass for a solid component before allowances. Speak each *Manufactured part mass from material density and finished volume* unit with the quantity it measures.

8 — Units

$$\text{kg/m}^3 \times \text{m}^3 = \text{kg}$$

9 — Convention

Convention. For *Manufactured part mass from material density and finished volume*, keep estimating feedstock mass for a solid component before allowances on one declared boundary. Apply $m_{\text{part}} = \rho \times V$ under that convention. Real feedstock demand is higher when supports, machining allowance, failed builds or porosity control are included.

10 — Why this operation

Why this operation. $m_{\text{part}} = \rho \times V$ answers the *Manufactured part mass from material density and finished volume* question because it represents estimating feedstock mass for a solid component before allowances. In this case it yields: Ideal finished-part mass is 8.1 kg.

11 — Assumptions

Assumptions. Treat the *Manufactured part mass from material density and finished volume* values as one teaching case. For estimating feedstock mass for a solid component before allowances, keep a single physical or operational boundary. Real feedstock demand is higher when supports, machining allowance, failed builds or porosity control are included.

12 — Unit check

Unit check. Reduce $m_{\text{part}} = \rho \times V$ for *Manufactured part mass from material density and finished volume*. The required dimension is $\text{kg/m}^3 \times \text{m}^3 = \text{kg}$. A different dimension invalidates “Ideal finished-part mass is 8.1 kg.”.

13 — Numerical case

$$\rho = 2,700 \text{ kg/m}^3$$

$$V = 0.0030 \text{ m}^3$$

$$m_{\text{part}} = 2700 \times 0.0030 = 8.1 \text{ kg}$$

14 — Why each operation

Why each operation. For *Manufactured part mass from material density and finished volume*, substitute $\rho = 2,700 \text{ kg/m}^3$; $V = 0.0030 \text{ m}^3$; $m_{\text{part}} = 2700 \times 0.0030 = 8.1 \text{ kg}$ into $m_{\text{part}} = \rho \times V$. Then verify the independent statement “ $8.1/2700 = 0.0030 \text{ m}^3$ ”.

15 — Algebra check

Algebra check. Reverse $m_{\text{part}} = \rho \times V$ for *Manufactured part mass from material density and finished volume* using “ $8.1/2700 = 0.0030 \text{ m}^3$ ”. The recovered input should follow “A 10% volume increase raises ideal mass by 10% at fixed density.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Manufactured part mass from material density and finished volume*. Compare that rough scale with “Ideal finished-part mass is 8.1 kg.”. If they diverge sharply, inspect $m_{\text{part}} = \rho \times V$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Manufactured part mass from material density and finished volume*, Ideal finished-part mass is 8.1 kg. Operationally: Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity. The interpretation remains limited by “Real feedstock demand is higher when supports, machining allowance, failed builds or porosity control are included.”.

18 — What it does not prove

What it does not prove. *Manufactured part mass from material density and finished volume* cannot support claims outside estimating feedstock mass for a solid component before allowances. Real feedstock demand is higher when supports, machining allowance, failed builds or porosity control are included. Use the result only to justify: Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity.

19 — Sensitivity or limit case

A 10% volume increase raises ideal mass by 10% at fixed density.

20 — Practice

Guided exercise — Manufactured part mass from material density and finished volume. $\rho=7,800$ kg/m³, $V=0.0015$ m³. Find ideal mass.

Guided correction — Manufactured part mass from material density and finished volume

1. $m=11.7$ kg.
2. Add process yield and qualification coupons separately.

Autonomous exercise — Manufactured part mass from material density and finished volume.

Build a second case from “A 10% volume increase raises ideal mass by 10% at fixed density.”. Re-evaluate $m_{\text{part}} = \rho \times V$. Name the changed input. Decide whether “Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity.” still follows.

Autonomous correction — Manufactured part mass from material density and finished volume

For *Manufactured part mass from material density and finished volume*, state the altered case. Preserve $\text{kg/m}^3 \times \text{m}^3 = \text{kg}$. Match the direction in “A 10% volume increase raises ideal mass by 10% at fixed density.”. Respect “Real feedstock demand is higher when supports, machining allowance, failed builds or porosity control are included.”. Finish by retaining or revising: Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity.

21 — Mission decision

Use ideal part mass as the lower bound for feedstock and handling calculations, not the procurement quantity.

Useful production throughput — derate nameplate by availability and efficiency

$$Q_{\text{use}} = Q_{\text{nom}} \times A \times \eta$$

1 — Concrete question

For **Useful production throughput — derate nameplate by availability and efficiency**, how does $Q_{\text{use}} = Q_{\text{nom}} \times A \times \eta$ inform closing realistic production rate from machine capacity, uptime and process yield and the operational choice “Use useful throughput, not nameplate, for stockpile and crew-support commitments.”?

2 — Intuition without symbols

Intuition. Nameplate production is not the same as useful production. Availability removes downtime and process efficiency removes losses, so real campaign output is a derated fraction of the advertised rate.

3 — Quantities first

Q_nom is nameplate rate; A availability fraction; eta useful-output efficiency/yield; Q_use useful average rate.

4 — Formula

$$Q_{\text{use}} = Q_{\text{nom}} \times A \times \text{eta}$$

5 — Read aloud

“Q useful equals Q nominal times availability times eta.”

6 — Symbols

Symbol map for Useful production throughput — derate nameplate by availability and efficiency.

Q_nom is nameplate rate; A availability fraction; eta useful-output efficiency/yield; Q_use useful average rate.

7 — Pronunciation

Pronunciation. Say $Q_{\text{use}} = Q_{\text{nom}} \times A \times \text{eta}$. For *Useful production throughput — derate nameplate by availability and efficiency*, use the step-three names tied to closing realistic production rate from machine capacity, uptime and process yield. Speak each *Useful production throughput — derate nameplate by availability and efficiency* unit with the quantity it measures.

8 — Units

$$\text{kg/h} \times \text{dimensionless} \times \text{dimensionless} = \text{kg/h}$$

9 — Convention

Convention. For *Useful production throughput — derate nameplate by availability and efficiency*, keep closing realistic production rate from machine capacity, uptime and process yield on one declared boundary. Apply $Q_{\text{use}} = Q_{\text{nom}} \times A \times \text{eta}$ under that convention. Availability and yield must be independently defined; multiplying overlapping derating factors can double-count losses.

10 — Why this operation

Why this operation. $Q_{\text{use}} = Q_{\text{nom}} \times A \times \text{eta}$ answers the *Useful production throughput — derate nameplate by availability and efficiency* question because it represents closing realistic production rate from machine capacity, uptime and process yield. In this case it yields: Useful average throughput is 60 kg/h.

11 — Assumptions

Assumptions. Treat the *Useful production throughput — derate nameplate by availability and efficiency* values as one teaching case. For closing realistic production rate from machine capacity, uptime and process yield, keep a single physical or operational boundary. Availability and yield must be independently defined; multiplying overlapping derating factors can double-count losses.

12 — Unit check

Unit check. Reduce $Q_{use} = Q_{nom} \times A \times \eta$ for *Useful production throughput — derate nameplate by availability and efficiency*. The required dimension is $\text{kg/h} \times \text{dimensionless} \times \text{dimensionless} = \text{kg/h}$. A different dimension invalidates “Useful average throughput is 60 kg/h.”.

13 — Numerical case

$$Q_{nom} = 100 \text{ kg/h}$$

$$A = 0.80$$

$$\eta = 0.75$$

$$Q_{use} = 100 \times 0.80 \times 0.75 = 60 \text{ kg/h}$$

14 — Why each operation

Why each operation. For *Useful production throughput — derate nameplate by availability and efficiency*, substitute $Q_{nom} = 100 \text{ kg/h}$; $A = 0.80$; $\eta = 0.75$; $Q_{use} = 100 \times 0.80 \times 0.75 = 60 \text{ kg/h}$ into $Q_{use} = Q_{nom} \times A \times \eta$. Then verify the independent statement “ $100 \times 0.80 = 80$ operating-equivalent kg/h; $\times 0.75 = 60$ useful kg/h”.

15 — Algebra check

Algebra check. Reverse $Q_{use} = Q_{nom} \times A \times \eta$ for *Useful production throughput — derate nameplate by availability and efficiency* using “ $100 \times 0.80 = 80$ operating-equivalent kg/h; $\times 0.75 = 60$ useful kg/h”. The recovered input should follow “Raising availability from 0.80 to 0.90 increases useful rate from 60 to 67.5 kg/h at same yield.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Useful production throughput — derate nameplate by availability and efficiency*. Compare that rough scale with “Useful average throughput is 60 kg/h.”. If they diverge sharply, inspect $Q_{use} = Q_{nom} \times A \times \eta$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Useful production throughput — derate nameplate by availability and efficiency*, Useful average throughput is 60 kg/h. Operationally: Use useful throughput, not nameplate, for stockpile and crew-support commitments. The interpretation remains limited by “Availability and yield must be independently defined; multiplying overlapping derating factors can double-count losses.”.

18 — What it does not prove

What it does not prove. *Useful production throughput — derate nameplate by availability and efficiency* cannot support claims outside closing realistic production rate from machine capacity, uptime and process yield. Availability and yield must be independently defined; multiplying overlapping derating factors can double-count losses. Use the result only to justify: Use useful throughput, not nameplate, for stockpile and crew-support commitments.

19 — Sensitivity or limit case

Raising availability from 0.80 to 0.90 increases useful rate from 60 to 67.5 kg/h at same yield.

20 — Practice

Guided exercise — Useful production throughput — derate nameplate by availability and efficiency. $Q_{nom}=150$ kg/h, $A=0.70$, $\eta=0.80$. Find useful rate.

Guided correction — Useful production throughput — derate nameplate by availability and efficiency

1. $Q=150 \times 0.70 \times 0.80=84$ kg/h.
2. Compare against measured campaign data.

Autonomous exercise — Useful production throughput — derate nameplate by availability and efficiency. Build a second case from “Raising availability from 0.80 to 0.90 increases useful rate from 60 to 67.5 kg/h at same yield.”. Re-evaluate $Q_{use} = Q_{nom} \times A \times \eta$. Name the changed input. Decide whether “Use useful throughput, not nameplate, for stockpile and crew-support commitments.” still follows.

Autonomous correction — Useful production throughput — derate nameplate by availability and efficiency

For *Useful production throughput — derate nameplate by availability and efficiency*, state the altered case. Preserve $\text{kg/h} \times \text{dimensionless} \times \text{dimensionless} = \text{kg/h}$. Match the direction in “Raising availability from 0.80 to 0.90 increases useful rate from 60 to 67.5 kg/h at same yield.”. Respect “Availability and yield must be independently defined; multiplying overlapping derating factors can double-count losses.”. Finish by retaining or revising: Use useful throughput, not nameplate, for stockpile and crew-support commitments.

21 — Mission decision

Use useful throughput, not nameplate, for stockpile and crew-support commitments.

Mass yield — useful product divided by feed mass

$$Y_m = m_{\text{prod}} / m_{\text{feed}}$$

1 — Concrete question

For **Mass yield — useful product divided by feed mass**, how does $Y_m = m_{\text{prod}} / m_{\text{feed}}$ inform tracking how much incoming material becomes qualified product and the operational choice “Track yield with quality; a high mass yield of out-of-spec product is not mission success.”?

2 — Intuition without symbols

Intuition. Mass yield asks how much useful product emerges from the feed that entered the process. It exposes losses without claiming where those losses occurred.

3 — Quantities first

m_{prod} is qualified product mass; m_{feed} is feed mass crossing the process boundary; Y_m is mass yield.

4 — Formula

$$Y_m = m_{\text{prod}} / m_{\text{feed}}$$

5 — Read aloud

“Y mass equals m product divided by m feed.”

6 — Symbols

Symbol map for Mass yield — useful product divided by feed mass. m_{prod} is qualified product mass; m_{feed} is feed mass crossing the process boundary; Y_m is mass yield.

7 — Pronunciation

Pronunciation. Say $Y_m = m_{\text{prod}} / m_{\text{feed}}$. For *Mass yield — useful product divided by feed mass*, use the step-three names tied to tracking how much incoming material becomes qualified product. Speak each *Mass yield — useful product divided by feed mass* unit with the quantity it measures.

8 — Units

kg/kg = dimensionless

9 — Convention

Convention. For *Mass yield — useful product divided by feed mass*, keep tracking how much incoming material becomes qualified product on one declared boundary. Apply $Y_m = m_{\text{prod}} / m_{\text{feed}}$ under that convention. Yield depends on boundary: recyclable scrap, tailings and coproducts can change the apparent number.

10 — Why this operation

Why this operation. $Y_m = m_{\text{prod}} / m_{\text{feed}}$ answers the *Mass yield — useful product divided by feed mass* question because it represents tracking how much incoming material becomes qualified product. In this case it yields: Sixty percent of feed mass becomes qualified product under this boundary.

11 — Assumptions

Assumptions. Treat the *Mass yield — useful product divided by feed mass* values as one teaching case. For tracking how much incoming material becomes qualified product, keep a single physical or operational boundary. Yield depends on boundary: recyclable scrap, tailings and coproducts can change the apparent number.

12 — Unit check

Unit check. Reduce $Y_m = m_{\text{prod}} / m_{\text{feed}}$ for *Mass yield — useful product divided by feed mass*. The required dimension is $\text{kg/kg} = \text{dimensionless}$. A different dimension invalidates “Sixty percent of feed mass becomes qualified product under this boundary.”.

13 — Numerical case

$$m_{\text{prod}} = 72 \text{ kg}$$

$$m_{\text{feed}} = 120 \text{ kg}$$

$$Y_m = 72/120 = 0.60 = 60\%$$

14 — Why each operation

Why each operation. For *Mass yield — useful product divided by feed mass*, substitute $m_{\text{prod}} = 72 \text{ kg}$; $m_{\text{feed}} = 120 \text{ kg}$; $Y_m = 72/120 = 0.60 = 60\%$ into $Y_m = m_{\text{prod}} / m_{\text{feed}}$. Then verify the independent statement “ $0.60 \times 120 = 72 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $Y_m = m_{\text{prod}} / m_{\text{feed}}$ for *Mass yield — useful product divided by feed mass* using “ $0.60 \times 120 = 72 \text{ kg}$ ”. The recovered input should follow “If product stays 72 kg while feed rises to 144 kg, yield falls to 50%.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Mass yield — useful product divided by feed mass*. Compare that rough scale with “Sixty percent of feed mass becomes qualified product under this boundary.”. If they diverge sharply, inspect $Y_m = m_{\text{prod}} / m_{\text{feed}}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Mass yield — useful product divided by feed mass*, Sixty percent of feed mass becomes qualified product under this boundary. Operationally: Track yield with quality; a high mass yield of out-of-spec product is not mission success. The interpretation remains limited by “Yield depends on boundary: recyclable scrap, tailings and coproducts can change the apparent number.”.

18 — What it does not prove

What it does not prove. *Mass yield — useful product divided by feed mass* cannot support claims outside tracking how much incoming material becomes qualified product. Yield depends on boundary: recyclable scrap, tailings and coproducts can change the apparent number. Use the result only to justify: Track yield with quality; a high mass yield of out-of-spec product is not mission success.

19 — Sensitivity or limit case

If product stays 72 kg while feed rises to 144 kg, yield falls to 50%.

20 — Practice

Guided exercise — Mass yield — useful product divided by feed mass. Product=95 kg from 125 kg feed. Find yield.

Guided correction — Mass yield — useful product divided by feed mass

1. $Y=95/125=0.76=76\%$.
2. State whether rework and recycled material are inside the boundary.

Autonomous exercise — Mass yield — useful product divided by feed mass. Build a second case from “If product stays 72 kg while feed rises to 144 kg, yield falls to 50%.”. Re-evaluate $Y_m = m_{prod} / m_{feed}$. Name the changed input. Decide whether “Track yield with quality; a high mass yield of out-of-spec product is not mission success.” still follows.

Autonomous correction — Mass yield — useful product divided by feed mass

For *Mass yield — useful product divided by feed mass*, state the altered case. Preserve $kg/kg = \text{dimensionless}$. Match the direction in “If product stays 72 kg while feed rises to 144 kg, yield falls to 50%.”. Respect “Yield depends on boundary: recyclable scrap, tailings and coproducts can change the apparent number.”. Finish by retaining or revising: Track yield with quality; a high mass yield of out-of-spec product is not mission success.

21 — Mission decision

Track yield with quality; a high mass yield of out-of-spec product is not mission success.

Process energy from specific energy consumption

$$E = e_{\text{spec}} \times m$$

1 — Concrete question

For **Process energy from specific energy consumption**, how does $E = e_{\text{spec}} \times m$ inform estimating campaign electrical or thermal energy for a processed mass and the operational choice “Use specific energy to connect ISRU production targets to power-system capacity and storage.”?

2 — Intuition without symbols

Intuition. A process with high energy demand per unit product consumes more campaign energy as production grows. Specific energy turns a production target into an electrical or thermal energy requirement.

3 — Quantities first

e_{spec} is energy required per unit processed/product mass under a defined basis; m is corresponding mass; E total energy.

4 — Formula

$$E = e_{\text{spec}} \times m$$

5 — Read aloud

“ E equals e specific times m .”

6 — Symbols

Symbol map for Process energy from specific energy consumption. e_{spec} is energy required per unit processed/product mass under a defined basis; m is corresponding mass; E total energy.

7 — Pronunciation

Pronunciation. Say $E = e_{\text{spec}} \times m$. For *Process energy from specific energy consumption*, use the step-three names tied to estimating campaign electrical or thermal energy for a processed mass. Speak each *Process energy from specific energy consumption* unit with the quantity it measures.

8 — Units

$$\text{kWh/kg} \times \text{kg} = \text{kWh}$$

9 — Convention

Convention. For *Process energy from specific energy consumption*, keep estimating campaign electrical or thermal energy for a processed mass on one declared boundary. Apply $E = e_{\text{spec}} \times m$ under that convention. Specific energy changes with scale, temperature, feed composition, standby losses and process boundary.

10 — Why this operation

Why this operation. $E = e_{\text{spec}} \times m$ answers the *Process energy from specific energy consumption* question because it represents estimating campaign electrical or thermal energy for a processed mass. In this case it yields: The batch requires 100 kWh on the stated specific-energy basis.

11 — Assumptions

Assumptions. Treat the *Process energy from specific energy consumption* values as one teaching case. For estimating campaign electrical or thermal energy for a processed mass, keep a single physical or operational boundary. Specific energy changes with scale, temperature, feed composition, standby losses and process boundary.

12 — Unit check

Unit check. Reduce $E = e_{\text{spec}} \times m$ for *Process energy from specific energy consumption*. The required dimension is $\text{kWh/kg} \times \text{kg} = \text{kWh}$. A different dimension invalidates “The batch requires 100 kWh on the stated specific-energy basis.”.

13 — Numerical case

$$e_{\text{spec}} = 2.5 \text{ kWh/kg}$$

$$m = 40 \text{ kg}$$

$$E = 2.5 \times 40 = 100 \text{ kWh}$$

14 — Why each operation

Why each operation. For *Process energy from specific energy consumption*, substitute $e_{\text{spec}} = 2.5 \text{ kWh/kg}$; $m = 40 \text{ kg}$; $E = 2.5 \times 40 = 100 \text{ kWh}$ into $E = e_{\text{spec}} \times m$. Then verify the independent statement “ $100/40=2.5 \text{ kWh/kg}$ ”.

15 — Algebra check

Algebra check. Reverse $E = e_{\text{spec}} \times m$ for *Process energy from specific energy consumption* using “ $100/40=2.5 \text{ kWh/kg}$ ”. The recovered input should follow “A 20% increase in e_{spec} raises batch energy to 120 kWh.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Process energy from specific energy consumption*. Compare that rough scale with “The batch requires 100 kWh on the stated specific-energy basis.”. If they diverge sharply, inspect $E = e_{\text{spec}} \times m$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Process energy from specific energy consumption*, The batch requires 100 kWh on the stated specific-energy basis. Operationally: Use specific energy to connect ISRU production targets to power-system capacity and storage. The interpretation remains limited by “Specific energy changes with scale, temperature, feed composition, standby losses and process boundary.”.

18 — What it does not prove

What it does not prove. *Process energy from specific energy consumption* cannot support claims outside estimating campaign electrical or thermal energy for a processed mass. Specific energy changes with scale, temperature, feed composition, standby losses and process boundary. Use the result only to justify: Use specific energy to connect ISRU production targets to power-system capacity and storage.

19 — Sensitivity or limit case

A 20% increase in e_{spec} raises batch energy to 120 kWh.

20 — Practice

Guided exercise — Process energy from specific energy consumption. $e_{\text{spec}}=1.8$ kWh/kg for 75 kg. Find energy.

Guided correction — Process energy from specific energy consumption

1. $E=1.8 \times 75=135$ kWh.
2. Then add distribution/storage losses if they are outside e_{spec} .

Autonomous exercise — Process energy from specific energy consumption. Build a second case from “A 20% increase in e_{spec} raises batch energy to 120 kWh.”. Re-evaluate $E = e_{\text{spec}} \times m$. Name the changed input. Decide whether “Use specific energy to connect ISRU production targets to power-system capacity and storage.” still follows.

Autonomous correction — Process energy from specific energy consumption

For *Process energy from specific energy consumption*, state the altered case. Preserve $\text{kWh/kg} \times \text{kg} = \text{kWh}$. Match the direction in “A 20% increase in e_{spec} raises batch energy to 120 kWh.”. Respect “Specific energy changes with scale, temperature, feed composition, standby losses and process boundary.”. Finish by retaining or revising: Use specific energy to connect ISRU production targets to power-system capacity and storage.

21 — Mission decision

Use specific energy to connect ISRU production targets to power-system capacity and storage.

Campaign duration from target stock and useful production rate

$$t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$$

1 — Concrete question

For **Campaign duration from target stock and useful production rate**, how does $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ inform estimating how long a production campaign must run after derating and the operational choice “Start production early enough that conservative campaign time still closes before the stock is needed.”?

2 — Intuition without symbols

Intuition. A production campaign ends when the required stock has been made at the useful rate the system can sustain. Higher real throughput shortens the campaign; lower throughput extends it.

3 — Quantities first

Stock_target is required product mass; Q_use verified useful average throughput; t_campaign required productive campaign duration.

4 — Formula

$$t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$$

5 — Read aloud

“t campaign equals stock target divided by Q useful.”

6 — Symbols

Symbol map for Campaign duration from target stock and useful production rate. Stock_target is required product mass; Q_use verified useful average throughput; t_campaign required productive campaign duration.

7 — Pronunciation

Pronunciation. Say $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$. For *Campaign duration from target stock and useful production rate*, use the step-three names tied to estimating how long a production campaign must run after derating. Speak each *Campaign duration from target stock and useful production rate* unit with the quantity it measures.

8 — Units

$$\text{kg}/(\text{kg}/\text{h}) = \text{h}$$

9 — Convention

Convention. For *Campaign duration from target stock and useful production rate*, keep estimating how long a production campaign must run after derating on one declared boundary. Apply $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ under that convention. Calendar duration is longer when shifts, maintenance, setup and resource interruptions are outside Q_use.

10 — Why this operation

Why this operation. $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ answers the *Campaign duration from target stock and useful production rate* question because it represents estimating how long a production campaign must run after derating. In this case it yields: Twenty hours of useful production are required at the stated average rate.

11 — Assumptions

Assumptions. Treat the *Campaign duration from target stock and useful production rate* values as one teaching case. For estimating how long a production campaign must run after derating, keep a single physical or operational boundary. Calendar duration is longer when shifts, maintenance, setup and resource interruptions are outside Q_{use} .

12 — Unit check

Unit check. Reduce $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ for *Campaign duration from target stock and useful production rate*. The required dimension is $\text{kg}/(\text{kg}/\text{h}) = \text{h}$. A different dimension invalidates “Twenty hours of useful production are required at the stated average rate.”.

13 — Numerical case

$$\text{Stock_target} = 1,200 \text{ kg}$$

$$Q_{\text{use}} = 60 \text{ kg/h}$$

$$t_{\text{campaign}} = 1200/60 = 20 \text{ h}$$

14 — Why each operation

Why each operation. For *Campaign duration from target stock and useful production rate*, substitute $\text{Stock_target} = 1,200 \text{ kg}$; $Q_{\text{use}} = 60 \text{ kg/h}$; $t_{\text{campaign}} = 1200/60 = 20 \text{ h}$ into $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$. Then verify the independent statement “ $20 \times 60 = 1200 \text{ kg}$ ”.

15 — Algebra check

Algebra check. Reverse $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ for *Campaign duration from target stock and useful production rate* using “ $20 \times 60 = 1200 \text{ kg}$ ”. The recovered input should follow “If useful rate falls 25% to 45 kg/h, duration rises to 26.7 h.”. If not, recheck units and boundaries.

16 — Mental estimate

Mental estimate. Round the dominant inputs for *Campaign duration from target stock and useful production rate*. Compare that rough scale with “Twenty hours of useful production are required at the stated average rate.”. If they diverge sharply, inspect $t_{\text{campaign}} = \text{Stock_target} / Q_{\text{use}}$ for units, signs or boundaries.

17 — Interpretation

Interpretation. For *Campaign duration from target stock and useful production rate*, Twenty hours of useful production are required at the stated average rate. Operationally: Start production early enough that conservative campaign time still closes before the stock is needed. The interpretation remains limited by “Calendar duration is longer when shifts, maintenance, setup and resource interruptions are outside Q_{use} .”.

18 — What it does not prove

What it does not prove. Campaign duration from target stock and useful production rate cannot support claims outside estimating how long a production campaign must run after derating. Calendar duration is longer when shifts, maintenance, setup and resource interruptions are outside Q_{use} . Use the result only to justify: Start production early enough that conservative campaign time still closes before the stock is needed.

19 — Sensitivity or limit case

If useful rate falls 25% to 45 kg/h, duration rises to 26.7 h.

20 — Practice

Guided exercise — Campaign duration from target stock and useful production rate. Target=2,100 kg, useful rate=70 kg/h. Find productive time.

Guided correction — Campaign duration from target stock and useful production rate

1. $t = 2100 / 70 = 30$ h.
2. Convert to calendar time only after adding the operating schedule and downtime model.

Autonomous exercise — Campaign duration from target stock and useful production rate. Build a second case from “If useful rate falls 25% to 45 kg/h, duration rises to 26.7 h.”. Re-evaluate $t_{campaign} = \text{Stock_target} / Q_{use}$. Name the changed input. Decide whether “Start production early enough that conservative campaign time still closes before the stock is needed.” still follows.

Autonomous correction — Campaign duration from target stock and useful production rate

For Campaign duration from target stock and useful production rate, state the altered case. Preserve $\text{kg} / (\text{kg/h}) = \text{h}$. Match the direction in “If useful rate falls 25% to 45 kg/h, duration rises to 26.7 h.”. Respect “Calendar duration is longer when shifts, maintenance, setup and resource interruptions are outside Q_{use} .”. Finish by retaining or revising: Start production early enough that conservative campaign time still closes before the stock is needed.

21 — Mission decision

Start production early enough that conservative campaign time still closes before the stock is needed.