COMPASSION8INNOVATION
FIRST EDITION · 2026

A STUDY BOOK IN SPACE SYSTEMS ENGINEERING

**PART 4** ANSWERS, GLOSSARY, UNITS AND SOURCES

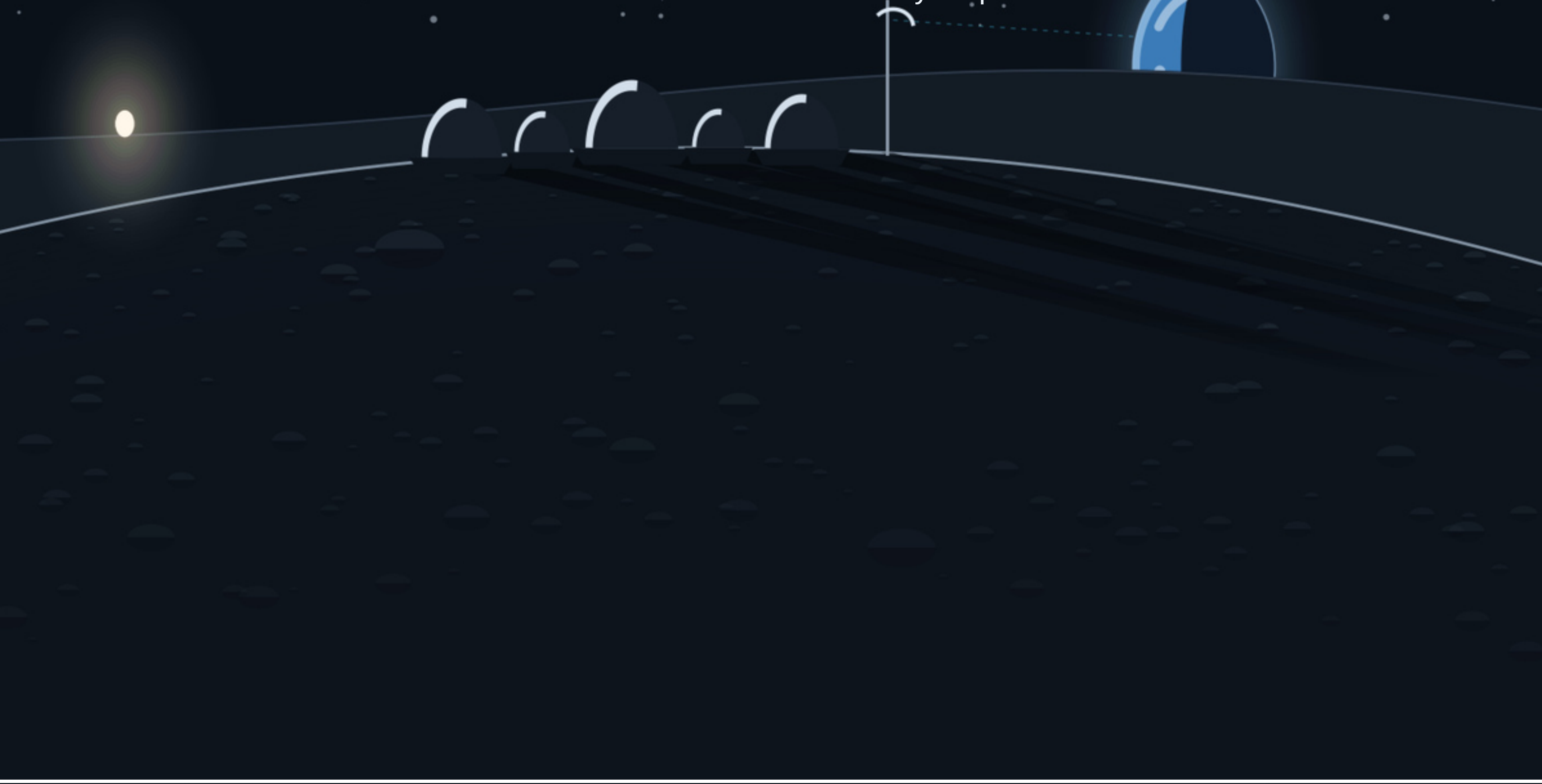
# LUNAR HABITAT ACT

SITE **89°41′ S** · SHACKLETON RIM · CREW **4** · ROTATION **180 D** · LANDED **48.3 T**

*Made from the ground it stands on*

WRITTEN BY

Vaisakh Ramakrishna Sarma · Joydeep Hazra



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COMPASSION8INNOVATION

SCIENCE AND ENGINEERING TITLES

A STUDY BOOK IN SPACE SYSTEMS ENGINEERING

# LUNAR HABITAT ACT

Five pressure vessels on skirts of compacted regolith, around a central core. The purpose of this outpost is not shelter. It is to keep four people alive long enough to build the Moon's first infrastructure.

# Lunar Habitat ACT

A study book in space systems engineering


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| WRITTEN BY | Vaisakh Ramakrishna Sarma and Joydeep Hazra |
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Every checkable figure in this book was put against the published record: NASA technical reports and standards, the Lunar Orbiter Laser Altimeter and Diviner data products, the Lunar Sourcebook, and peer reviewed papers. Where a source disagrees with the design, this book prints the source figure and says where the difference lies. Where nothing could be found to check a figure against, it says that too. The back matter carries every source and a full list of what the check found.

The cover shows the outpost looking north across the landing pad, from the design's own visualisation. Maps of the south polar region are drawn from published crater positions and are schematic: they are meant to show where things lie in relation to each other, not to be navigated by.

# Contents

BACK MATTER

# Answers, glossary, units and sources

The answers are worked rather than stated, because the working is what is worth learning, and where a question asks for a judgement the answer is the design's own, which a reader may argue with. After the answers come the glossary, the units and constants the book uses, the sources every figure traces to, and the list of every place where the published record disagreed with the design.

## Answers

Every answer is worked rather than stated, because the working is the part worth learning. Where a question asks for a judgement, the answer given is the one the design itself makes, and a different well argued answer may be just as good.

### CHAPTER 1 · WHY BUILD, AND WHERE

**1** Forty kilograms landed once costs about 40 million dollars, so 15 million of development buys a 25 million saving on the first flight alone and the same again on every flight after it. It is a good trade whenever the hardware is landed more than once, and a marginal one if it lands once and never flies again.

**2** The Moon's spin axis is tilted 1.54 degrees to the plane of its orbit around the Sun, so at the pole the Sun's elevation can never exceed about that angle. It does not rise and set; it circles the horizon at grazing incidence all year, and darkness comes from terrain rather than from the calendar.

**3** Recovery of 85 per cent leaves 15 per cent to land: 24 kg × 0.15 = 3.6 kg a day, which is 1,314 kg a year and about 1.3 billion dollars at the landed rate. Push closure to 95 per cent and the bill falls to 438 kg and about 440 million: three times cheaper, for ten points of closure.

**4** A lander on unprepared regolith throws grit at close to orbital speed and damages everything already standing, the shielding included. Shielding is also not one flight but hundreds of tonnes of digging done by machines that arrive on later landings. The pad is what makes those landings survivable, so it comes first. The order is set by asking what breaks if a step is done later, not by ranking which step matters most.

**5** Size against 112 hours or worse. Choosing 66 and finding the true figure is 112 leaves the base dark for two days, and the error is not symmetric: sizing high costs mass, sizing low costs the crew. Take the worst modelled figure at any comparable site as the design case, commission a terrain model at the actual mast position before anything is built, and remember the reactor runs through a spell of any length, so the store only has to cover the reactor's own outages.

**6** 100 t × 0.056 = 5.6 t of water, about 5,600 litres. Four people at 3 litres a day for 180 days need 2,160 litres, so that regolith covers about 2.6 rotations of drinking water. The catch is the error bar: at 2.7 per cent it covers 1.3 rotations, and at zero it covers nothing.

### CHAPTER 2 · READING THE DRAWINGS

**1** Ten metres printed as 40 millimetres is a scale of 1 to 250, since 10,000 mm ÷ 40 mm = 250. A tunnel measuring 34 millimetres is therefore 34 × 250 = 8,500 mm, or 8.5 metres, which is the run to a 5.0 metre module.

**2** V ÷ A = d ÷ 4, so the cupola at 4.5 metres gives 1.125 cubic metres per square metre of hull and the greenhouse at 5.0 gives 1.25. Both sit between the airlock's 1.0 and the core's 2.0, as they must, because the ratio depends on width alone.

**3** A pressure hull is tensioned by the air inside pushing outward. Soil on the crown pushes inward, against a structure designed for the opposite load, and it would have to be carried by the hull. Banked at the foot it rests on the ground and on the part of the hull that is braced, and it doubles as the shielding the crew stand behind.

**4** 415 − 204 = 211 square metres of extra hull. At 12 kilograms a square metre that is about 2,530 kilograms, near 2.5 tonnes, and about 2.5 billion dollars at the landed rate. That is the price of four rooms that survive a breach in a fifth.

**5** Without a common ground line, the airlock could be drawn standing on a mound and the tunnel on level ground, so a door and a tunnel that line up on paper would not line up on site; and two modules of different heights could be drawn to the same apparent height, hiding a step at the connector. The ground line is what makes heights comparable.

**6** Which document is the budget costing: this plan, or an earlier one with the modules closer together? What is the connector's actual structural definition, since a 9 metre pressurised tunnel needs ring frames the budget may not carry? And was the 38 cubic metres a placeholder that nobody updated? The evidence that settles each is, in turn, the revision history, the structural drawings, and the author of the line.

## CHAPTER 3 · THE SITE PLAN

**1** Surveyor 3 was damaged at 155 metres by a small lander on bare ground. The pad at 65 metres is sintered, so the plume has nothing loose to throw, and the 29 metre berm intercepts the low angle fan that would reach the hulls. The standoff is short because the ground has been taken away from the plume, not because the plume is gentler.

**2** Dose falls with the square of distance, so at ten times the range it is a hundredth: 4 mSv/h × $(100 \div 1000)^2$ = 0.04 mSv/h. That is why the early metres of standoff are worth so much and the later ones so little.

**3** The face sits beyond the plant so that loaded haulage runs from the face to the plant and stops there, a dead end, and never crosses the living area. Swapped, every loaded trip from the face would pass the modules, carrying dust, vibration and the risk of a collision to the one place they must not go.

**4** Doubling the standoff quarters a dose that is already small against the sky's 380 mSv a year, so it buys almost nothing measurable, and it costs another kilometre of cable, a few hundred kilograms at 500 volts and tonnes at 120, plus another kilometre of graded road at 5.6 square metres a day, which is about 536 days of work.

**5** The advantage is a clean sheet that shows the arrangement without a thicket of dimension lines, and a scale bar that stays true when the drawing is reduced. The risk is that every undimensioned distance depends on the reader's ruler, so two people can read two figures off the same sheet and neither is wrong by the drawing's own rules.

**6** 260 ÷ 5.6 = 46 days for the equipment pads alone. Since the array and the plant cannot be set down until their pads exist, and the apron takes 68 days before that, the site is close to four months of surfacing before the first working system stands on prepared ground, which is why the order of increments matters more than their dates.

## CHAPTER 4 · THE BUDGETS THAT CLOSE

**1** The core is a living space: its racks, galley and equipment take a quarter of the gross and leave three quarters to stand in. The greenhouse is a machine: six tiers of trays fill the vessel from the deck up, and a person stands in the 22 cubic metres left between them. One is a room with equipment in it and the other is equipment with a room in it.

**2** 10,046 − 6,000 = 4,046 kg. That is 45 per cent of the 8,894 kg power line and 8.4 per cent of the 48,286 kg total, and about 4 billion dollars at the landed rate. It has to come out of some other line or onto another flight.

**3** Installed capacity is what the sources could deliver together at their best: 48 kW of array in full sun plus 40 kW of reactor. The array gives nothing in a dark spell and less than its peak whenever the Sun is low or the panels are dusty, and the reactor cannot be run at its nameplate without margin. A designer plans on the reactor alone in the dark, which is 40 kW against 54 of demand, and that is why loads have to shed.

**4** The plan needs 34.75 metres of 2.2 metre tunnel, about 240 square metres of hull, where 38 cubic metres of tunnel is about 10 metres and 69 square metres. The correction adds roughly 170 square metres of hull, about 2 tonnes at 12 kilograms a square metre, and 84 cubic metres of usable volume.

**5** The 54.0 includes the 9 kW construction gantry and omits the 0.6 kW margin line; the 45.6 does the reverse. Size the battery against what cannot be shed, the 27.6 kW reduced load, since a battery only has to hold the loads that must survive the dark. Size the reactor and array against the 54.0, since they have to run everything at once when the Sun is up.

6 A volume margin against the connector gap, paid for by accepting the plan's 132 cubic metres; a mass margin of about 4 tonnes against the reactor, paid for by deferring the gantry to a later flight; and a power margin of about 10 per cent against dust and degradation, paid for by array area. What gets cut is whatever line is least certain and last needed, which on this base is the printed shell trial.

## CHAPTER 5 · POWER

1 66 h × 27.6 kW = 1,822 kWh, and at 0.25 kWh/kg that is 7,290 kg, about 7.3 tonnes of bare cell. Against a 10 tonne reactor the battery is the lighter option for this spell; against the 6 tonne goal it is the heavier. The reactor wins on horizon independence and scale, not on mass.

2 The power a surface collects is proportional to the cosine of the angle between the sunlight and the surface's normal. At the pole the Sun sits within 1.5 degrees of the horizon, so a vertical panel faces it almost square on while a horizontal panel receives light at grazing incidence and collects almost nothing. At the equator the Sun climbs overhead and the argument reverses.

3 A coarse map averages the terrain over 240 metre cells and cannot see a boulder or a ridge smaller than that, so it reports the ground as smoother and the shadows as shorter than they are. A finer map resolves the small obstacles and finds the longer gaps they cast. Size for the finer figure, and better still, for a map of the exact site, which does not yet exist.

4 The cell mass equals the reactor mass when 27.6 kW × t ÷ 0.25 kWh/kg = 10,046 kg, so t = 10,046 × 0.25 ÷ 27.6 = 91 hours. At the 6 tonne goal the crossing moves to 54 hours, which is below the 66 hour rim spell, and that is exactly the difference between the design's verdict and this book's.

5 Lettuce and greens tolerate a few days of darkness by pausing growth, drawing on stored sugars and dropping leaf quality; tomato and pepper set fruit less well. Two or three such spells a year are survivable; weekly shedding would turn the bay into a loss. The load is sheddable in an emergency and not as a routine.

6 Harder: rejecting forty times the waste heat through radiators, shielding the crew from a core forty times more active, and controlling a core that has never been run at that power. Easier: the ratio of shielding and structure to output falls with size, so the specific mass per kilowatt improves.

## CHAPTER 6 · THERMAL CONTROL

1 620 kg × 180 kJ/kg = 111,600 kJ, or 112 MJ. At 6.2 kW that lasts 111,600 ÷ 6.2 = 18,000 seconds, which is 5.0 hours. Eleven hours would need either a draw of 112 MJ ÷ 39,600 s = 2.8 kW, or 6.2 kW × 39,600 s ÷ 180 kJ/kg = 1,364 kg of salt.

2 Dust raises absorptivity, how much sunlight the panel takes in, far more than it lowers emissivity. A horizontal panel presents its whole face to falling dust and to the low Sun at once; a vertical one sheds dust and sees the Sun only edge on for most of the month, so it keeps its low absorptivity longer.

3 The disagreement is 4.4 − 1.1 = 3.3 kW, which at 385 W/m² is 8.6 square metres of panel. The radiator table's margin is 4 per cent of 46 kW, about 2 kW or 5 square metres, so the disagreement is larger than the margin. Carry 4.4, because losing conversion heat that turns out to be real is the failure that freezes lines.

4 The diodes convert 42 to 93 per cent of their electricity into photons, and almost every photon that lands on a leaf or a tray is absorbed and re emitted as heat; the plants keep only the small fraction they fix as sugar. The other 1.4 kilowatts is the dry matter built, the light that escapes to the walls, and the part carried away as transpired water.

5 A clean panel at 95 °C seeing only sky sheds 958 W/m², so 28 m² would shed 26.8 kW. The panel also absorbs sunlight and infrared from the warm ground, its face is partly dusted, and part of its view is the hull rather than sky. The difference between 26.8 and 13.1 is the margin the design carries for all of those, roughly a factor of two.

6 At 150 °C, 423.15 K, the panel sheds $0.92 \times 5.67 \times 10^{-8} \times 423.15^4 = 1{,}672$ W/m², so 13.1 kW needs 7.8 square metres. What gets harder is holding a loop at 150 degrees: pump seals, fluid choice and the heat

exchanger that must keep that loop away from the crew.

## CHAPTER 7 · AIR AND WATER

**1** The crew breathe 3,360 ÷ 32 = 105 moles of oxygen and exhale 4,200 ÷ 44 = 95.5 moles of carbon dioxide. Each carbon dioxide reduced gives back one oxygen, so even with every molecule reduced the return is 95.5 ÷ 105 = 91 per cent. The missing 9.5 moles left the body as water, in breath, sweat and urine, and are recovered by the water loop instead.

**2** Water leaves the crew as water, in urine, sweat and breath, and comes back as water after filtering and distillation; nothing about the molecule changes. Oxygen leaves the crew as carbon dioxide, and getting it back means breaking a chemical bond and finding hydrogen to do it with, and the methane that results carries half the hydrogen away. One loop moves a substance; the other has to remake it.

**3** The assumption is that the water the plants transpire came from the cabin loop in the first place, so crediting it is not double counting. If the plants are watered from a separate nutrient reservoir that the crew top up from landed stock, the 2.1 kg is a transfer from one tank to another and not a recovery. What settles it is where the irrigation water is drawn from and whether that draw appears on the demand side.

**4** Reducing 95.5 moles of carbon dioxide needs 4 × 95.5 = 382 moles of hydrogen. Electrolysis of the 191 moles of water produced returns 191 moles of hydrogen, so the shortfall is 191 moles, which at 2.016 grams a mole is 385 grams, about 0.38 kg a day and 140 kg a year.

**5** With every hydrogen atom recovered, the loop is limited only by the crew's own ratio of carbon dioxide to oxygen, so it reaches the 91 per cent ceiling of question 1. NASA's 75 per cent is lower because pyrolysis cracks only part of the methane, leaves carbon that has to be handled, and has to be stated as a minimum a flight system can be held to.

**6** If 28 kg lasts four people 96 hours, then 78 kg lasts 96 × 78 ÷ 28 = 267 hours, about eleven days. In that time the base has to repair or replace the sieve, since the powder never gives its carbon dioxide back and there is no third line of defence.

## CHAPTER 8 · RADIATION

**1** Loose regolith needs 300 ÷ 1.5 = 200 cm; compacted needs 300 ÷ 1.8 = 167 cm. The mass moved is the same either way, since areal density is mass, but the compacted cover is a third of a metre thinner, more stable on a dome, and less likely to slump. Aim for compacted.

**2** The gray counts energy deposited and the sievert weights it for harm. A shield that shatters heavy nuclei into light fragments leaves the same energy arriving but spread across particles with a lower quality factor, so the sieverts fall while the grays do not. The shield is changing the kind of radiation, not stopping it.

**3** 180 g/cm² is 1.2 metres of loose regolith and 400 g/cm² is 2.7 metres, plus a liner. Carry Matthiä and Berger's 200 mSv a year for the two metre cover rather than the design's 126, because it is the published figure closest to the design case. What to measure: a dosimeter on this rim, under this cover, through a full rotation, which no one has yet done.

**4** 1,369 µSv/day × 365 = 500 mSv a year, against the design's 380. The detector counted charged particles only, at solar minimum when galactic dose is highest, and in a small volume rather than a body; the 380 is a modelled whole body figure at a different point in the solar cycle. Both can be right about what they measured.

**5** Thirty minutes at 1 metre a second is 1,800 metres, but a crew member has to be inside before the protons arrive and must allow for terrain, fatigue and the airlock cycle, so half that, about 900 metres, is the honest planning radius. Suit reserves and the walk back rule limit it further.

**6** With the cover in place a rotation costs 78.6 mSv, so 600 ÷ 78.6 = 7.6, seven full rotations. Without it a rotation costs about 200 mSv, so 600 ÷ 200 = 3 rotations. The cover triples a crew member's career on the surface.

## CHAPTER 9 · DUST

**1** One curtain passes 0.04, two pass $0.04^2 = 0.0016$, three pass $0.04^3 = 0.000064$. One part in ten thousand is 0.0001, so three curtains are needed; two leave sixteen times too much.

**2** A limit is a decision about how much uncertainty to carry on the crew's side. None of the animals breathed polar soil, the exposure is months rather than a shift, and the crew cannot leave. Setting the limit below every analysis is the committee stating that the analyses do not cover the case. It could be raised by measurements on polar dust, on the actual size distribution at the site, and on people rather than rodents.

**3** If polar dust is finer than the mature soils sampled, the fraction below 10 micrometres rises and the 20 per cent bound rises with it, so the same 96 per cent capture leaves more in the air. Until it is measured, a designer treats the requirement as a lower bound on the capture needed, adds a third boundary or a higher capture stage, and puts a particle counter in the airlock so the first crew measure what everyone has guessed.

**4** At a cabin pressure of 8.2 psi the blood holds less dissolved nitrogen than at 14.7, and with the oxygen fraction raised to 34 per cent the crew still get enough oxygen to breathe. Less dissolved nitrogen means less to purge before the suit's lower pressure, so the prebreathe shrinks from hours to minutes. The risk is fire: 34 per cent oxygen burns materials that would not burn in air, which is why NASA has moved its testing to 28.5 per cent.

**5** Two EVAs a day at about four hours each is 8 hours a day, 1,440 hours a rotation across the crew, or 720 hours per suit if two suits are outside at a time. Apollo suits leaked after 8 hours. The suits therefore need dust seals good for hundreds of hours, a servicing regime at the ports, and enough suits to rotate them out.

**6** A suit port is a hatch in the pressure hull with a structural ring the suit docks to, and it fixes the airlock's geometry, its pressure boundary and its vestibule; none of those can be cut into a finished vessel on the Moon. The decision to be made before the airlock is built is which suit the ports fit, since a port built for one suit does not take another.

## CHAPTER 10 · MAKING IT ON SITE

**1** The 400 kg plant: 14 kW × 8,760 h ÷ 1,000 kg = 123 kWh/kg. The 1,593 kg plant: 56.5 kW × 8,760 h ÷ 10,000 kg = 49 kWh/kg. This plant draws the same 14 kW but makes 657 kg a year, so 122,640 ÷ 657 = 187 kWh/kg: the same chemistry, less output, and the same standing loss divided among fewer kilograms.

**2** A cell loses heat through its walls, and wall area grows with the square of its size while the melt it holds grows with the cube. A small cell is therefore mostly wall and a large cell mostly melt, so the standing loss that has to be paid whether or not oxygen is coming off is a large share of a small plant's energy and a small share of a large one's.

**3** Water is 88.8 per cent oxygen, so 1.8 kg of oxygen needs 2.03 kg of water, and at 5.6 per cent by mass that is 36 kg of regolith a day, against 14 kg for the melt. What would really decide between them is not the mass but where it is: the ice sits in a crater floor at 40 to 110 kelvin, kilometres away, where nothing has yet dug, while the oxide is under the base's own boots and has been sampled eleven times.

**4** Mare: 45.4 × 0.53 + 14.9 × 0.47 + 14.1 × 0.22 + 11.8 × 0.29 + 9.2 × 0.40 + 3.9 × 0.40 = 24.1 + 7.0 + 3.1 + 3.4 + 3.7 + 1.6 = 42.9 per cent. Iron oxide, a fifth of mare soil and only 22 per cent oxygen, is what pulls the mare column below the highlands.

**5** Mass is conserved: 14.00 kg of soil in must equal 1.80 + 2.40 + 9.20 + 0.60 = 14.00 kg out. The oxygen leaves as gas, the iron and silicon as an alloy at the cathode, the calcium, aluminium and magnesium oxides as glassy slag, and the fines are screened out before melting and go back to the face. A process diagram whose outputs do not add to its inputs has lost something.

**6** If the true cost is 187 and the five non loss items are 8.4 + 4.9 + 3.1 + 0.7 + 1.4 = 18.5, then losses and standby are 187 − 18.5 = 168 kWh/kg, not 2.2. Nine tenths of the plant's energy is leaving through the walls and the anode, which says the cell is small, poorly insulated for its size, and running hot around the clock whether or not it is producing.

## CHAPTER 11 · CONSTRUCTION

**1** At 14 kg an hour: 1,850,000 kg ÷ 14 kg/h = 132,000 hours, or 5,500 days, about 15 years. At 6 tonnes a day: 1,850 ÷ 6 = 308 days. To finish in 310 days the excavator has to move 1,850 ÷ 310 = 5.97 tonnes a day, every day, around the clock.

**2** A course cooled slowly radiates and conducts its heat evenly, so the glass contracts as one piece. Forced cooling chills the surface while the interior is still hot, the two contract at different rates, and the slab cracks from thermal shock before it has ever carried a load. Slow is what makes it strong.

**3** A pad is loaded in compression, where the glass holds 20 to 45 megapascals; a pressure shell is loaded in tension by the air inside it, where the same material holds 2 to 4. The trial has to show that a printed shell with iron in it, from the plant's own alloy, can carry a pressure load in tension, which is a different structure and not a thicker slab.

**4** A 50 mm course is 75 kg a square metre, needing 75 × 0.86 = 64.5 kWh, so a 216 kWh day lays 216 ÷ 64.5 = 3.3 square metres. The 380 square metre apron then takes 380 ÷ 3.3 = 115 days rather than 68. Depth is bought in days.

**5** 2,100 ÷ 8.5 = 247 days at the road rate. The design's 190 days implies 2,100 ÷ 190 = 11.1 square metres a day, which is the claimed slab rate for the pad course and not the road rate the design states for itself. The corrected figure is 247 days.

**6** At 10 to 20 per cent beam efficiency, 9 kW of electricity is 0.9 to 1.8 kW of melt power, so the 5.6 square metres a day becomes 0.56 to 1.1 unless the laser is fed 45 to 90 kW. The rest of the input is waste heat inside the laser head, which has to be carried off by its own coolant loop and radiated away.

## CHAPTER 12 · FOOD

**1** By energy, 120 ÷ 12,000 = 1.0 per cent. By dry mass, 30 grams a day against 2,720 grams is 30 ÷ 2,720 = 1.1 per cent. The two agree, which is a check that the harvest, the energy and the dry matter were counted consistently.

**2** The lamps are red and blue because a red diode delivers 5.5 micromoles of photons per joule and a green one 1.9, so red buys nearly three times the light for the same electricity; a photon, once absorbed, drives photosynthesis about as well whatever its colour. A few green diodes are added because under pure red and blue every leaf looks black and a crew cannot see whether a plant is wilting, yellowing or diseased.

**3** At 6 to 8 grams per square metre a day, 22 square metres gives 132 to 176 grams of dry matter a day, four to six times the 30 grams the design budgets. Either the bay runs at a fraction of the chamber's light, which is consistent with 14 kW over 22 m² being well under the chamber's intensity, or the budget is conservative, or the harvest is limited by crew hours rather than by yield. The gap is a question for the first rotation.

**4** A = (0.1 × 3,000) ÷ (0.027 × 205) = 300 ÷ 5.5 = 54 square metres to grow a tenth of one person's calories in salad. That is two and a half times the whole bay, for one person, for a tenth of their diet.

**5** The greenhouse is the largest load because its 14 kW are spent manufacturing sunlight, and it is sheddable because plants survive a few days of darkness by pausing. Over 66 hours greens lose quality and growth, fruit set falls, and the harvest that week is smaller; nothing dies. Shed it in a dark spell, not as a habit.

**6** The credited water is transpired by the plants, condensed on the cold surfaces of the bay and returned to the cabin loop. To keep the balance the crew must put back into the nutrient solution what the plants took up, both water and the dissolved nutrients, and the water they use to do that is the same water the loop just recovered.

## CHAPTER 13 · MEDICINE

**1** Three quarters of four crew is 3 expected cases of optic disc swelling; 16 per cent of four is 0.64. The chart's 1.1 sits between them, which shows the denominator dispute: one figure counts a finding on an image, the other a diagnosed syndrome, and both are honest. The design has chosen a middle figure without saying which definition it uses.

**2** A consultation is a conversation, and a conversation tolerates a 2.56 second gap the way a poor telephone line does. A procedure needs a hand guided in real time, and a hand that acts on a picture 2.56 seconds old cannot be guided. So the base trains two crew as medical officers, carries written protocols and an ultrasound the crew can operate with remote guidance between steps, and treats in place.

**3** The split is right for the risk the chart shows: bone loss is certain and trauma is rare, and the exercise hardware is used every day by every crew member. Mass would move the other way if the programme ran many rotations, since the 0.05 events per rotation compound, or if the base acquired a way to evacuate faster, since then stabilisation would buy more than four days.

**4** Twenty rotations is 39.4 person years, so E = 0.0253 × 39.4 = 1.0. The chance of no serious trauma is 1 ÷ e = 0.37, so the chance of at least one is 63 per cent. Once it is more likely than not, the argument for surgical capability, or for a faster ride home, becomes hard to refuse.

**5** Six months at 0.3 per cent a month is about 1.8 per cent of bone mineral density; at 0.5 per cent it is about 3.0. Neither can be trusted here because both were measured in weightlessness, and at 0.166 g the skeleton is loaded to some unknown fraction of normal, which has never been measured on anyone.

**6** Store the drugs where the dose rate is lowest: in the storm shelter under the core deck, ringed by the water tanks, which is the best shielded place on the base. It costs the crew a walk and a hatch every time something is needed, and it means the pharmacy is in the one place that is crowded during a solar event.

## CHAPTER 14 · COMMUNICATIONS

**1** With the rover's antenna on the ground the mast has to see 12 kilometres on its own: $h = (12 \div 1.86)^2 = 41.6$ metres. With a 1.7 metre antenna the rover sees 2.4 kilometres itself, so the mast needs only 12 − 2.4 = 9.6, and

$h = (9.6 \div 1.86)^2 = 26.6$ metres. Fifteen metres of mast were saved by 1.7 metres on the rover, because range is bought at both ends and the square root punishes buying it all at one.

**2** A voice conversation tolerates a delay because each party waits for the other; nothing moves in the gap. A machine keeps moving through the gap, 1.7 metres of it, and the operator is steering a picture of where it was. The base therefore puts the decisions on the machine and keeps Earth for goals and logs.

**3** The figure moves with the exact height and position of the mast, with the libration cycle over a year, and with the crater rim's profile along the bearing to Earth; a lower mast or a point a few hundred metres around the rim could see markedly less. At 40 per cent the relay would carry most of the traffic, the direct dish would become a backup, and the store at the mast would have to be sized for longer gaps.

**4** From the surface the satellite is visible while it is above the horizon, which on a smooth sphere is an arc of $2 \times \arccos(R \div (R + h)) = 2 \times \arccos(1{,}737.4 \div 1{,}837.4) = 38$ degrees of its orbit. Thirty eight degrees of a 117.8 minute orbit is 12.4 minutes, and only for a pass straight overhead. At 200 kilometres the arc widens and the period lengthens, giving about 18.6 minutes.

**5** A decibel is a tenth of a factor of ten in power, so 51 decibels is a factor of $10^{5.1}$, about 126,000. The link could lose that much and still close. But a signal blocked by a berm is not attenuated, it is absent, and multiplying zero by 126,000 is still zero.

**6** The image file is a priority 4 bundle: the mast keeps custody, the transfer pauses, and it resumes from where it stopped on the next pass. The caution and warning message is priority 1 and duplicated: it goes by the direct dish as well, and if both are down it waits at the front of the queue. The voice call degrades: video drops first, then voice falls back to text queued for the next path.

## CHAPTER 15 · NAVIGATION

**1** Slip: $0.0185 \times 4{,}500 = 83$ metres along the track. Heading: $0.00873 \times 4{,}500 = 39$ metres sideways. Combined by Pythagoras: $\sqrt{(83^2 + 39^2)} = 92$ metres, which is 46 hatch widths. A rover coming home on odometry alone would not find the door.

**2** A compass needle settles on whatever crustal patch is nearest, which points in a direction frozen in billions of years ago and unrelated to the pole, so it gives a confident wrong answer. A star tracker gives attitude, which way the rover is pointing, with great precision, but a heading is not a position: it tells you which way you face and nothing about where you stand.

**3** It costs the base a dependency on four objects it surveyed itself with the same instruments it is now checking, so any error in the survey is built into every fix; and it confines ten metre accuracy to the mast's horizon. It could be given up when a relay transmits the Augmented Forward Signal the LunaNet specification defines, and when that signal has been checked on this site against the beacons.

**4** The combined error is $L \times \sqrt{(0.0185^2 + 0.01745^2)} = L \times 0.0254$, and it equals 20 metres at $L = 20 \div 0.0254 = 787$ metres. It comes sooner than the slip line's 1,081 metres because two errors at right angles grow faster together than either does alone.

**5** The shadow is height divided by the tangent of the elevation, so a 30 metre shadow needs $\tan(e) = 1.8 \div 30 = 0.06$, and $e = 3.4$ degrees. The Sun at this site never exceeds about 1.5 degrees, so a shadow that short never happens here.

**6** The sum needs the distance home, the walking speed in a suit, the oxygen and power reserve, the terrain on the way and a margin for a fall or a detour. The navigation system is responsible for the first of these, and everything else is only as good as it: a position wrong by 500 metres is 500 metres of oxygen nobody planned for.

## CHAPTER 16 · AUTONOMY

**1** At 0.25 m/s the machine travels $0.25 \times 3.4 = 0.85$ metres blind. To hold blind travel under 0.5 metres the speed must be under $0.5 \div 3.4 = 0.147$ m/s, about 15 centimetres a second.

**2** The safety layer runs on its own hardware so that a fault in the autonomy software cannot take it down with it. Its only authority is to stop because stopping is safe from every state a machine can be in, and a layer that could also start would need the judgement it was built to avoid. No layer above it may overrule a stop because the moment a cleverer system can override the simple one, the simple one guarantees nothing.

**3** Confidence would rise with hours of unsupervised haulage on the graded road, with a falling rate of stops per hour, and with faults that the machines classified and recovered from themselves. It would sink with any stop the safety layer commanded that the autonomy had not seen coming, with a collision near the hulls, or with a machine that lost its link and did not come home.

**4** Move up: laser sintering on the apron, once a hundred courses have been laid without incident, since a bad course is scrapped and relaid. Move down: haulage past the modules on the graded route, because the worst case there is a tonne of regolith against a pressure hull, which cannot be undone.

**5** Machines running 18 hours a day for 180 days is 3,240 machine hours. At one crew hour saved for every four machine hours, that is 810 crew hours a rotation, about 40 days of one person's working time. At 0.043 mSv an hour outside, it is about 35 millisieverts of dose not received.

**6** It costs the base the ability to adapt inside a week: a machine that meets a new kind of rock on Tuesday behaves the same way on Friday. The design accepts that because a system whose behaviour changes between reviews cannot be certified, and an uncertified system cannot be trusted next to four people and a pressure hull.

## CHAPTER 17 · THE LOOPS AND THE BUILD ORDER

**1** 13.1 ÷ 14 = 94 per cent. Almost every watt the plant draws leaves as heat, which means that anyone reading the power budget should read the thermal budget at the same time: 14 kilowatts of plant is 13.1 kilowatts of radiator, and the two cannot be sized apart.

**2** The greenhouse draws 14 kW of electricity, returns 12.6 kW of heat, transpires 2.1 kg of water a day into the cabin loop and gives back 0.03 kg of oxygen. Make it smaller and the power and heat fall together, the water credit falls, and the oxygen credit, already negligible, disappears; make it larger and every one of those lines moves the other way. It cannot be resized in one budget without resizing four.

**3** The allocated rate holds if the excavator is far larger than the pilot excavator, or if several machines work the face together, or if the cover is thinner than two metres. Until one of those is shown, the schedule should be read as an order of jobs with the durations treated as lower bounds, and the crew's dose planned on the open surface rate for longer than 310 days.

**4** Water 14.11 ÷ 14.40 = 98 per cent; oxygen 1.71 ÷ 3.36 = 51 per cent; food 0.03 ÷ 2.72 = 1.1 per cent; nitrogen 0 ÷ 0.16 = 0 per cent; all five together 15.85 ÷ 20.64 = 77 per cent. Nitrogen is the one no engineering improves, because a leak through the hull cannot be caught.

**5** At the open surface rate a rotation costs about 200 mSv. A 310 day cover job is 1.7 rotations, about 344 mSv for a crew member who stays for all of it. A 2,033 day job is 11.3 rotations, about 2,260 mSv, nearly four times the 600 mSv career limit, which means the cover would have to be finished by several crews in turn.

**6** Without the reactor the base runs on 48 kW of array and a 210 kWh store, the habitat survives every dark spell on the buffer, and the oxygen plant and gantry run only in sunlight, so oxygen is made at perhaps four fifths the rate and construction slows. The arguments about shielding, dust, life support and navigation survive intact. The arguments that the base is an industry rather than a camp, and that it makes more than it lands, do not.

## CHAPTER 18 · HOW IT COMPARES

**1** This base: 263 ÷ 4 = 65.8 cubic metres net habitable per person. NASA's reference: 127 ÷ 2 = 63.5 habitable per person. Comparing 372 with 127 sets a gross figure against a habitable one and a crew of four against a crew of two, and produces a factor of three that does not exist.

**2** The laboratory's 14.5 tonne launch mass over its 106 cubic metres is 137 kg/m³; with its racks and equipment installed the mass rises to give 239. Both are correct for what they count. This base's 48.3 tonnes includes equipment, so it should be compared against the equipped figure, and against 239 it looks thinner still.

**3** Scale linearly and 144 people at over 58 tonnes for four is over 2,090 tonnes landed. The estimate assumes the mass per person does not fall with scale, which it would, since shared systems do not multiply by crew. It is still worth making because it turns a rendering into a number, and a number of two thousand tonnes says immediately that the plan has no relation to any launch capacity that exists.

**4** At 150 kg/m³ over 372 cubic metres the base would mass 55.8 tonnes, 7.5 tonnes more than it lands. The missing mass is most likely in secondary structure, cabling, the connectors at their true length, and the reactor at its published figure, each of which the design carries light.

**5** The 12 tonne limit is a requirement, set by what a lander can put down. The 12,517 kilograms is a study estimate, from an equipment list on a date. The 144 person plan is a press figure, since nothing else was published with it. This book's 48,286 kilograms is a study estimate, and it says so.

**6** What does it mass, what does it draw, and who has paid for it. Put to the first row: the ISRO base publishes no mass, no power budget and no funding line, so on all three questions the honest entry is not published, which is the answer this book is written to change.

# Glossary

Every term the book introduces, in alphabetical order, with the chapter it first appears in.

**Anode.** The positive electrode of an electrolysis cell, where oxidation happens and the oxygen comes off. Chapter 10.

**Areal density.** The mass in the path of a particle per unit of area, in grams per square centimetre; the quantity shielding is measured in. Chapter 8.

**Attitude.** Which way a vehicle is pointing, as distinct from where it is. Chapter 15.

**Augmented Forward Signal.** The satellite navigation style broadcast the LunaNet specification defines for lunar relay satellites, which nothing transmits yet. Chapter 15.

**Basis of comparison.** The crew size, stay length and definitions two designs must share before their numbers can be set side by side. Chapter 18.

**Benchmark dose.** The exposure that produces a small, stated increase in a measured effect, read off a curve fitted to the data. Chapter 9.

**Blast berm.** A wall of piled soil that intercepts the low angle spray of grit thrown by a landing or launching spacecraft. Chapter 3.

**Blind travel.** The distance a remotely driven machine covers between an operator seeing something and the machine acting on it. Chapter 16.

**Bone mineral density.** The amount of mineral held in a given amount of bone, the standard measure of how strong a skeleton is. Chapter 13.

**Brine processor.** The stage that recovers the water a urine still leaves behind in its concentrated residue. Chapter 7.

**Closure.** The fraction of a consumable that a life support loop recovers and returns rather than losing; for the base as a whole, the share of what it consumes that it recovers or makes rather than importing. Chapters 1 and 17.

**Closing a budget.** Demonstrating that the allowance and the need agree, with the margin stated rather than assumed. Chapter 4.

**Concurrent design facility.** A room and a team that assess a whole concept in a few sessions, so every subsystem is sized against the others. Chapter 18.

**Connector.** The pressurised tunnel joining one vessel to another, with a shut off at each end so a breach stays where it happened. Chapter 2.

**Coupling.** A place where one system's output is another system's input. Chapter 17.

**Crew medical officer.** A crew member trained to treat the others from written protocol, without being a physician. Chapter 13.

**Dead reckoning.** Working out a position by adding up how far and in what direction you have travelled from a known point. Chapter 15.

**Definitive care.** The treatment that resolves a condition rather than holding it steady, and the place where it can be given. Chapter 13.

**Dependency.** Something that has to exist before a piece of work can start. Chapter 17.

**Depth of discharge.** The fraction of a battery's capacity actually used before it is recharged. Chapter 5.

**Dimension line and extension line.** The arrowed line that carries a measurement, and the thin line that brings a feature out to meet it. Chapter 2.

**Dry matter.** What is left of a plant when all its water is driven off, and the part photosynthesis actually built. Chapter 12.

**Ejecta.** Material thrown out from a surface by an impact or an engine plume. Chapter 3.

**Electrodynamic dust shield.** Transparent electrodes on a surface, driven out of phase so that a travelling field walks charged grains off the edge. Chapter 9.

**Electrolysis.** Splitting water into oxygen and hydrogen by passing an electric current through it. Chapter 7.

**Emissivity.** How well a surface gives off heat as radiation, on a scale from 0 to 1 against a perfect emitter. Chapter 6.

**Energy intensity.** The energy a process spends for each kilogram of product, in kilowatt hours per kilogram. Chapter 10.

**Expected number.** A rate multiplied by an exposure: the average count over many repeats, not a prediction of any one of them. Chapter 13.

**Fault detection, isolation and recovery.** Noticing a fault, putting it in a state where it can do no more harm, and returning the system to useful work. Chapter 16.

**Feedstock.** The raw material a process consumes, in the state in which it is fed to it. Chapter 10.

**Fission surface power.** A nuclear reactor built to supply electricity on a planetary surface. Chapter 5.

**Food acceptance.** How willing a crew remain to eat what they are given, which falls on a monotonous diet. Chapter 12.

**Galactic cosmic ray.** A very high energy atomic nucleus arriving continuously from outside the solar system. Chapter 8.

**Glass ceramic.** A solid made by melting and cooling a silicate: strong when squeezed, weak when pulled, and brittle. Chapter 11.

**Gray and sievert.** The gray is absorbed dose, one joule per kilogram of matter; the sievert is dose equivalent, the same energy weighted for the harm the radiation does. Chapter 8.

**Gross, habitable and net habitable volume.** What the shape encloses; what is left once structure and unreachable space come out; what is left once racks, stowage and machinery come out too. Chapter 2.

**Ground rule.** A design constraint treated as fixed and stated with its reason, as against an assumption, which may be traded. Chapter 18.

**Heartbeat.** A signal sent at a fixed interval whose absence is itself the alarm. Chapter 16.

**High grade heat.** Waste heat available at a high temperature, which is easier to reject and more useful to reuse. Chapter 6.

**Horizon distance.** How far an antenna at a given height can see over a smooth sphere, 1.86 times the square root of the height in metres on the Moon, in kilometres. Chapter 14.

**Hydroponics.** Growing plants with their roots in a nutrient solution rather than in soil. Chapter 12.

**In situ resource utilisation, or ISRU.** Making what you need out of what is already at the site, rather than shipping it. Chapter 1.

**Incidence rate.** The number of new cases of a condition arising in a stated population over a stated time. Chapter 13.

**Installed capacity.** What the power sources could deliver at their best, as against what a designer may safely plan on. Chapter 4.

**Interface heat exchanger.** The unit where two coolant loops pass heat to one another without the fluids ever mixing. Chapter 6.

**Kalman filter.** An algorithm that combines several imperfect measurements into one estimate, weighting each by how far it can be trusted. Chapter 15.

**Kilocalorie.** The unit of food energy, 4.184 kilojoules; what a food label calls a Calorie. Chapter 12.

**Landed mass.** The mass actually delivered to the lunar surface, as against the larger mass that left Earth. Chapter 1.

**Landing apron.** The prepared and fused surface a spacecraft lands on, sized so its exhaust cannot dig into loose ground. Chapter 11.

**Latent heat.** The energy a material takes in or gives out when it melts or freezes, without changing temperature. Chapter 6.

**Light time.** The time a radio signal takes to travel one way between two places, 1.28 seconds between Earth and the Moon at mean distance. Chapter 14.

**Line of sight.** The straight path between two antennas, which on an airless body is the only path a signal has. Chapter 14.

**Load and sheddable load.** The electrical power a system consumes; a load that can be switched off for a time without harming the crew or the mission. Chapters 4 and 5.

**Long lead item.** Hardware whose delivery time is set outside the project and cannot be shortened by working harder. Chapter 17.

**Margin.** Capacity deliberately left unused, so that growth in one line does not break the design. Chapter 4.

**Mass growth allowance.** The growth a design is expected to show between the drawing and the hardware, budgeted from the outset. Chapter 4.

**Mass to volume ratio.** Landed kilograms per cubic metre of pressurised volume, the quickest check on whether a habitat mass is credible. Chapter 18.

**Master equipment list.** The itemised running total of a vehicle's mass, part by part, valid at a stated date. Chapter 18.

**Molecular sieve.** A bed of material that holds one gas out of a mixture and gives it up again when heated or opened to vacuum. Chapter 7.

**Molten regolith electrolysis.** Melting lunar soil and passing a direct current through it to split its oxides into oxygen and metal. Chapter 10.

**Overpotential.** The extra voltage a real cell needs above the theoretical minimum, and the energy that voltage wastes. Chapter 10.

**Partial gravity.** Any steady gravity between weightlessness and Earth's, such as the Moon's 0.166 g, where almost no long duration human data exists. Chapter 13.

**Permanently shadowed region.** Ground low enough, and near enough the pole, that direct sunlight has not reached it for billions of years. Chapter 1.

**Permissible exposure limit.** The concentration of a contaminant a crew may breathe over a stated mission length without harm being expected. Chapter 9.

**Photon efficacy.** The photons a lamp delivers for each joule of electricity, in micromoles per joule. Chapter 12.

**Photoperiod.** The number of hours a day a crop is given light. Chapter 12.

**Plan, section, elevation.** The three standard views: cut horizontally and seen from above, cut vertically and seen from the side, and an uncut straight view of one face. Chapter 2.

**Plume impingement.** The effect of a rocket exhaust striking the ground and throwing the material outward. Chapter 17.

**Prebreathe.** Time spent breathing oxygen before going outside, to purge dissolved nitrogen from the blood. Chapter 9.

**Production rate.** The finished work a machine completes in a stated time, which means nothing until the task is named. Chapter 11.

**Reference concept.** A design an agency builds to understand a problem and to buy well, never intending to fly it. Chapter 18.

**Regenerative fuel cell.** A store that makes electricity from hydrogen and oxygen and uses surplus power to split the water back. Chapter 5.

**Regolith.** The layer of broken rock and dust that covers the whole Moon, from millimetres of powder down to metres of rubble. Chapter 1.

**Residual.** The part of a daily demand that recovery does not return, and which has to come from outside. Chapter 17.

**Respirable fraction.** The part of an airborne dust fine enough to reach the deep lung, below 2.5 micrometres. Chapter 9.

**Sabatier reaction.** The reaction that turns carbon dioxide and hydrogen into methane and water over a hot catalyst. Chapter 7.

**Safety layer.** Simple, separately verified hardware whose only authority is to stop a machine, never to start one. Chapter 16.

**Scale bar.** A ruler drawn on the sheet itself, which stays true when the drawing is reduced. Chapter 2.

**Shadow shield.** A slab of dense material placed on one side of a reactor only, casting a cone of low radiation in the direction that matters. Chapter 3.

**Sintering and vitrification.** Heating loose grains until their surfaces fuse without fully melting; melting a material and letting it freeze into a glass. Chapters 3 and 11.

**Slag.** The glassy residue left behind once the useful products have been drawn off a melt. Chapter 10.

**Solar particle event.** A sudden burst of protons thrown off the Sun by a flare or an eruption, lasting hours to days. Chapter 8.

**Specific energy.** Energy stored per kilogram of battery, in watt hours per kilogram. Chapter 5.

**Standoff.** The distance deliberately kept between two things so that one cannot harm the other. Chapter 3.

**Stefan Boltzmann law.** The rule that a surface radiates heat in proportion to the fourth power of its absolute temperature. Chapter 6.

**Stoichiometry.** The fixed whole number ratio in which substances combine in a chemical reaction. Chapter 7.

**Suit port.** A hatch on the outside of a hull that a suit stays docked to, so its dirty exterior never comes inside. Chapter 9.

**Supervised autonomy.** The machine executes the task while a human watches, approves each step and may stop it. Chapter 16.

**Teleoperation.** Direct control of a machine's motion by a human at a distance, command by command. Chapter 16.

**Tensile strength.** The pull a material takes across a section before it comes apart, in megapascals. Chapter 11.

**Terrain relative navigation.** Fixing a position by matching what a camera sees against a map made from orbit. Chapter 15.

**Thermal shock.** Cracking caused by one part of a solid changing temperature faster than the part next to it. Chapter 11.

**Wheel slip.** The fraction of a wheel's turning that never becomes ground covered, which makes odometry read long. Chapter 15.

## Units, constants, and how to check a number

The book uses SI units throughout, with three tolerated exceptions: kilowatt hours for energy, because that is how power systems are bought; pounds per square inch beside kilopascals for cabin pressure, because the flight literature uses both; and kilocalories for food, because every label does.

**Table C.1.** The constants the book relies on.

| Quantity | Value | Used for |
|---|---:|---|
| Radius of the Moon | 1 737.4 km | Horizon distance, relay pass duration, latitude rings on the maps |
| Lunar gravitational parameter | 4 902.8 $km^3/s^2$ | Orbital period of a relay |
| Mean Earth Moon distance | 384 400 km | Light time of 1.28 s one way |
| Speed of light | 299 792 km/s | Light time |
| Tilt of the Moon's spin axis to its orbit | 1.54° | The maximum height of the polar Sun |
| Lunar escape speed | 2.38 km/s | What plume ejecta is measured against |
| Stefan Boltzmann constant | $5.67 \times 10^{-8}$ $W/m^2K^4$ | Radiator sizing |
| Loose regolith bulk density | about 1.5 $g/cm^3$ | Areal density of shielding, mass of a slab course |
| Kilocalorie | 4.184 kJ | Food energy |
| Kilowatt hour | 3 600 kJ | Energy accounting |
| Molar masses | $O_2$ 32, $CO_2$ 44, $H_2$ 2.016 g/mol | The air loop stoichiometry |
| Landed cost of mass, order of magnitude | about $1 million per kg | Every trade in the book |

Constants from JPL Solar System Dynamics and NASA's published lunar fact sheet; regolith density from the Lunar Sourcebook.

### THE HABIT THAT CATCHES MOST MISTAKES

Before trusting any number, in this book or anywhere else, put it through three checks that take a minute between them. First, carry the units. Write them beside every figure and cancel them like fractions; a kilowatt hour divided by a kilogram is a kilowatt hour per kilogram, and if the units do not come out as the thing you wanted, the arithmetic is wrong however good it looks. Most of the errors in the original design documents were unit errors: a rate for a machine applied to a different task, a fraction applied to the wrong base.

Second, check the order of magnitude against something you know. A battery for the equatorial night came out at 39 tonnes; the whole base is 48. A reactor came out at 6 tonnes; the only point design ever drawn is 10. Two metres of soil over a room came out at 151 tonnes; the base lands 48.

Each of those comparisons is faster than the calculation it checks, and each would have caught an error of a factor of ten.

Third, ask where the number came from and whether it was measured, estimated or allocated. A measurement carries the conditions it was taken under. An estimate carries a method. An allocation carries a decision somebody made in a meeting, and it is the kind of number most often mistaken for one of the other two. Most of the figures in any concept design are allocations, this one included, and the annex that follows lists the ones that turned out not to survive contact with a measurement.

## Sources and further reading

Every number in this book came from somewhere, and this is the list of somewheres. Agency documents and peer reviewed papers carry the weight, because each comes with a method a reader can inspect and a figure somebody put their name to. Entries are grouped by subject and sorted by author or agency within each group. Where a document has a stable identifier, an NTRS number or a DOI, it is given in place of a web address, because addresses rot and identifiers do not.

The habit worth taking from this page is telling a primary source from a secondary one. A primary source is the first appearance of a fact in the record: the paper written by the people who took the measurement, the standard that sets the limit, the mission report written by the team that flew it. A secondary source describes that work at one remove. Both are useful, but only the primary one can be checked, and only the primary one carries the conditions under which the number holds. Two entries below are openly secondary and say so.

### THE MOON ITSELF: ENVIRONMENT AND TERRAIN

Gläser et al., Illumination conditions at the lunar poles: implications for future exploration. *Planetary and Space Science*, 2018, NTRS 20170007365. Average illumination of 77 to 88 per cent two metres above the Shackleton rim clusters, and the longest shadow of 65 to 66 hours.

Heiken, Vaniman and French, *Lunar Sourcebook: a user's guide to the Moon*. Cambridge University Press for the Lunar and Planetary Institute, 1991. The oxide table, the grain size distribution, and the bulk density that turns shielding depth into metres.

Hollick and O'Brien, Lunar weather measurements at three Apollo sites 1969 to 1976. *Space Weather*, 2013, doi 10.1002/2013SW000978. Dust settling measured by the Apollo dust detector experiments.

Mazarico et al., Illumination conditions of the lunar polar regions using LOLA topography. *Icarus*, 2011, NTRS 20120010094. The Shackleton rim site with 240 days of continuous sun and a longest dark spell of about 1.5 days, at 240 metres per pixel.

NASA, Moon facts. NASA Science. Mean distance and radius, behind the light time and the horizon formula.

NASA Space Science Data Coordinated Archive, Lunar Prospector magnetometer. The crustal magnetic anomalies, and why a compass answers nothing on the Moon.

Sverdrup Henson crater: a candidate location for the first lunar south pole settlement. *iScience*, 2023. Earth visible 57 per cent of the time from a point on the Shackleton rim.

Szalay and Horányi, The search for electrostatically lofted grains above the Moon with the Lunar Dust Experiment. *Geophysical Research Letters*, 2015. The LADEE upper limit on lofted dust.

Williams et al., Seasonal polar temperatures on the Moon. *JGR Planets*, 2019, doi 10.1029/2019JE006028. Diviner maps of the poles, cold traps below 110 kelvin, and the 1.54 degree spin axis tilt.

### RADIATION

Bell and Bannova, Lunar habitat micrometeoroid and radiation shielding: options, applications and assessments. *Journal of Aerospace Engineering* 24, 2011.

Horst et al., Thick shielding against galactic cosmic radiation: a Monte Carlo study with focus on the role of secondary neutrons. *Life Sciences in Space Research* 33, 2022. Getting below about 100 mSv a year needs 400 g/cm² and a polyethylene liner.

Matthiä and Berger, Radiation exposure and shielding effects on the lunar surface. *Space Weather* 22, 2024, doi 10.1029/2024SW004095. About 306 mSv a year unshielded and 190 behind 180 g/cm² of regolith, with neutrons about half the dose equivalent at depth.

NASA, NASA STD 3001, Volume 1, Revision C, Crew health. NASA technical standard, 2023. The 600 mSv career effective dose limit and the blood forming organ limits.

Reitz, Berger and Matthiä, Radiation exposure in the moon environment. *Planetary and Space Science* 74, 2012, doi 10.1016/j.pss.2012.07.014. About 380 mSv a year at solar minimum, the design value.

Zhang et al., First measurements of the radiation dose on the lunar surface. *Science Advances* 6, eaaz1334, 2020, doi 10.1126/sciadv.aaz1334. The Chang'e 4 dosimeter: 1,369 microsieverts a day, the one direct measurement there is.

## POWER AND ENERGY

Kopp and Lean, A new, lower value of total solar irradiance. *Geophysical Research Letters*, 2011, doi 10.1029/2010GL045777. The solar constant of 1,360.8 W/m².

NASA, Demonstration proves nuclear fission system can provide space exploration power. NASA news release, May 2018. KRUSTY, the 1 kWe class Kilopower ground test at the Nevada National Security Site.

NASA, Directive on Fission Surface Power. NASA, 4 August 2025. A minimum of 100 kWe on a heavy class lander, ready to launch by the first quarter of 2030.

NASA, Regenerative fuel cell power systems for lunar and Martian surface exploration. NASA Glenn Research Center, 2017, NTRS 20170009088. Specific energy goals of 110 to 550 Wh/kg.

NASA, State of the art of small spacecraft technology, chapter 3, Power. NASA Ames Research Center, revision of May 2026. Delivered battery pack figures of 119 to 187 Wh/kg.

Oleson et al., A deployable 40 kWe lunar fission surface power concept. NASA Glenn COMPASS team, NETS 2022, NTRS 20220004670. The 10,046 kg point design, the kilometre standoff behind a shadow shield, and the cable mass anchor.

## THERMAL CONTROL

Gaier, Waters, Misconin, Banks and Crowder, Effect of simulant type on the absorptance and emittance of dusted thermal control surfaces in a simulated lunar environment. NASA/TM 2010 216786. The measured emissivity of a fully dusted radiator.

Hirschey et al., Review of inorganic salt hydrates with phase change temperature in the range of 5 to 60 °C. International Refrigeration and Air Conditioning Conference, Purdue, 2018. Sodium sulfate decahydrate melting at 32.4 °C.

NASA, Human Landing System Lunar Thermal Analysis Guidebook. HLS UG 001, January 2021, NTRS 20210010030.

NASA, International Space Station active thermal control system overview. Precedent for water inside the hull and ammonia outside it.

## DUST AND ITS CONTROL

Gaier, The effects of lunar dust on EVA systems during the Apollo missions. NASA TM 2005 213610, NTRS 20050160460. The primary record: suit wear, seal leak rates, clogged mechanisms, and the Cernan quotation.

NASA, Dust shield successfully repels lunar regolith on the Moon. NASA news release, March 2025. Blue Ghost clearing glass and radiator samples electrodynamically.

NASA Johnson Space Center, Suitport feasibility. 2012. Pre EVA time cut from hours to under thirty minutes.

Scully and Meyers, Risk of adverse health and performance effects of celestial dust exposure. NASA evidence report, NASA JSC, 2015. The derivation of the 0.3 mg per cubic metre limit and the analyses behind it.

## REGOLITH, RESOURCES AND CONSTRUCTION

Colaprete et al., Detection of water in the LCROSS ejecta plume. *Science*, 2010, doi 10.1126/science.1186986. Water at 5.6 plus or minus 2.9 per cent by mass at the Cabeus impact site.

Guerrero Gonzalez and Zabel, System analysis of an ISRU production plant: extraction of metals and oxygen from lunar regolith. *Acta Astronautica* 203, 2023. Hydrogen reduction competitive only above 7.5 per cent ilmenite.

Immer et al., Apollo 12 lunar module exhaust plume impingement on Lunar Surveyor III. *Icarus* 211, 2011. Surveyor 3 pitted at 155 metres.

Laser melting versus laser sintering: large area heat processing of lunar south pole simulant. *Additive Manufacturing Frontiers*, 2025. Sintering from about 1,180 °C, full melt above 1,360 °C, and the melt depth behind the slab rate.

Modeling energy requirements for oxygen production on the Moon. *PNAS*, 2025, doi 10.1073/pnas.2306146122. 24.3 kWh per kilogram for a complete ilmenite reduction chain.

NASA, Analysis of Surveyor 3 material and photographs returned by Apollo 12. NASA SP 284, 1972, NTRS 19720019081. The sandblasting record that puts the pad first.

NASA, ISRU Pilot Excavator technology readiness level 5 design overview. AIAA ASCEND, 2024. The 10 tonne, 11 day autonomous excavation target.

NASA, The behaviour of high velocity dust generated by lunar landers. AAS guidance and control conference, 2020, NTRS 20205003594. Plume ejecta above 2 km/s for the finest fraction.

Schreiner et al., A parametric sizing model for molten regolith electrolysis reactors to produce oxygen on the Moon. *Advances in Space Research*, 2016, doi 10.1016/j.asr.2016.01.006. A 400 kg, 14 kW plant for 1,000 kg of oxygen a year, the sizing behind the plant.

Toro Medina et al., Large scale demonstration of molten regolith electrolysis for oxygen production in a relevant environment. ICES 2026 300, NASA Kennedy with Lunar Resources Inc. The Kennedy vacuum run and the measured melt energy.

## LIFE SUPPORT, FOOD AND MEDICINE

Crucian et al., Incidence of clinical symptoms during long duration orbital spaceflight. *International Journal of General Medicine*, 2016. The station incidence record behind the medical event chart.

Jones, Moon base life support design depends on launch cost, crew size and mission duration. ICES 2019, NTRS 20190027610. The 0.84 kg per crew member per day oxygen figure and the lithium hydroxide sizing.

Kusuma, Pattison and Bugbee, From physics to fixtures to food: current and potential LED efficacy. *Horticulture Research*, 2020. The 5.5 micromole per joule ceiling for 660 nm red.

NASA, Life support baseline values and assumptions document, revision 2. 2022, NTRS 20210024855. Oxygen, carbon dioxide and metabolic heat per crew member per day.

NASA, NASA achieves water recovery milestone on the International Space Station. NASA news release, June 2023. The 98 per cent figure and the 93 to 94 it stood at before the brine processor.

NASA, NASA's contributions to vertical farming. NASA technical memorandum, 2020. Biomass Production Chamber yields, light levels and area per person.

NASA, Risk of early onset osteoporosis due to spaceflight. NASA Human Research Program evidence report. Bone loss rates and what the resistive exercise device recovers.

Samplatsky et al., Development and integration of the flight Sabatier assembly on the ISS. 41st International Conference on Environmental Systems, AIAA 2011 5151. Flight heritage for the carbon dioxide reduction stage.

## COMMUNICATIONS, NAVIGATION AND AUTONOMY

CCSDS 734.2, Bundle Protocol. Consultative Committee for Space Data Systems. The delay tolerant stack the traffic table assumes.

Effect of time delay on lunar sampling teleoperations. *Applied Ergonomics*, 2023. Measured operator performance at 0, 0.5 and 3 seconds of delay.

ESA, Moonlight programme and Lunar Pathfinder. European Space Agency. Pathfinder no earlier than 2027, initial services by the end of 2028, full service by 2030.

NASA, Assessment of M2020 terrain relative landing accuracy: flight performance versus predicts. NASA JPL, 2023, NTRS 20230007014. The 60 metre requirement and the roughly 5 metres achieved.

NASA, LuGRE acquires GPS and Galileo signals on the Moon. NASA news release, March 2025. The first satellite navigation fix on the lunar surface, 3 March 2025.

NASA, LunaNet Interoperability Specification, version 5. February 2025. The relay, delay tolerant networking, timing and positioning services this design assumes, and the Augmented Forward Signal.

NASA, Lunar Roving Vehicle navigation system performance summary. The 1.85 per cent wheel slip assumption and the traverse closure errors Apollo recorded.

Nokia, Nokia and Intuitive Machines deliver first cellular network to the Moon. Nokia, March 2025. About 25 minutes of powered operation and no call placed.

ECSS E ST 70 11C, Space segment operability. European Cooperation for Space Standardization. The E1 to E4 autonomy levels.

### HABITAT DESIGN AND PRECEDENTS

Burke et al., Internal layout of a lunar surface habitat. ASCEND 2022, NTRS 20220013669. The two crew 127 m³ reference habitat and its 8.2 psi cabin at 34 per cent oxygen.

NASA, Artemis III. The surface mission profile, up to five days in lunar orbit before the return leg.

NASA, Apollo 17 mission details. The 75 hour surface stay, the longest anyone has spent at one sixth gravity.

Whitmire et al., Minimum acceptable net habitable volume for long duration exploration missions. NASA Human Research Program, 2014, NTRS 20140016951. The 25 m³ net habitable volume per person used as the floor.

Destiny laboratory module. Wikipedia. 106 m³ pressurised at 14.5 tonnes, the flown benchmark for mass per cubic metre. A secondary source, carried for a figure nobody disputes.

## What the check found

Every checkable number in the design was put against the published literature and against its own tables. Most of it held. These are the places where it did not, and where this book prints the corrected figure rather than the design's. Each entry gives what the design said, what the check gives, and the source or the arithmetic behind the difference.

**Table E.1.** Where the design and the record disagree, and what this book carries.

| Item | The design says | The check gives | Basis |
|---|---|---|---|
| Connector length pressurisable without intermediate structure | 2.2 m | No such limit exists; the plan needs runs of 8.5 to 9.0 m | Pressure vessel mechanics; the plan drawing |
| Connector volume for four spokes | 38 m³ gross | About 132 m³ gross at 2.2 m diameter over the runs the plan needs; the base is 466 m³ gross, not 372 | Arithmetic on the design's own tables |
| Oxygen content of regolith by mass | Mare 44.6%, highland 44.3% | Mare 42.9%, highland 44.5%; the pair was the wrong way round | Stoichiometric sum of the design's own oxide rows |
| Fission surface power unit as budgeted | 6 000 kg | 10 046 kg for the three deployed elements with growth allowance and margin; 7 446 kg basic mass alone | Oleson et al., NETS 2022, NTRS 20220004670 |
| Cable mass for a kilometre at bus voltage | Hundreds of kilograms | A few hundred kilograms at 500 V, 8 to 16 tonnes at 120 V for 40 kW | NASA's 3 km, 500 V anchor of 3 300 kg; resistivity calculation |
| Mass of the 210 kWh battery | 890 kg | About 1 200 kg at 175 Wh/kg pack level; 1 120 to 1 760 kg on NASA's delivered pack figures | NASA small spacecraft technology report, power chapter |
| Phase change buffer hold with no power | 11 hours | 5.0 hours at 6.2 kW; eleven hours needs 2.8 kW of draw or 1 364 kg of salt | Arithmetic on the design's own three numbers |
| Radiator emissivity after two years of dust | 0.68 | About 0.83, 0.9 times the clean value | Gaier et al., NASA/TM 2010 216786 |
| Shielding depth at which secondaries stop further gains | A few centimetres, then a knee at 250 g/cm² | Returns stop at 10 to 20 g/cm², 7 to 13 cm of regolith | Matthiä and Berger, Space Weather 2024 |
| Dose under two metres of regolith | 126 mSv a year | About 200 mSv a year behind 180 g/cm²; 100 only with 400 g/cm² and a polyethylene liner | Matthiä and Berger 2024; Horst et al. 2022 |
| Range of derived dust exposure limits | 0.2 to 0.7 mg/m³ | 0.4 to 1.0 mg/m³; the 0.3 was set below that range by an external committee | Scully and Meyers, NASA evidence report 2015 |
| Lithium hydroxide for a 96 hour supply | 78 kg | About 28 kg; the 78 is a 2.8 times margin, not a requirement | Jones, ICES 2019; stoichiometry of $2LiOH + CO_2$ |
| Sabatier product water recovered per day | 0.9 kg | 1.89 kg; the reactor that returns 1.68 kg of oxygen must make 1.89 kg of water | Stoichiometry |
| Hygiene water recovered per day | 1.5 kg | 6.27 kg, from the design's own consumables table | Internal consistency |
| Energy cost of oxygen from the plant | 20.7 kWh/kg | 187 kWh/kg at 14 kW and 1.8 kg a day; the 20.7 describes a plant fifty times larger | Division; Schreiner et al. 2016; Kennedy vacuum run, 108 to 136 kWh/kg |
| Sintered slab rate on a 9 kW beam | 11 m² a day | 5.6 m² a day at 30 mm; 11 would need 17.8 kW held continuously | Melt energy of 3 100 kJ/kg, Toro Medina et al.; |

| | | | |
|---|---|---|---|
| | | | melt depth from the laser study |
| Graded roads, 2 100 m² | 190 days | 247 days at the design's own road rate of 8.5 m² a day; 190 corresponds to the slab rate | Arithmetic on the design's own rates |
| Module cover, 1 850 t at 6 t a day | 310 days | Holds only with an excavator 6.6 times faster than the pilot excavator target of 0.91 t a day; 5.6 years at the demonstrated rate | NASA ISRU Pilot Excavator, ASCEND 2024 |
| Signal delay in the telemedicine diagram | 2.6 s each way | 1.28 s one way, 2.56 s round trip | Mean Earth Moon distance and the speed of light |
| Pass duration of a relay in low lunar orbit | A few tens of minutes | At most 12.4 minutes from 100 km, only directly overhead; 18.6 minutes at 200 km | Kepler, with the Moon's gravitational parameter and radius |
| Mars 2020 landing accuracy requirement | 40 m | 60 m required, about 5 m achieved | NASA JPL assessment, NTRS 20230007014 |
| Lunar Pathfinder launch | No earlier than late 2026 | No earlier than 2027 | Firefly Blue Ghost Mission 2 page, September 2026 |
| Autonomy levels credited to NASA TX10 | Levels from TX10 | TX10 contains no levels; the ladder is ECSS E ST 70 11C, E1 to E4 | The two documents themselves |

Four figures in the design could not be checked against any published source and are carried as the design states them, marked in the text where they appear: the 6.2 kW survival heating load, the gas lost per suit port cycle, the 15 per cent area penalty for per module radiators, and the 1,240 kg solar array mass. The longest dark spell at the exact position of the mast has never been computed, and no dosimeter has yet been worn on this site.

## ABOUT THIS EDITION

This book was built from the Lunar Habitat ACT concept definition, revision A: a technical blueprint of plan, section and elevation drawings with volume, mass and power budgets, and twelve subsystem documents. Every checkable number was extracted from those documents and put against the published literature. Where a source disagreed with the design, the book prints the source figure and says so, in the chapter where the number is used and in the table above. Where nothing could be found, it says that instead of guessing. Every drawing and chart was generated from the design's own dimensions and the sources listed, and every worked example was recomputed before it was typeset.

None of this makes the design wrong. It makes it what a concept definition is: a set of decisions with the arithmetic showing, some of which will survive contact with hardware and some of which will not. The purpose of a study book is to teach the reader to tell which is which, and the surest way to do that is to show the places where the authors had to.