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FIRST EDITION · 2026

A STUDY BOOK IN SPACE SYSTEMS ENGINEERING

PART 3 PUTTING IT BACK TOGETHER

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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SCIENCE AND ENGINEERING TITLES

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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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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.

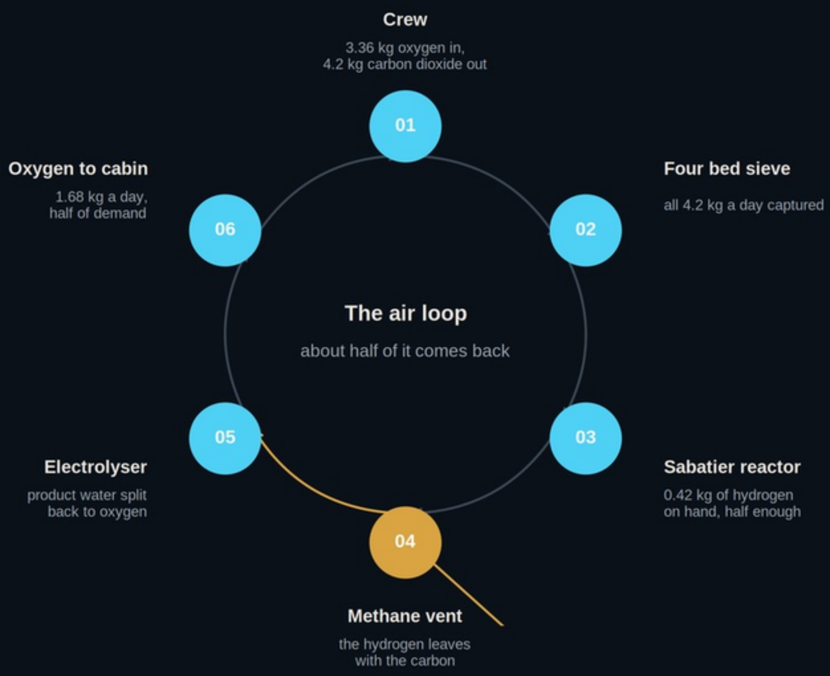
The cover shows the outpost looking north across the landing pad, from the design's own visualisation. Maps of the south polar region are drawn from published crater positions and are schematic: they are meant to show where things lie in relation to each other, not to be navigated by.

Contents

PART THREE

Putting it back together

Taking a design apart is the easy half. This part puts it back: how the loops feed one another, in what order the base is actually built, and how the whole thing measures up against what the space agencies of India, the United States and everywhere else have published. The last of those is the chapter that matters most, because a design nobody has compared against the field is only a drawing.



The loops and the build order

Twelve chapters took this base apart one system at a time, and each of them ended with a mass and a power figure as though the system could be bought on its own. None of them can. What one makes, another needs, and the order the site is built in follows from that.

WHAT THIS CHAPTER WILL TEACH YOU

1 Trace a substance round a loop and say, at each step, what is added and what leaves.

2 Work out the closure of a loop from a recovery figure and a demand figure, for one substance and one day.

3 Put a set of construction jobs in order by asking what breaks if each one is done later.

4 Turn a mass of earthworks and a machine rate into a duration, then test that rate against something demonstrated.

51 per cent
OXYGEN LOOP CLOSED

98 per cent
WATER RECOVERED

1 850 tonnes
REGOLITH OVER THE MODULES

310 days
LONGEST SINGLE JOB

17.1 Twelve systems, or one system read twelve ways

The oxygen plant appears in the power budget at 14 kilowatts, in the heat budget at 13.1 kilowatts, and in the life support budget at 1.65 kilograms of oxygen a day. Those are not three facts about three systems. They are three views of one machine, and moving any one of them moves the other two.

Throttle the plant to save power and the base starts importing oxygen again. Leave it running and thermal control has to find radiator area for 13.1 kilowatts it did not ask for. This chapter puts the twelve back together.

Start with the air, because it runs fastest and it is the loop the crew would notice failing. Four people take 3.36 kilograms of oxygen a day and give back 4.2 kilograms of carbon dioxide. A four bed molecular sieve catches all of it. The Sabatier reactor takes that carbon dioxide, adds hydrogen and makes methane and water, and the electrolyser splits the water into oxygen for the cabin and hydrogen for the reactor. Drawn as a ring it looks closed. It returns 1.68 kilograms of oxygen a day against the 3.36 demanded, which is half, and the other half leaves through the methane vent for a reason no reactor design can fix.

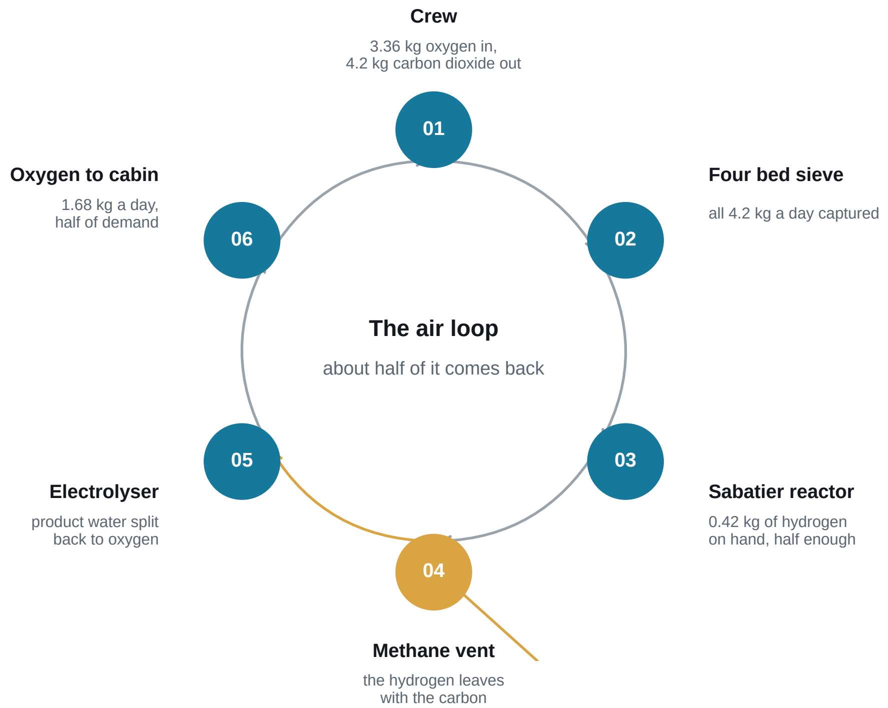


Figure 17.1. The air loop drawn as the ring it is trying to be, and step 04 is the answer to why it is not one. Reducing one carbon dioxide takes four hydrogen molecules, the two waters that come back give only two, and the methane carries the other two out of the base with the carbon still attached. Half the hydrogen the reactor was fed never returns, so it can treat only 55 per cent of the carbon dioxide the crew produce, and that returns 50 per cent of the oxygen.

Every loop on this base has a place like that vent, and finding it is the useful part of reading one. Water comes back at 98 per cent and loses the remainder to the brine. Nitrogen recovers nothing at all, because a leak through the hull cannot be caught and put back. Add the five consumables together and four people demand 20.64 kilograms a day, recovery returns 15.85, and 4.79 is left standing: 1.65 of it is oxygen the plant makes on site, and the other 3.14 is flown, which is 1,146 kilograms a year.

THE ONLY FORMULA IN THIS CHAPTER

$$C = R \div D$$

C is closure, the share of a daily demand met from inside the base; R the mass recovered and returned in a day, in kilograms; D the mass the crew demand in a day. A ratio carries no unit. Water on this base is 14.11 ÷ 14.40 = 98 per cent. Oxygen is 1.71 ÷ 3.36 = 51 per cent, which the design rounds to about half. Quote one closure figure for a base as a whole and you have hidden which loop is leaking.

WHERE PEOPLE GO WRONG

The phrase closed loop life support invites the idea that a good base recycles everything and a leaky one has been built badly. Three of the five consumables here will never close. Nitrogen goes out through the hull and is gone. Food is open on purpose, because growing staple calories costs more in power and volume than shipping them does, so the bay grows about one per cent of the crew's calories and the rest is flown. And heat is not a loop in any sense: energy arrives as sunlight or as fission and leaves as infrared, 46 kilowatts of it at peak, and no arrangement of pipes will bring it back. A working base closes the loops worth closing, prices the rest, and puts the bill where the reader can see it.

17.2 What breaks if this is done later

Because the systems feed each other, the order they are built in is not a matter of taste either. Ask what breaks if this is done later of every job on the site and the sequence falls out on its own. Most jobs turn out to be indifferent to when they happen, and can be scheduled around convenience, solar activity and who is on the surface. A few turn out not to be. Those few are the whole of the build order.

The first of them is the pad, for the reasons chapter 11 gave: a lander on unprepared ground sandblasts everything already standing, so the front of the programme is forced. Survey, grade, compact, sinter the apron, raise the berm, and only then land anything else nearby. Run the test the other way and the shielding is the job everybody wants first and nobody can have first. Two metres of regolith over the pressure vessels takes the routine dose from about 380 millisieverts a year toward the 126 the design claims, and it is placed on the modules, so until the modules are down there is nothing to place it on. The first crews therefore live at the open surface rate, roughly 190 millisieverts a rotation, which is inside the 250 this design budgets for one. Nothing breaks if the greenhouse is late. Almost everything breaks if the pad is.

Table 17.1. The build order read as a set of dependencies rather than as a calendar.

Increment	What it adds	What it waits for	Heaviest item
1 Land and survive	Graded bed, sintered apron, five modules on compacted skirts, storm shelter, 48 kW array and a 210 kWh store	Nothing on the surface. Every part of it is flown in	28.7 t of pressure vessel, landed
2 Cover and close	Blast berm, two metres of regolith over every vessel, Sabatier and brine processor, one electrolysis cell	The modules being down. There is nothing to shield until they are	1 850 t of regolith, moved on site
3 Power and plant	The 40 kWe unit a kilometre out, three cells at 1.8 kg of oxygen a day, four graded roads	Hardware that does not exist, on a schedule nobody here sets	6.0 t of reactor as budgeted, landed
4 Make the structure	**Printed shell trial, alloy tapped to the printer, slag cast into pavers, more array for the gantry**	**Increment three's metal and its power**	**0 t of shell, made on site**

The last column carries the argument in four lines. Increment one is almost entirely launched, increment two is almost entirely local, and by increment four the largest structure being built arrived on no lander at all.

WORKED EXAMPLE 17.1 · HOW LONG DOES TWO METRES OF COVER TAKE?

1,850 tonnes of regolith to place over five pressure vessels, an excavator allocated 6 tonnes a day, and NASA's ISRU Pilot Excavator target of 10 tonnes in 11 days for a machine of this class. Time is mass divided by rate.

1. Divide the mass by the allocated rate.
   1 850 t ÷ 6 t/day = 308 days, which the build order rounds to 310
2. Turn the demonstration target into a rate in the same units.
   10 t ÷ 11 days = 0.91 t/day
3. Run the same job at the demonstrated rate instead of the allocated one.
   1 850 t ÷ 0.91 t/day = 2 033 days
4. Put that in years, and take the ratio of the two rates.
   2 033 ÷ 365 = 5.6 years; 6 ÷ 0.91 = 6.6 times

ANSWER The 310 day figure assumes an excavator 6.6 times faster than the only comparable target anybody has published. At the demonstrated rate the same job takes five and a half years, and the crew spend every rotation of it at the open surface dose. The build order is not wrong, but it rests on either a much larger machine than the pilot excavator or several of them working the face together, and neither has flown. Notice what the arithmetic does not depend on. The 1,850 tonnes is scaled off a drawing and will not change. All of the uncertainty sits in the rate, which is why a schedule built on allocated rates should be read as an order of jobs rather than as a set of dates.

> **Construction days are not calendar days.** The jobs overlap and several of them queue for the same excavator, and each figure is that job at full duty. Holding the machines to daylight costs less here than the design assumes: this rim is lit 77 to 88 per cent of the year, so the 310 day cover takes 352 to 402 days rather than the two years an equatorial site would cost.

17.3 The dependency nobody here controls

Every dependency so far is inside the project. Grade before sintering, land before shielding, tap metal before printing with it. One is not. Increment three needs a 40 kilowatt electric class fission unit and no such machine exists. The closest relative ever run is KRUSTY, a 1 kilowatt class core operated in Nevada in March 2018, and in August 2025 NASA moved the target to at least 100 kilowatts electric by the first quarter of 2030. If it slips, the base does not stop. It runs on 48 kilowatts of array and a 210 kilowatt hour store, and what gets shed is the oxygen plant and the sintering gantry, the two loads that ought not to have to follow the sun. That is a schedule risk rather than a habitat risk. Nobody's life depends on the reactor arriving, but the argument for the base does.

QUESTIONS

1. The oxygen plant draws 14 kilowatts of electricity and hands 13.1 kilowatts to the radiators. Find the share, and say what it means for anyone reading the power budget. APPLY

2. Explain why the greenhouse appears in the power budget, the heat budget, the water loop and the air loop at the same time, and what that does to anyone who wants to make it smaller. EXPLAIN

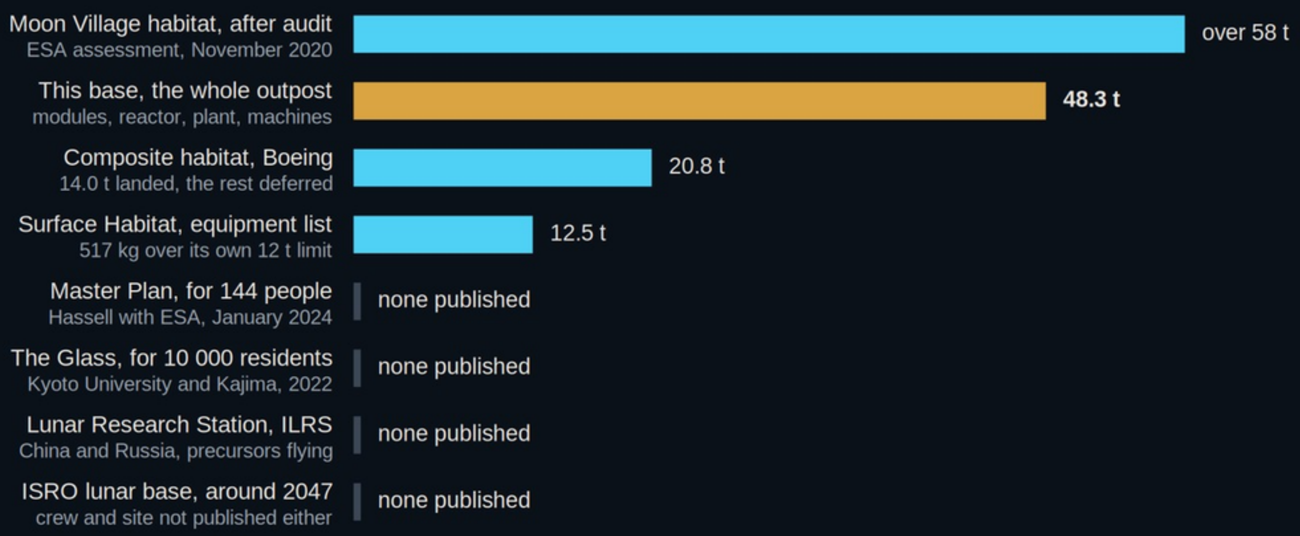
3. The 310 day cover assumes a rate 6.6 times the only comparable target published. Say what would have to be true for the allocated rate to hold, and how a reader should treat the whole schedule until it is. EXTEND

4. Work out the closure of each of the five consumables from the figures in section 17.1, and rank them. Say which one no engineering could improve. CALCULATE

5. The first crews live at the open surface dose until the cover is placed. Using the rates in Table 8.1, find how many rotations the cover job would cost a crew member in dose if it took 310 days, and if it took 2,033. CALCULATE

6. Increment three depends on a reactor that does not exist. Describe what the base looks like if it never arrives, and say which of the book's arguments survive that case and which do not. EXTEND

CHAPTER EIGHTEEN



How it compares

A design nobody has measured against the field is only a drawing. Measuring turns out to be the harder half, because almost no two published concepts are counting the same things.

WHAT THIS CHAPTER WILL TEACH YOU

1. Fix the basis of a comparison first: crew size, stay length, and what a volume or a mass actually counts.
2. Tell a requirement from a study estimate from a press figure, and say which kind any given number is.
3. Audit any proposal with three questions: what does it mass, what does it draw, and who has paid for it.
4. Set this base against the published programmes and say, with numbers, where it is thin.

67 published
PROGRAMMES SURVEYED

48.3 t
THIS BASE, LANDED

12 t
NASA HABITAT LIMIT

144 people
ONE PLAN IS SIZED FOR

18.1 Two numbers are not comparable until you know what they count

Start with volume, because the trap there is the easiest to see. This base carries 372 cubic metres of pressurised volume for four people. NASA's reference surface habitat carries 127 cubic metres of habitable volume for two.

Set 372 against 127 and this base looks nearly three times the size. One figure is gross and the other is habitable, and one serves twice the crew. Take net habitable volume per person and this base holds 65.8 cubic metres against NASA's 63.5. Two designs that looked a factor of three apart are within four per cent of each other.

So before two numbers are allowed near each other, write down the crew size, the stay length and what each of them counts. NASA's architecture of record, of December 2024, gives its initial surface habitat two crew for a minimum of 7 to 33 days. This base is four crew on 180 day rotations. Those are different machines, and no ratio turns one into the other. Then ask what kind of number you are holding, because a requirement, a study estimate and a press figure are three different objects wearing the same clothes.

One question settles most of the field before any arithmetic starts. Does this proposal carry a mass budget, or only a picture? Hassell's Lunar Habitat Master Plan, made with ESA and Cranfield University, is sized for 144 people, and that is the only number in the release. Kyoto University and Kajima's Glass gives two dimensions and a spin rate for up to 10,000 residents. Shimizu's Luna Ring, 11,000 kilometres of solar array round the equator, has sat on a corporate website since 2011 with no funding, and never once mentions dust. None of that is dishonest. A reader setting any of them beside an engineering study should simply be told which is which.

> **Three kinds of number.** A requirement is what a design must meet, and it comes with a reason. A study estimate is what a design came out at, on a date. A press figure is what an organisation said in public. NASA's 12 tonne habitat limit is the first. The 12,517 kilograms on the master equipment list of May 2022 is the second. Four astronauts for a month, from a blog post of October 2020, is the third.

18.2 The one time a rendering met engineers

In October 2019 the architects SOM, with ESA and MIT, published a Moon Village habitat for four crew on the western rim of Shackleton crater. It is more detailed than most engineering papers: floor areas to the hundredth of a square metre, a structural system, a pressure schedule. ESA then did something rare and put it through its concurrent design facility, in November 2020, and the audit found the four person habitat massing over 58 tonnes. That is the only published case in this survey of a studio design being independently weighed, and it is the reason the SOM building sits at the top of Figure 18.1 rather than in the row of blanks.

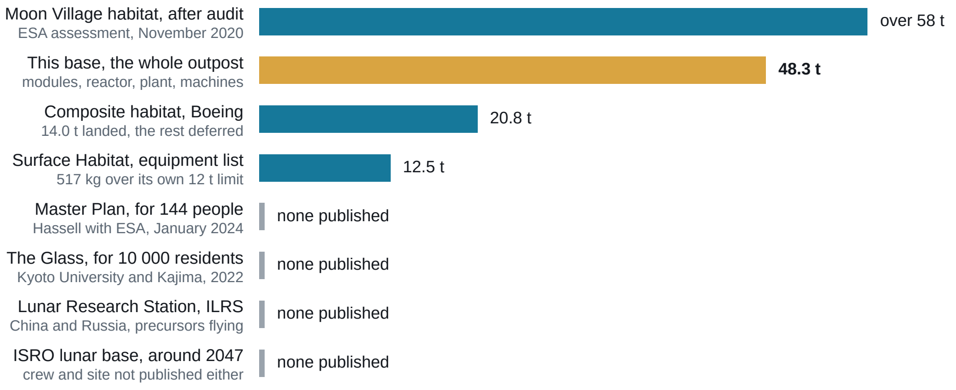


Figure 18.1. Landed mass in tonnes, for every proposal in this chapter that publishes one and for four that do not. The hairlines at the bottom are not small bases. Two of them are settlements drawn for 144 and 10,000 people, and one is a national programme with hardware already flying. The bars you cannot draw are the most useful thing on this chart.

The pressure vessels and connectors come to 28,700 kilograms. Set 28.7 against 12 and the two are arguing about the same object. Set 48.3 against 12 and they are not, and the argument that follows is about nothing. The second quick check, and the one that is hardest on this design, is mass against volume.

WORKED EXAMPLE 18.1 · IS 48.3 TONNES A CREDIBLE MASS FOR 372 CUBIC METRES?

A landed mass of 48,286 kilograms and a pressurised volume of 372 cubic metres, set against three flown or fully counted benchmarks: station node 1 at 150 kilograms per cubic metre, Boeing's composite habitat at 165, and the station laboratory with its equipment installed at 239.

1. Divide the mass by the volume, in the units the benchmarks use.
   $48\,286 \text{ kg} \div 372 \text{ m}^3 = 130 \text{ kg/m}^3$
2. Set it against the lightest benchmark, and find what mass that ratio would demand for this volume.
   $150 \text{ kg/m}^3 \times 372 \text{ m}^3 = 55\,800$ kg, which is 55.8 t
3. Find the gap.
   55.8 t − 48.3 t = 7.5 t, about 15 per cent
4. Then do the same against the equipped laboratory, which is the fairest comparison for a base that counts its equipment.
   $239 \text{ kg/m}^3 \times 372 \text{ m}^3 = 88.9$ t, nearly twice what the design lands

ANSWER At 130 kilograms per cubic metre this base is lighter than every fully counted habitat there is, by 15 per cent against the lightest and by nearly half against the one that counts its equipment the way this design does. That does not prove the budget wrong; it says the design has to defend the difference module by module, and it does not. The missing mass, if it is missing, 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.

WHERE PEOPLE GO WRONG

Headline masses get quoted as though every concept counts the same things. NASA's 12 tonnes is a habitat on its own, under a limit set by what a lander can carry. This base's 48.3 tonnes is a whole outpost, and it includes the reactor, the construction machines, the oxygen plant and a first rotation of consumables. Compare like with like or compare nothing.

18.3 Ten programmes, and where this one is thin

Table 18.1. The published field, and this base in it. Where a cell says not published, the programme has published nothing on that line.

Programme	Crew	Site	Power	Status
ISRO lunar base, around 2047	Not published	Not published	Not published	Policy, no design
BHEEM, IISc Bengaluru	16	Not designated	Not published	Preprint, February 2025
Surface Habitat, NASA reference	2, for 30 days	South pole	10 to 15 kW solar	Reference concept only
Composite habitat, Boeing	4, for 28 days	Near the south pole	Not published	Industry study, 2025
Constellation Scenario 12	4, for 180 days	Polar	Fission, no figure	Cancelled in 2010
Moon Village habitat, SOM	4, for 300 days	Shackleton rim	About 60 kW	Study, audited by ESA
Lunar Research Station, ILRS	Not published	South pole region	40 kW, 2033 to 2035	Funded, precursors fly
Master Plan, Hassell with ESA	144	Shackleton edge	Not published	Rendering, January 2024
Lunar Habitat ACT	**4, for 180 days**	**Shackleton rim**	**88 kW installed**	**Concept, fully budgeted**

China and Russia have money and launches, and publish no habitat mass and no crew size. SOM published a floor by floor breakdown of a building nobody will fund. Score a proposal on both axes, because funded and documented are different virtues.

Turn the same questions on this base. It publishes all five things a comparison needs, mass, power, volume, crew and site, with a source for each, and of the 67 programmes surveyed here only SOM's audited habitat does the same. Then it fails its own test twice, and the failures are worth more to a reader than the spine is. Landed mass over pressurised volume is the quickest check on whether a habitat mass is credible, and the worked example above runs it: 130 kilograms per cubic metre, under every fully counted benchmark there is, and the design does not defend the difference module by module.

The second failure is delivery. Nothing in the design names a lander class or an arrival order, and worked example 4.1 is the reason that matters: 48.3 tonnes is anywhere between four and thirty three landings depending on whose vehicle is assumed, and no vehicle that has flown can take the 9.4 tonne core. The third gap is the one this chapter is least comfortable with. Every proposal above was asked who has paid for it, and this design has no published cost at all. ESA's Argonaut descent element was contracted at 862 million euro, and nothing of that kind can be set beside this base.

The first row of the table is the one this book has most to say about. India has landed near the lunar south pole, has committed in public to a crewed landing in 2040 and a base around 2047, and has published no crew size, no module count, no habitat mass, no power budget and no site for it. Publishing all five, with the arithmetic showing and the thin places marked, is the reason a study like this one exists.

> **130 kg/m³** This base's landed mass over its pressurised volume, against 150 for station node 1, 165 for Boeing's composite habitat and 239 for the station laboratory with its equipment installed

QUESTIONS

1. This base has 263 cubic metres net habitable for four crew. NASA's reference surface habitat has 127 cubic metres habitable for two. Work out both per person, and say why comparing 372 with 127 misleads. APPLY

2. The station laboratory can be quoted as 137 or as 239 kilograms per cubic metre. Explain how one module has two correct answers, and say which figure this base should be compared against. EXPLAIN

3. ESA's audit found that one four person habitat masses over 58 tonnes. Estimate the landed mass of a settlement for 144 people, then say what your estimate assumes and why it is still worth making. EXTEND

4. Find the mass this base would have to land to reach the node 1 benchmark of 150 kilograms per cubic metre, and say where you would expect the missing mass to be hiding. CALCULATE

5. Classify each of the following as a requirement, a study estimate or a press figure: the 12 tonne habitat limit, the 12,517 kilogram equipment list, the 144 person master plan, and this book's 48,286 kilograms. APPLY

6. Write the three questions you would put to any lunar base proposal before believing a number in it, and apply them to the first row of Table 18.1. EXTEND