COMPASSION8INNOVATION

FIRST EDITION · 2026

A STUDY BOOK IN SPACE SYSTEMS ENGINEERING

PART 1 THE DRAWINGS, AND THE BUDGETS THAT CLOSE

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

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.

How to use this book

This is a course in engineering built around one real design. It takes a plan for a lunar outpost, called ACT, and works through it system by system until every number in it has been justified, corrected or admitted to be a guess. Nothing here was invented to make a lesson come out neatly.

The design is unusual, and the difference shows up on the first page. Almost every Moon base you have seen drawn is a shelter: somewhere for people to live. This one is a building site. Its job is to keep four people alive long enough to build the landing pad, the roads, the blast walls and the radiation cover that everything after it will need. Read the design that way and choices that look strange start to look obvious.

Work through the chapters in order if you can. Part one teaches the two skills the rest of the book leans on: reading an engineering drawing, and closing a budget. Part two takes the twelve systems one at a time, from power to autonomy. Part three puts them back together and asks how this outpost stands against what the space agencies have published.

WHAT YOU NEED BEFORE YOU START

School physics to about the age of sixteen: force, energy, power, pressure, density, and how heat moves. A calculator. There is no calculus anywhere in the book. If you can work out how long a kettle takes to boil, you have the mathematics for every worked example here.

HOW EACH CHAPTER RUNS

The same five moves every time. First the problem the Moon sets, which is usually not the problem you expect. Then the physics that governs it. Then how this design answers it, with the actual numbers from the design documents. Then a worked example you can follow with a calculator. Then six questions, with answers at the back.

WHAT THE MARGINS CARRY

Definitions, key figures, and the places where the design is honest about what nobody knows yet. Read them as you go, or read past them and come back.

> **A word about the numbers.** A figure you cannot trace is not a figure, it is a rumour. Learning to tell one from the other is most of what engineering judgement turns out to be, which is why this book shows its working even when the working is unflattering.

THIS DESIGN DOES NOT CLOSE, AND THAT IS THE POINT

Three of the outpost's budgets are checked in chapter 4. One of them closes. The other two do not, and the gaps are printed rather than smoothed over: the connectors carry about a third of the volume the plan actually needs, and the reactor is about four tonnes lighter on paper than the published design of the same class. A design with its open questions named is worth more than one that has been quietly made to add up, and you will learn more from the gaps than from the parts that work.

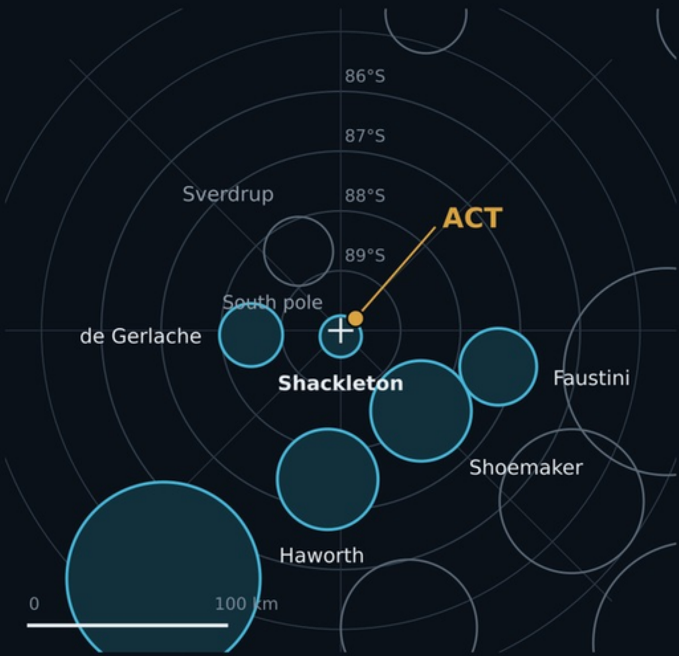
Contents

PART ONE

The drawings, and the budgets that close

Before anybody argues about reactors or greenhouses, somebody has to draw the thing and add it up. This part teaches the two skills the rest of the book leans on: reading an engineering drawing, and closing a budget. A budget is closed when the allowance and the need agree, and the margin between them is written down rather than hoped for. Most designs fail here, quietly, long before anything fails in the hardware.

CHAPTER ONE



THE ONLY PLACE A BASE CAN STAND

Rings
Each ring is one degree of latitude, about 30 kilometres of ground.

Cyan floors
Craters deep enough that sunlight has never reached the bottom.

The rim
High ground beside Shackleton, lit for most of the year.

ACT
The outpost, on the rim at 89°41′ south.

Why build, and where

Twelve people have walked on the Moon and none of them stayed longer than three days. Going back is a transport problem. Staying is a different problem, and it turns on one number and one place.

WHAT THIS CHAPTER WILL TEACH YOU

1. Why the cost of landing mass governs every other decision in the design.
2. How to use the closure of a life support loop to work out a resupply bill.
3. Why the Sun never climbs at a lunar pole, from the tilt of the Moon's spin axis.
4. Why darkness at the pole is set by the terrain rather than by the lunar day.

4	**180 days**	**3 days**	**$1M / kg**
CREW	ONE ROTATION	LONGEST STAY SO FAR	COST TO LAND

1.1 The number everything argues with

Landing one kilogram on the surface of the Moon costs about a million dollars. Hold that in your head and most of this design explains itself.

That was NASA's planning figure in 2019. By 2023, on contracts it had actually signed, it was nearer 1.2 million, which is also roughly what Astrobotic charges a customer today. Treat it as an order of magnitude rather than a price list. Even so it settles almost everything, because it turns every engineering question into the same question: how much mass does this need, and can we avoid landing it?

Read the design that way and the strange choices stop being strange. The base makes its own oxygen, not because making oxygen is clever but because shipping it is ruinous. The pressure vessels sit under two metres of soil, not mainly because soil is a fine shield, though it is, but because the soil is already there and weighs nothing on the manifest. Nearly every good idea in this book is that same idea wearing a different coat: use what is already there, and land only what you cannot make.

> **Landed mass** is the mass that actually reaches the lunar surface, as against the much larger mass that left the ground on Earth. When engineers argue about a base, this is almost always the number they are arguing about.

WORKED EXAMPLE 1.1 · THE PRICE OF SIMPLY BREATHING

Four crew, a rotation of 180 days, and an oxygen consumption of 0.84 kilograms per person per day. Is it cheaper to ship the oxygen or to make it?

1. Find the oxygen one person breathes over the rotation.
   0.84 kg/day × 180 days = 151.2 kg
2. Multiply by the crew.
   151.2 kg × 4 = 604.8 kg, call it 605 kg
3. Price it at the landed cost of mass.
   605 kg × $1 000 000/kg = $605 million
4. Now price the plant that makes the oxygen instead. The mass budget carries it at 1 000 kilograms.
   1 000 kg × $1 000 000/kg = $1 000 million
5. Compare them over two rotations rather than one, since the plant keeps working and the tanks do not.
   Shipped: 2 × $605 M = $1 210 M. Plant: $1 000 M, once.

ANSWER The plant costs more than a single rotation's oxygen and less than two. Anything that keeps working pays for itself in landings avoided, and that is the whole argument for making things on site rather than bringing them. Note what the sum quietly assumes: that the plant works for two rotations without a spare part arriving from Earth.

1.2 Why the pad comes before the shielding

The order things get built in looks wrong the first time you see it. Shielding protects people. A landing pad protects equipment. So why does this base build the pad first?

Because of what a lander does to bare ground. A spacecraft coming down on loose regolith does not push the surface aside, it digs in and throws it. The finest grains leave at over two kilometres a second, against the 2.4 kilometres a second it takes to escape the Moon altogether, and because there is no air to slow them and no weather to bring them down, they simply keep going until they hit something. Apollo 12 landed about 155 metres from the Surveyor 3 probe and sandblasted it: paint stripped, camera housing pitted. The crew cut pieces off and brought them home, which is how we know.

Until there is a pad, in other words, every arrival damages what is already standing. The pad is not a convenience. It is the thing that makes a second delivery possible, and a base that cannot take a second delivery is not a base, it is a visit.

WHERE PEOPLE GO WRONG

This base recovers or remakes about 85 per cent of what its crew consumes each day, and it is natural to read that as cutting the resupply bill by 85 per cent. It does not work that way for long. What you pay for is the leak, not the loop. Push closure from 85 to 95 per cent and the bill falls by a factor of three, because the leak has gone from fifteen parts in a hundred to five. The last few percentage points of closure are far harder to buy than the first eighty, which is why chapter 7 spends its length on where the loop leaks rather than on how much it recovers.

1.3 One place on the Moon

Now the second half of the chapter title. Almost anywhere on the Moon, the night lasts about fourteen and three quarter days: long enough that a solar powered base would need a battery bank heavier than the base itself. That is the fact everybody knows, and it is the reason most people assume a Moon base has to be nuclear.

It is not true at the poles, and the reason is a single number. The Moon's spin axis is tilted only 1.54 degrees to the plane of its orbit around the Sun. Earth's is tilted 23.4 degrees, which is why we have seasons and long polar nights. With a tilt that small, the Sun at a lunar pole never rises and never sets: it circles the horizon, never climbing more than about a degree and a half above it, all year, every year.

That changes the question completely. Darkness at a lunar pole is not the Sun going down. It is a ridge or a crater wall getting in the way. Stand on high ground and you can be lit almost continuously; stand in a hollow a hundred metres away and you can be in shadow for days. So the length of the night at a polar base is a question about terrain, and terrain is measured by mapping, and mapping has a resolution.

> *Darkness at the pole is not the Sun going down. It is something getting in the way.*

Table 1.1. The same ridge, measured twice.

Study	Map resolution	Longest dark spell	What it means for the design
Mazarico and others, 2011	240 m	about 1.5 days	240 days of continuous sun at the best rim site
Gläser and others, 2018	20 m	65 to 66 hours	Lit 77 to 88 per cent of the year, measured at 2 metres height
Gläser and others, 2018, cluster C1	**20 m**	**112 hours**	**Nearly five days without sun, at a site otherwise excellent**

Ask a coarse map how long the dark lasts and you get one answer. Ask a fine map of the same ground and you get a longer one, because a fine map can see smaller obstacles. This is not a disagreement between scientists. It is one ridge, measured twice. Sources: Mazarico and others, Icarus, 2011, from LOLA topography; Gläser and others, Planetary and Space Science, 2018.

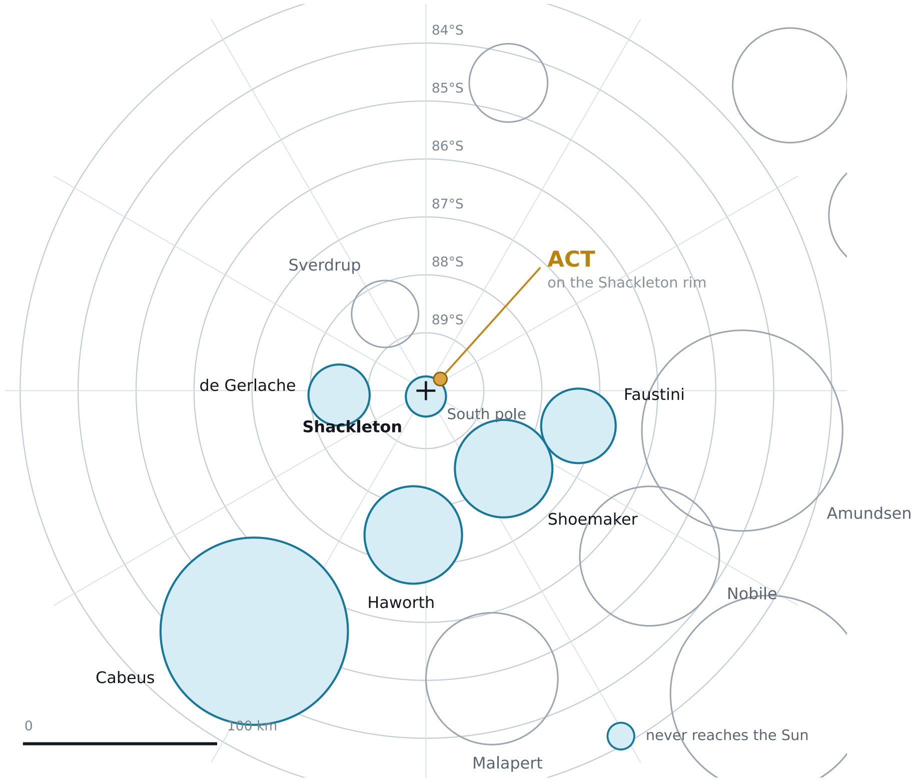


Figure 1.1. The lunar south pole, and the one strip of ground this base can stand on. Each ring is a degree of latitude, about 30 kilometres. The craters shaded blue are deep enough that direct sunlight has never reached their floors, which is why the water is there and why nothing can be built in them. ACT sits on the rim of Shackleton, high ground that is lit for most of the year and a few kilometres from the ice in Cabeus. Drawn from published crater positions; the map is schematic and is meant to show what lies where rather than to be navigated by.

A designer sizes the battery against the longer figure, because a shadow the map failed to resolve is still a shadow. And here is the honest part: the dark spell at the exact position of this base's mast has never been computed by anyone. The book says so wherever it matters, rather than quietly picking whichever number makes the design look better.

1.4 The ice next door, and why the base does not depend on it

There is water at the lunar south pole. In 2009 the LCROSS mission deliberately crashed a spent rocket stage into the floor of Cabeus crater and flew a second spacecraft through the plume it raised, and found about 5.6 per cent water by mass. Cabeus lies a few kilometres from this site, in a crater floor that has been in shadow so long it has never been warm enough to lose what it holds.

That is a real resource, and this base does not rely on it. The first attempt to drill for that ice, PRIME 1 aboard Intuitive Machines 2 in March 2025, extended its drill through its full travel and never touched the ground, because the lander had come to rest on its side. Until a drill actually reaches ice and brings some up, an outpost that assumes ice is an outpost built on a press release.

This is worth sitting with, because it is the difference between a design and a wish. Water on the Moon is real. Water that a machine can dig, move, melt and clean, at a rate a base can plan around, is not yet anything. So the design assumes nothing from the ice, and takes its water from the tanks it lands with and the loop that keeps recycling it. If the ice comes good later, the base gets a bonus. If it does not, nobody dies of thirst waiting for it.

QUESTIONS

1. A subsystem can be made 40 kilograms lighter for an extra $15 million of development. At the landed cost used in this chapter, is that a good trade? APPLY

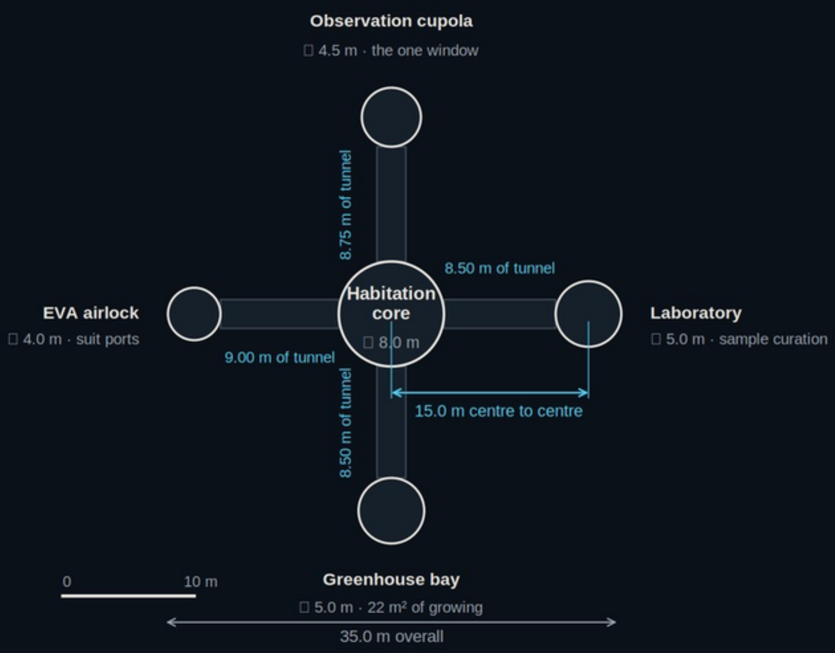
2. Explain, from the tilt of the Moon's spin axis, why the Sun never climbs high at a lunar pole. EXPLAIN

3. The base recovers 85 per cent of what the crew consumes. Four people consume about 24 kilograms a day in all. What is the annual resupply mass, and what does it cost to land? CALCULATE

4. Why is a landing pad built before radiation shielding, when shielding protects people and a pad protects only hardware? EXPLAIN

5. Chapter 1 gives a longest dark spell of 65 to 66 hours at the best rim clusters and 112 hours at one otherwise excellent site on the same 20 metre map. The spell at the exact spot where this base stands has never been computed. Which figure would you size a battery against, and what would you do about the gap in the evidence? EXTEND

6. LCROSS found 5.6 per cent water by mass in the Cabeus plume. Suppose you could mine 100 tonnes of that regolith a year. How much water is that, and how many 180 day rotations of drinking water would it cover at 3 litres per person per day? CALCULATE



HOW TO READ THIS SHEET

Plan
The base cut horizontally and seen from straight above.

Dimension lines
The arrowed lines carry a measurement; the thin ones bring the feature out.

Centre to centre
The 15.0 metres is measured between centres, not between hulls.

Scale bar
The ruler for everything the sheet does not dimension.

Reading the drawings

An engineering drawing is not a picture of a building. It is a set of promises about sizes, written in a language of about six symbols. Learn those and this base stops being a shape and starts being a machine you can argue with.

WHAT THIS CHAPTER WILL TEACH YOU

1. Read a plan, a section and an elevation, and say what each one can and cannot tell you.
2. Tell a dimension line from an extension line, and know when a scale bar is the only ruler you have.
3. Work out how much room a cylinder gives you for each square metre of hull, and why the answer ignores its height.
4. Say why this base is five rooms rather than one, and what that choice costs.

5	8.0 m	15.0 m	35.0 m
PRESSURE VESSELS	CORE DIAMETER	MODULE CENTRES	OVERALL FOOTPRINT

2.1 Three views, one object

Everything an engineer needs to say about a building can be said with three drawings, and each one is made by imagining a cut.

A **plan** is what you would see if you passed a knife horizontally through the building about a metre above the floor, lifted the top half off and looked straight down. A **section** is that same knife stood on end: everything in front of the cut is thrown away, everything behind it is drawn as you would see it, and anything solid the blade passed through is hatched. An **elevation** cuts nothing at all. It is a straight view of one face, and the thing that makes it honest is the common ground line every object is drawn standing on. Take that line away and one module can sit on a mound while its neighbour sits in a hollow, and no two heights on the sheet mean the same thing any more.

Figure 2.1 is the plan of this base. Before you read the shapes, read the lines. The thin lines running out from each module are **extension lines**; they carry a feature out into clear space so that it can be measured without cluttering the drawing. The arrowed lines they meet are **dimension lines**, and the four that read 15.0 metres run centre line to centre line rather than hull to hull, which matters enormously the moment you try to work out how long the tunnels between modules have to be. The chain line lettered A marks where the section is taken. The bar at the foot is the scale, and it is the ruler for everything the sheet does not bother to dimension.

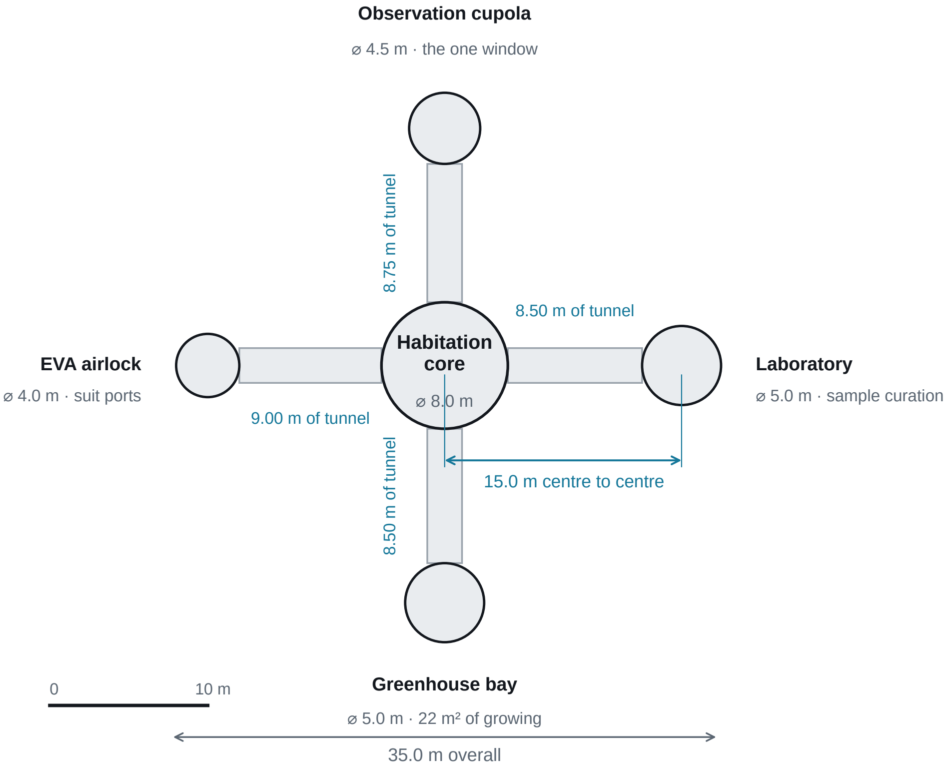


Figure 2.1. The plan: the base cut horizontally and seen from above. Five pressure vessels, four tunnels, one dimension you are given and a scale bar for everything else. The tunnel lengths shown in cyan are not on the design's own sheet. They are what the geometry demands, and section 2.4 explains why that difference matters. Drawn from the design's plan drawing, revision A.

> **Scale bar.** A ruler drawn on the sheet itself. It is better than writing "1:200" in the corner, because if the drawing is photocopied at 80 per cent the printed ratio becomes a lie while the bar shrinks with everything else and stays true.

2.2 What the section is really about

Read the section of this base and you might expect its subject to be the rooms. It is not. The subject is the feet.

Each hull stands on a skirt of compacted regolith that rises to about a fifth of its height: 1.1 metres of packed soil against the 5.5 metre core, meeting the wall along a flat band half a metre wide and falling away outside at about thirty degrees, which is roughly the angle loose soil settles at when you tip it into a heap. Nothing is piled on the crown of the vessel. That is deliberate, and the reason is worth understanding because it comes back in the radiation chapter.

A pressure vessel spends its whole life being pushed outward from inside. The air in it presses on every square metre of the wall, and the wall is shaped and tensioned to take exactly that. Pile soil on top and you are pushing the other way, against a structure built to resist the opposite load. So the skirt takes the weight around the base, where the hull is already braced and where the soil doubles as the shielding the crew stand behind, and the crown stays clear.

2.3 One big room, or five

Here is a piece of arithmetic that decides the whole shape of the base, and you can do it in your head once you have seen it once.

Take a cylinder. Its volume grows with the square of its width, while the wall wrapped around it grows only in proportion to that width. So the two never keep pace, and if you divide one by the other the height falls out of the sum entirely:

THE ONLY FORMULA IN THIS CHAPTER

$$V \div A = d \div 4$$

V is the swept volume in cubic metres, A is the area of the wall around it in square metres, and d is the diameter in metres. It comes straight out of $V = (\pi/4)d^2h$ for the volume and $A = \pi dh$ for the wall: divide one by the other and the height h cancels. The room a vessel gives you for each square metre of wall depends on its width and on nothing else.

Put the base's own numbers in. The habitation core, 8.0 metres across, gives 2.0 cubic metres of room for every square metre of hull. The EVA airlock, at 4.0 metres, gives 1.0. Wall is the part you launch, and at a million dollars a kilogram, wall is the part you pay for. By this argument alone you should build one enormous room.

Nothing on the Moon is built that way, and the reason is that a pressure hull is a single point of failure. Air leaves a holed vessel through the hole, and it takes every room joined to that vessel with it. Five separate vessels answer this, provided each one can be shut off at its connector, and then a breach in the greenhouse costs the crew the greenhouse rather than the base.

The design puts a price on that safety. Put the same volume into one cylinder 5.5 metres tall and it would have to be 11.8 metres across, and it would wrap about 204 square metres of wall around 601 cubic metres of air. The five separate vessels wrap about 415 square metres around the same air. Roughly twice the hull, landed at a million dollars a kilogram, buys the crew four other places to be when one of them fails.

> *Wall is the part you launch. Rooms are the part you live in. Every base is an argument between those two sentences.*

2.4 Where this drawing and this budget disagree

Now the part of the chapter that teaches the most, because it is where the design contradicts itself and you can catch it with a calculator.

The plan says the modules sit on 15.0 metre centres around a core 8.0 metres across. The tunnels between them are 2.2 metres in diameter. So how long is each tunnel? Take the distance between centres, subtract the core's radius of 4.0 metres, and subtract the radius of the module at the far end. For the two 5.0 metre modules that leaves 8.5 metres of tunnel each. For the 4.0 metre airlock, 9.0 metres. For the 4.5 metre cupola, 8.75 metres. Call it 34.75 metres of tunnel in all.

The design's own volume budget carries one line of 38 cubic metres for all four connectors. A tunnel 2.2 metres across has a cross section of 3.8 square metres, so 38 cubic metres buys about ten metres of tunnel, shared between four spokes: two and a half metres each, against the eight and three quarter metres the plan leaves at every one of them.

One of the two has to give. Either the modules stand much closer together than the plan says, or the connectors hold about 132 cubic metres rather than 38. This book takes the plan, because the plan is dimensioned and the budget line is not broken down, and it prints the consequences rather than quietly adjusting them. The design also states a maximum connector length of 2.2 metres that can be pressurised without intermediate structure; no such limit exists in the engineering literature, and the plan's own geometry needs runs of eight and a half to nine metres.

WORKED EXAMPLE 2.1 · DOES 38 CUBIC METRES OF TUNNEL REACH THE MODULES?

Four modules on 15.0 metre centres round a core 8.0 metres across. Connectors 2.2 metres in diameter. The outboard modules are 5.0, 5.0, 4.5 and 4.0 metres across.

1. Find the clear run to each module.
   15.0 − 4.0 − 2.5 = 8.5 m (each 5.0 m module)
   15.0 − 4.0 − 2.25 = 8.75 m (cupola) 15.0 − 4.0 − 2.0 = 9.0 m (airlock)
2. Add them up.
   8.5 + 8.5 + 8.75 + 9.0 = 34.75 m of tunnel

3. Find the cross section of a 2.2 metre tunnel.
   $(\pi \div 4) \times 2.2^2 = 3.80\ m^2$
4. Multiply to get the volume the plan actually needs.
   $3.80\ m^2 \times 34.75\ m = 132\ m^3$
5. Compare with the budget line.
   $132 \div 38 = 3.5$

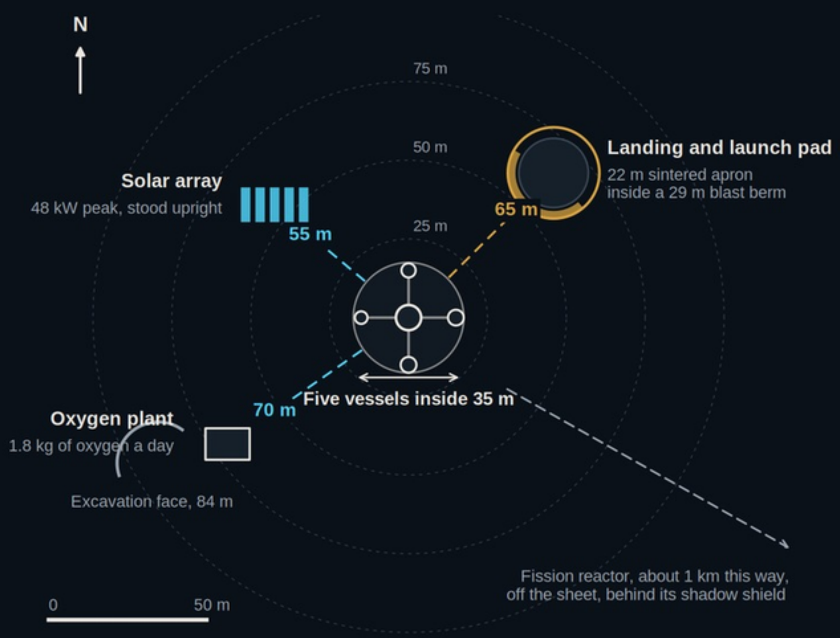
ANSWER The plan needs about three and a half times the connector volume the budget carries. Keep the plan and apply the same ratio of net habitable to gross that the budget itself uses for connectors, 34 to 38, and the tunnels hold 118 cubic metres of usable space. The base is then 466 cubic metres gross and 347 net habitable, which is 86.8 per person, against the 372, 263 and 65.8 the budget prints. That is not a rounding error. It is a third of the base.

WHERE PEOPLE GO WRONG

It is tempting to treat the mismatch as an argument about tunnels. It is not: it is an argument about whether the plan and the budget describe the same building. Two documents that disagree by a factor of three are not both right about a detail, they are describing two different bases. Whenever you find a gap like this, the useful question is never "which number is correct" but "which drawing is the other document actually costing".

QUESTIONS

1. A drawing shows a module 5.0 metres across with no other dimensions, and a scale bar 10 metres long that measures 40 millimetres on the page. What is the drawing's scale, and how long is a tunnel that measures 34 millimetres? APPLY
2. Use $V \div A = d \div 4$ to find the volume per square metre of hull for the 4.5 metre cupola and the 5.0 metre greenhouse. CALCULATE
3. Explain why soil is banked around the foot of a pressure vessel and never heaped on its crown. EXPLAIN
4. The five vessels wrap about 415 square metres of hull around the same air that one 11.8 metre cylinder would wrap in 204. If hull runs at roughly 12 kilograms a square metre, what does the five room layout cost in landed mass, and in dollars at a million a kilogram? CALCULATE
5. An elevation is drawn without a common ground line. Give two specific ways that drawing could mislead a reader who is checking whether the airlock door lines up with the tunnel. EXPLAIN
6. The plan and the volume budget disagree by a factor of three and a half. You are the engineer who has to resolve it before the next review. What three questions would you ask, and what evidence would settle each one? EXTEND



EVERY DISTANCE ANSWERS A HAZARD

15 metres
Module centres: a breach in one spoke must not reach the next.

65 metres
The pad: grit thrown above 2 km/s, with a berm in the way.

70 and 84 metres
Plant and excavation face, so loaded haulage never crosses the base.

About 1 kilometre
The reactor, off the sheet, behind its shadow shield.

The site plan

Nothing on this site stands where it does for convenience. Every distance on the sheet is the shortest one that answers a particular way of getting hurt, and on this base those distances run from fifteen metres to a kilometre.

WHAT THIS CHAPTER WILL TEACH YOU

1. Read a site plan, and say what a scale bar lets you measure that a dimension line does not.
2. Explain why a lander touching down on unprepared ground is the most destructive thing that can happen to a base.
3. Say what sets the reactor's one kilometre standoff, and why moving it further would not save shield mass.
4. Price a separation distance in cable, in graded road and in days of work.

35.0 m	65 m	1 km	2 km/s
OVERALL FOOTPRINT	PAD STANDOFF	REACTOR STANDOFF	SPEED OF THROWN GRIT

3.1 A site plan is a list of decisions

A map records where things happen to be. A site plan records where somebody decided they should go, and on this sheet almost every decision is a distance.

The five pressure vessels sit fifteen metres apart, centre to centre. The landing pad stands sixty five metres out on a north east bearing. The reactor is about a kilometre away, off the sheet entirely. Those three numbers span a factor of nearly seventy, and not one of them was picked for convenience. Each is the shortest distance that answers one particular hazard.

Shortest is the word doing the work. Distance is expensive on the Moon. Every metre between two things is cable that has to be landed, road that has to be graded and compacted, and time spent walking it in a suit that is exhausting to move in. So the rule this sheet is drawn to is not keep everything well apart. It is put everything as close together as the hazard allows, and no closer.

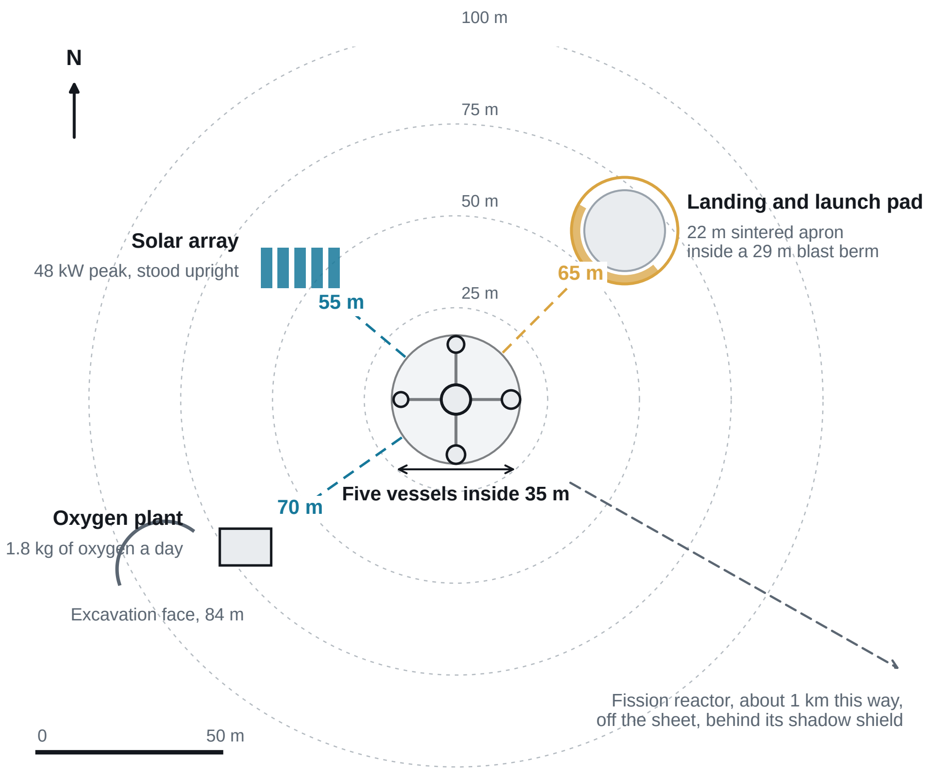


Figure 3.1. The whole site. Read the distances rather than the shapes. The five vessels cluster inside 35 metres and everything that can hurt them stands outside that ring: the pad 65 metres out on the north east bearing behind its berm, the array 55 metres to the north west, and the oxygen plant with its excavation face beyond it to the south west, so that loaded haulage never crosses the living area. Only the 65 metres is dimensioned on the design's own sheet. Every other distance has to be taken off the scale bar.

3.2 The pad, and why nothing lands without one

Chapter 1 said that a lander coming down on bare regolith is the worst thing that can happen to a base. Here is what actually occurs.

The engine plume does not blow the surface aside the way wind blows sand. It digs into the soil and throws what it digs, and the finest grains leave at more than two kilometres a second, which is faster than a rifle bullet and not far short of the 2.4 kilometres a second it takes to leave the Moon altogether. On Earth a sandstorm is survivable largely because air holds the grains back and gravity brings them down. Here there is no air and very little gravity to speak of, so the grains simply fly until they hit something.

We have one measurement of what that does, and it is a good one. In November 1969 Apollo 12 landed 155 metres from Surveyor 3, a probe that had been sitting on the Moon for two and a half years. The crew walked over, cut pieces off it and brought them home. The pieces told the story: the camera housing pitted, paint stripped, every surface facing the lander scoured by grit its own plume had thrown that far. It was a small lander, and 155 metres was not enough.

That measurement is what the 65 metre standoff and the 29 metre blast berm are answering. The berm is not there to be pretty. Most of the ejecta leaves at a very low angle, almost skimming the ground, so a wall of piled soil between the pad and the hulls intercepts the part of the fan that would otherwise arrive at the base. The pad itself is graded flat and sintered into a 22 metre apron, so the next lander touches down on a surface that has nothing loose left to throw.

> **155 m** How far Apollo 12's plume threw grit hard enough to strip paint off Surveyor 3, in November 1969

3.3 Every separation, and the hazard behind it

Table 3.1 is the whole site plan written as a list. Read the right hand column first: each row exists because of something in it.

Table 3.1. Every separation on the site, and the hazard that sets it.

What is separated	Distance	The hazard it answers
Module centres, core to each of the four spokes	15.0 m	A breach in one spoke reaching the module next door. The connector length argument sometimes given alongside it does not hold, for the reasons in chapter 2.
Solar array, 48 kW peak, stood upright and tracked on one axis	55 m	Kept clear of the cluster, on part of the 260 square metres of equipment pad laid so that the array and the plant do not settle into the soil.
Landing and launch pad, 22 m sintered apron inside a 29 m blast berm	**65 m**	**Ballistic ejecta leaving above 2 km/s, with the berm standing between the low angle fan and the hulls.**
Oxygen plant, and the excavation face beyond it	70 and 84 m	Loaded haulage crossing the living area. The face is put on the far side of the plant, so the heavy route is a dead end rather than a through road.
Fission reactor, 40 kWe	about 1 km	Neutron and gamma dose. This is the distance at which the shadow shield holds the crew below 50 millisieverts a year, against the 380 the open surface gives them anyway.

Distances as the design's site plan gives them. The reactor standoff follows the practice in NASA's fission surface power studies rather than a figure computed for this site.

3.4 Why the reactor sits a kilometre away, and why not further

A fission reactor throws neutrons and gamma rays in every direction. You can stop them with mass, or you can stop them with distance, and distance is the one that weighs nothing.

Radiation from a compact source falls off with the square of the distance, so doubling the separation quarters the dose. That makes the early metres extraordinarily cheap: going from ten metres to a hundred cuts the dose by a factor of a hundred, for the price of some cable. But the same law is what stops the argument. Once you are far enough away that the crew's dose from the reactor is a small fraction of what the sky is giving them anyway, moving it further buys nothing you can measure. At about a kilometre, the shadow shield plus the distance holds the crew under 50 millisieverts a year from the reactor, while the unshielded surface delivers something like 380 millisieverts a year from cosmic rays regardless. Pushing the reactor to two kilometres would remove three quarters of a number that is already small, and add a kilometre of cable to the manifest.

And cable is where this gets expensive, in a way the design underestimates. Conductor mass rises with the square of the length and falls with the square of the voltage, so the choice of bus voltage matters more than anything else in the trade. NASA's own fission power study gives the anchor point: a three kilometre run at 500 volts weighs about 3,300 kilograms. Scale that to one kilometre and it is a few hundred kilograms, which is manageable. Run the same power at 120 volts instead and a direct calculation for two kilometres of aluminium conductor gives something between eight and sixteen tonnes, depending on how much loss you are willing to accept. That is a third of the whole base's landed mass, spent on wire.

WORKED EXAMPLE 3.1 · WHAT DOES A KILOMETRE OF SEPARATION COST?

The reactor stands about a kilometre from the base. Price that separation three ways: in cable, in graded road, and in the time it takes to build the road.

1. Cable, at the sensible voltage. Take NASA's anchor: 3,300 kg for 3 km at 500 V. Conductor mass scales with length, so for 1 km:
   3 300 kg × (1 ÷ 3) = 1 100 kg, and about 370 kg if you also allow the lower current this shorter run needs

2. Cable, at the wrong voltage. Mass scales as the inverse square of voltage, so dropping from 500 V to 120 V multiplies it by $(500 \div 120)^2$.
   $(4.17)^2 = 17.4$ times heavier

3. Road. A graded route 3 metres wide over 1 000 metres.
   $3 \text{ m} \times 1\,000 \text{ m} = 3\,000 \text{ m}^2$

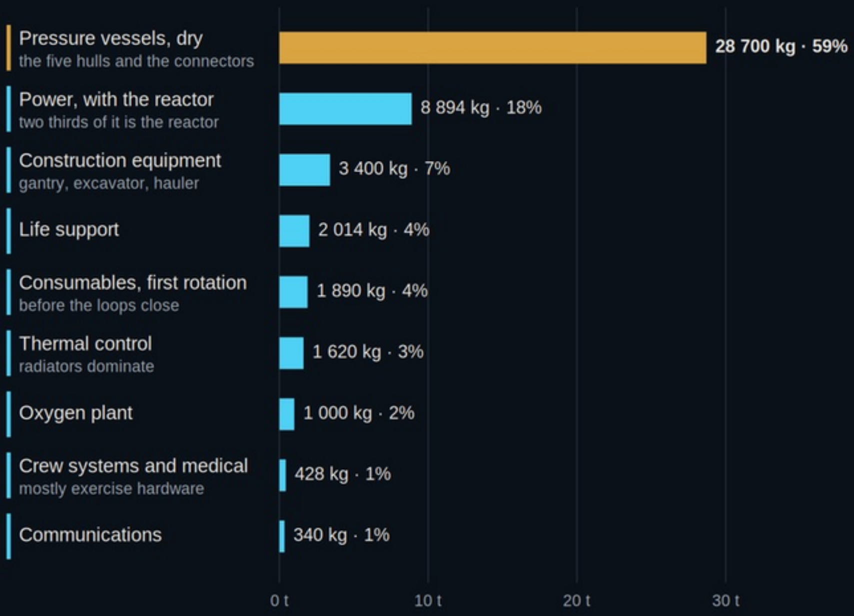
4. Time. At the surfacing rate this base can actually achieve, about 5.6 square metres a day.
   3 000 ÷ 5.6 = 536 days

ANSWER The cable is cheap if you choose the voltage well and ruinous if you do not. The road is the real cost: more than a year of continuous work, which is why the reactor route is graded rather than sintered, and why the machine that does the grading is on the first landing rather than the fifth. Distance is never free, but the price is almost never where you first look for it.

QUESTIONS

1. The pad stands 65 metres from the core and Apollo 12 damaged Surveyor 3 from 155. Explain how both facts can be true at once. EXPLAIN
2. Radiation falls off with the square of distance. If the dose at 100 metres from the reactor is 4 millisieverts an hour, what is it at 1 kilometre? CALCULATE
3. The oxygen plant sits at 70 metres and its excavation face at 84, with the face on the far side. Why that order, and what would go wrong if they were swapped? EXPLAIN
4. A designer proposes moving the reactor to 2 kilometres for extra safety. Using the numbers in this chapter, say what that buys and what it costs. APPLY
5. Only one distance on the design's site plan is dimensioned. Everything else must be scaled off. Give one advantage and one risk of drawing a sheet that way. EXPLAIN
6. The base has 260 square metres of equipment pad and a surfacing rate of about 5.6 square metres a day. How long does the equipment pad alone take, and what does that imply about the order the site gets built in? EXTEND

CHAPTER FOUR



WHERE THE 48 TONNES GOES

Hull
The five pressure vessels are 59 per cent of everything that gets landed.

Power
Another 18 per cent, and the reactor alone is two thirds of that.

Everything else
Life support, food, medicine, radios and machines: under 5 tonnes in all.

Margin
No line in this budget is called margin. Chapter 4 asks where it hides.

The budgets that close

Adding up is a check on your arithmetic. Closing is a check against the world, and it asks two more questions: can a lander actually put this down, and what is left over when it has?

WHAT THIS CHAPTER WILL TEACH YOU

1. Keep gross, habitable and net habitable volume apart, and say which one describes living somewhere.
2. Read a mass budget as a shape rather than a list, and find the line that decides everything.
3. Say what closing a budget means, and why a column that adds up may still not close.
4. Find the margin in a design that never uses the word.

372 m³
GROSS VOLUME, AS BUDGETED

48 286 kg
LANDED MASS

45.6 kW
CONTINUOUS LOAD

1 of 3
BUDGETS THAT CLOSE

4.1 Three columns, three different arguments

Every design carries three numbers that decide whether it is real: how much room it has, how much it weighs, and how much power it draws. This chapter takes the base's own three columns and asks of each one whether it closes.

A budget **adds up** when the lines total the figure at the bottom. That is arithmetic, and it is the easy half. A budget **closes** when what you have allowed for matches what you actually need, with the margin written down rather than hoped for. Most designs fail at the second test long before anything fails in the hardware, and they fail quietly, because a column that adds up looks finished.

4.2 Volume: the three distinctions a reader has to keep

Gross volume is what a shape encloses. Take out the structure and everywhere a person cannot reach, and what is left is **habitable volume**. Take out the racks, the stowage and the machinery as well, and what is left is **net habitable volume**, which is the only one of the three that tells you anything about living there.

This base, as the budget prints it, is 372 cubic metres gross and 263 net habitable. The habitation core keeps 112 of its 148. The greenhouse bay, six growing tiers deep, keeps only 22 of its 54, because the tiers fill the vessel from the deck upward and a person can stand in what is left. Quote the first figure and you have described a hull. Quote the third and you have described a room. When two designs are compared in chapter 18, this distinction turns a difference of three times into a difference of four per cent.

And as chapter 2 showed, this column does not close. The plan needs about 132 cubic metres of connector and the budget carries 38. Correct it and the base becomes 466 gross and 347 net habitable, which is 86.8 cubic metres a person rather than 65.8. Figure 4.1 shows both, side by side, because the honest way to publish a disputed number is to publish it twice.

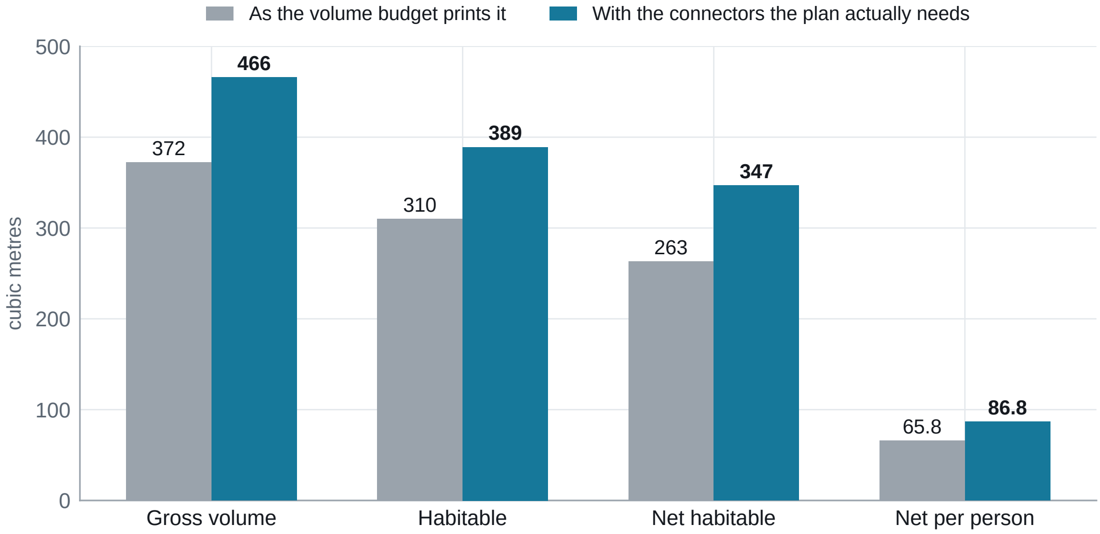


Figure 4.1. The same base, counted two ways. The grey bars are the design's own volume budget. The cyan bars are the same budget with connectors sized to the plan in chapter 2. A third of the base's usable volume sits in the difference between one line item and one drawing.

4.3 Mass: read it as a shape

Figure 4.2 is the mass budget, in the order the design lists it. Do not read it as a list. Read it as a shape, and one thing jumps out: the top bar is the building and the second is the power, and everything the base actually does fits into the short bars underneath.

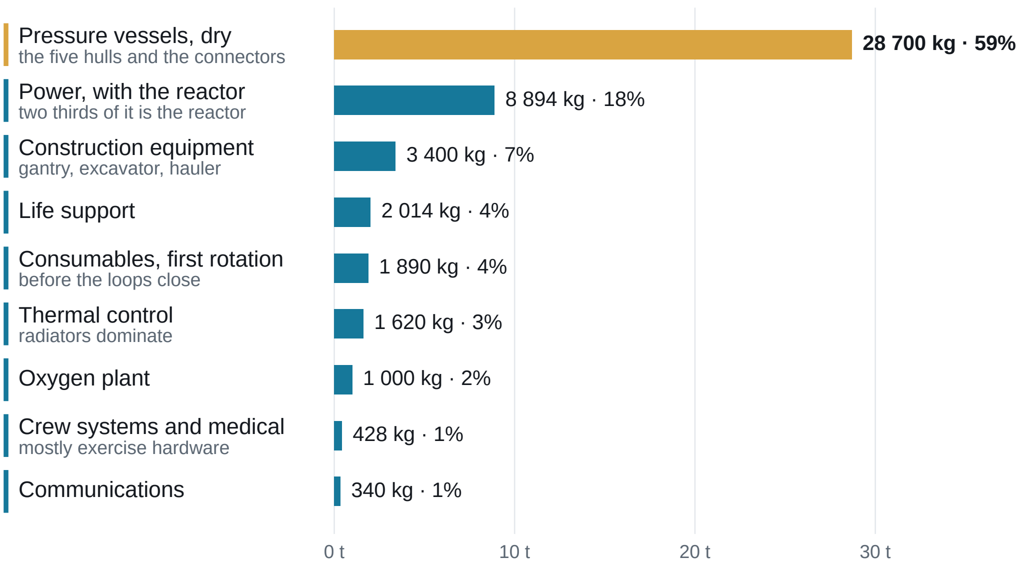


Figure 4.2. Landed mass by system, in kilograms, with each line as a share of the 48,286 kilogram total. The dry pressure vessels are the hulls themselves, so power, at 8,894 kilograms, is the heaviest working system on the site, and the fission unit is about two thirds of that line. Everything that keeps four people alive, fed and in touch with Earth comes to under 5 tonnes.

The total is 48,286 kilograms, and this column does add up. Whether it closes is a different question, and there is one line where the published record disagrees with it sharply.

The budget carries the fission surface power unit at 6,000 kilograms. NASA's own point design for a deployable 40 kilowatt lunar reactor comes out at 10,046 kilograms for the three deployed elements once mass growth allowance and system margin are counted, 8,929 without the margin, and 7,446 for the basic mass alone. NASA states plainly that its 6,000 kilogram goal was significantly exceeded. So the design is carrying a reactor about four tonnes lighter than the only comparable engineered figure in the literature, and four tonnes has to come from somewhere: it is eight per cent of the entire landed mass, and about four billion dollars at the landed rate.

> **Mass growth allowance.** The mass a design is expected to gain between paper and hardware, added deliberately at the start. Aerospace projects that skip it do not stay light; they simply find out later.

4.4 Power: the one that closes

Figure 4.3 is the load, subsystem by subsystem. Two things about it are worth noticing before any of the numbers.

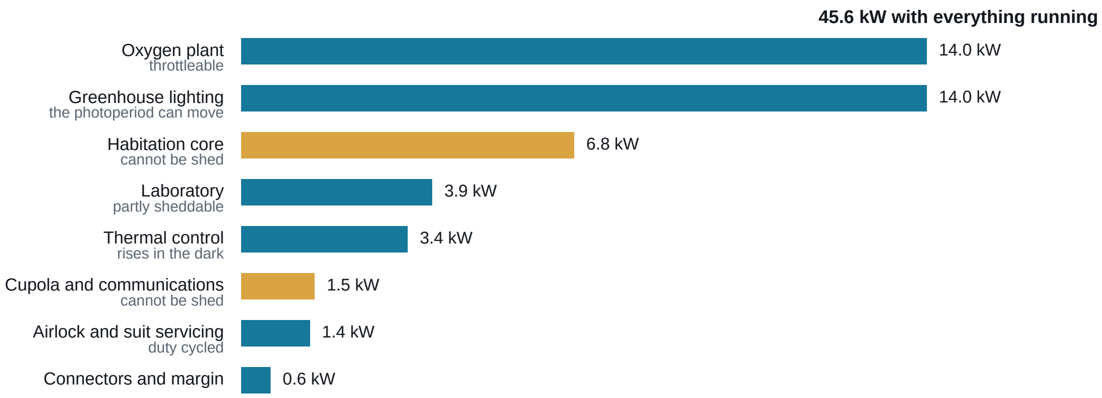


Figure 4.3. Continuous electrical load by subsystem, in kilowatts. Amber marks the loads that cannot be shed at all: the crew keep breathing whether the Sun is up or not. Everything here running at once comes to 45.6 kilowatts. The budget in the design's own documents totals 54.0 kilowatts for the same base, because it adds the 9 kilowatt construction gantry and leaves out the 0.6 kilowatt line for connectors and margin that this chart carries.

The first is that two loads dominate, and one of them is a surprise. The oxygen plant draws 14 kilowatts, which you might expect of a chemical works that takes rock apart. The greenhouse draws exactly the same, and a greenhouse is a room with salad in it. Photosynthesis is the only process on this base that has to manufacture its own sunlight, and manufacturing sunlight is expensive.

The second is that two documents describing the same base give two different totals, 45.6 and 54.0 kilowatts, and neither is wrong. They are counting different things. That is the commonest reason engineering numbers disagree, and the fix is never to argue about which total is right. It is to ask what each one counts.

This column closes, and it is the only one that does. Installed capacity is 48 kilowatts of array plus 40 kilowatts of reactor, and the 210 kilowatt hour battery was sized event by event against a list that came to 185, so the 25 left over is margin somebody actually wrote down. The cover disappears in a dark spell, when the array gives nothing and the reactor's 40 kilowatts sits below even the 54.0 of continuous demand, which is precisely why the plant and the gantry are built to be switched off.

WHERE PEOPLE GO WRONG

A column that adds up to its total row gets called a closed budget. It is not. Closing asks two more questions: can a lander put this down, and what is left over when it has? No line in this mass budget is called margin. The room it really has is the empty space in the last flight, which is a very different thing from a number somebody defended in a review, and it disappears the moment any single line grows.

WORKED EXAMPLE 4.1 · HOW MANY LANDINGS IS 48.3 TONNES?

A landed mass of 48,286 kilograms, and three published lander payloads: ESA's Argonaut at 1.5 tonnes, NASA's habitat ground rule of 12 tonnes, and the 15 tonne heavy class lander NASA told industry to assume in August 2025.

1. Divide by the European lander first, because it is the only one under contract.
   48 286 ÷ 1 500 = 32.2, so 33 flights
2. Now the 12 tonne class, which is the limit NASA sets because that is what a crew lander can put down.
   48 286 ÷ 12 000 = 4.02, so 5 landings
3. Now the 15 tonne heavy class assumed for the 100 kilowatt reactor.
   48 286 ÷ 15 000 = 3.22, so 4 landings

ANSWER Between four and thirty three flights, depending entirely on a vehicle that does not exist yet. Notice what the last step quietly assumes: that the base can be divided into four pieces, each of which fits inside a 15 tonne envelope and none of which needs to arrive before the others. A mass budget says nothing about that, and it is usually the thing that decides the schedule.

QUESTIONS

1. The core holds 112 net habitable cubic metres of its 148 gross, and the greenhouse 22 of its 54. Explain the difference from what each room is for. EXPLAIN
2. The budget carries the fission unit at 6,000 kilograms and NASA's point design comes out at 10,046. Find the difference, give it as a share of the 8,894 kilogram power line and of the 48,286 kilogram total, and price it at a million dollars a kilogram. APPLY
3. Explain why 88 kilowatts installed is never 88 kilowatts that a designer may plan on. EXPLAIN
4. Correcting the connectors takes net habitable volume from 263 to 347 cubic metres but adds hull, and hull runs at roughly 12 kilograms a square metre. Estimate what the correction costs in landed mass. CALCULATE
5. Two documents give the same base a load of 45.6 and 54.0 kilowatts. Reconcile them, and say which figure you would use to size a battery and which to size a reactor. APPLY

6 None of the three budgets carries a line called margin. Write the three margin lines you would add, say what each one is for, and say what you would cut to pay for them. EXTEND