How can a Lunar Starship stay cool on the Moon?

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Recently I was asked to analyze the thermal management of a Lunar Starship on the lunar surface.

Immediately I wondered, as I know many others have, "where are the radiators?"

(https://en.wikipedia.org/wiki/Starship_HLS#/media/File:Starship_HLS_Moon_landing.jpg)

The above artist's rendering shows a ~9.4m length of Starship covered, for the most part, by what appear to be solar panels, but there's no sign of radiators. This has led some to speculate the radiators might be on the other side, and this might be the case, but there is a problem with this solution. This requires a specific landing orientation to make sure the solar panels face the Sun, and the radiators are shaded.

Further, as the lunar day proceeds (29.5 Earth days relative to the Sun), the side facing the Sun will move around the ship, making stays of longer than a week or two infeasible. (It's worth noting here that many missions are expected to aim near the Moon's South Pole, where it's possible to get continuous solar coverage for months at a time).

Also, the rendering shows Starship's elevator at an angle to the viewer with solar panels extending to the edges of the view, giving a subtle visual cue that the solar panels probably wrap all the way around. (Far from conclusive evidence, I know.)

Others have suggested that maybe there are pop-out radiators that are not shown in the rendering. This is possible, though it's worth noting that the rendering shows quite a lot of detail regarding the elevator, supplies and a rover on the ground, communications equipment, landing legs and feet, landing thrusters, and solar panels. And the crew seems to be well on their way to setting up camp. At this stage, I'd expect any radiators that need to be deployed to be deployed, and to be shown in this highly detailed rendering.

There are a few other alternatives that come to mind (not to say these are the only ones possible), two of which I like:

1. The ship uses vented propellant (product of natural boil off) to cool the cabin.
2. The solar panels are actually combination solar-panel-radiators that generate electricity in the Sun and radiate waste heat in the shade.
3. The radiators are there (and not behind the solar panels), but we can't see them.

TLDR: Option (1) is good for brief stays of a few days (like a long Apollo mission) but not more than that. Options (2) and (3) are both good for indefinitely long stays -- with passive cooling at high latitudes and with active cooling at others (stays of a few days at low latitudes are also possible with passive cooling).

Let's analyze each of these possibilities.

Vented Propellant

Since we don't want to waste more propellant than necessary, I'm going to first try to estimate a low-ball figure for the prop boil-off rate.

We don't have a lot of details yet, but Starship's return mass to Gateway should be somewhere in the 80-130 ton range (note that this does not include cargo delivered to the surface). For determining how much propellant is available for use as coolant, using a lower mass figure provides a more conservative estimate, so I'll use 80 tons, though it doesn't make much of a difference in the end.

The approximate theoretical minimum for a lossless trip from the lunar surface to a surface skimming low lunar orbit followed by a Hohmann transfer to a 70,000km x 3,000km altitude NRHO is 2.38km/s. But this does not factor in gravity losses, a higher intermediate LLO, reserve propellant, docking maneuvers, or boil off. NASA describes this as an approximately 2.75km/s trip (20191030-NAC-HEOC-Smith-v3 pg 18 -- thanks for the link, EimajOzear). Again, for minimizing propellant available on the surface for a conservative estimate, let's go with a somewhat lower 2.6km/s.

With 380s isp Raptors doing the bulk of the ascent work, this gives us a propellant mass of a little over 80 tons, or roughly 50 cubic meters each for the liquid oxygen and the liquid methane, which can fit in two spherical header tanks with ~4.6m diameter.

On the one hand, this means that SpaceX might be able to fit all the ascent propellant into header tanks to minimize boil-off (this will effectively be a vacuum flask, at least for the methane tank, possibly for both) and extend surface stays. On the other hand, it might make this a less attractive option for cabin cooling.

So how much heat enters those tanks to boil off propellant?

I'm going to look only at sunlight directly hitting the outer tank walls and ignore minor heat sources like crew cabin and equipment and sunlight reflected from the surface, which for very high latitudes is really minimal. This is a reasonable simplification since we're looking for an approximation of a lower bound.

Solar heat flux absorbed into a surface is cos(theta)*solar_irradiance*(1-reflectivity), where theta is the angle of incidence (angle of sunlight relative to the line normal to the surface). I'll call this value H_in. This needs to match H_out from the wall surface, which is stefan_boltzmann_constant * temperature ^4 * emissivity.

The effective emissivity of the outer wall in this situation is the emissivity of the outer surface of the outer wall (the white paint) + a large fraction (more than 1/2, less than 1) of the emissivity of the inner wall. The balance of this fraction accounts for the part of the heat radiated inwards that's reflected back to and reabsorbed by the part of the outer wall that radiated it in the first place. This fraction will depend on geometry, but I'll approximate it as 3/4, since a bit of imprecision here doesn't matter, because the effective emissivity will be dominated by the outer surface and because we don't have very precise emissivity figures anyway.

The irradiance inwards is stefan_boltzmann_constant * temp^4 * inner_emmissivity.

Putting that all together we get:

inward_irradiance =
solar_irradiance*cos(theta)*(1-reflectivity)*inner_emmissivity/(outer_emmissivity + 3/4 * inner_emmissivity)

I'm also assuming, by the way, that there isn't a meaningful temperature difference between the outer surface and the inner surface of the outer wall. Whether this is a good assumption depends on whether the outer wall is covered merely in paint or a thicker insulating layer, but it's a pretty safe bet that if SpaceX manages to fit all the ascent propellant inside vacuum flasks, they probably won't bother with the added mass, cost, and complexity of an extra layer of insulation.

The inward irradiance will bounce around the low emissivity / high reflectivity stainless steel inner surfaces until it gets absorbed somewhere. It's reasonable to approximate this with the assumption that all the surfaces have equal likelihood of absorption.

This again depends on geometry, but for the sake of simplicity, I'll go with the infinite parallel plane approximation, which introduces a factor of ~0.5 (50% into inner wall, 50% into outer wall) relative to the cross sectional area of the inner wall in the plane normal to the incident light.

This gives us a tank heating value for a spherical inner tank of:

pi * tank_radius^2 * solar_irradiance * (1-reflectivity) * inner_emissivitiy / (outer_emissivity + 3/4 * inner_emmisivity) / 2

(The cos(theta) factor from earlier is rolled into the cross-section approximation for a low solar altitude angle, which we have at the poles.)

Using the following values:
tank_radius: 2.3m (from above)
solar_irradiance: 1.361kW/m^2

reflectivity: 0.85
outer_emissivity = 0.92

(reflectivity and emissivity figures for white silicate PSBN paint from https://www.acktar.com/thermal-control-coatings/)

inner_emissivity = 0.075 (room temp polished stainless per engineeringtoolbox.com) we get a heating rate in each tank of a little over 130W. This corresponds to propellant boil off rates of double digit kilograms per day, which is great for long term stays, but is not sufficient to keep things cool in the cabin.

Both methane and oxygen have a heat of vaporization comparable to their heat capacity at low temps * the ~200K temp increase to go from boiling point to ambient. So we're looking at a cooling potential on the order of 250W from this residual gas. (Note that these are very rough numbers intended to give an order of magnitude estimate just for determining feasibility.)

Also worth noting here that these values are so low that Lunar Starship might avoid surface boil off altogether by allowing propellant temperatures to rise a little.

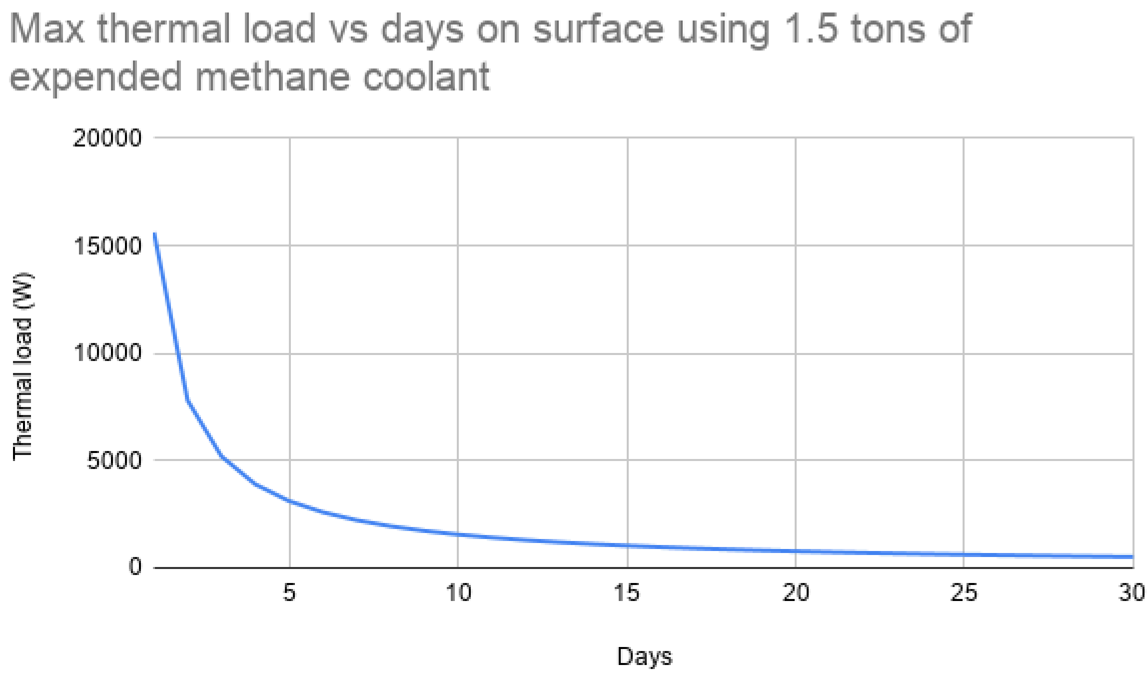
This all means that if we want to cool with propellant, we're going to have to use some that we wouldn't be venting anyway.

For mass efficiency, the best choice for this is methane, which has over twice the heat capacity of oxygen. With a heat capacity (for this temperature range) of around 2.15 kJ/K/kg multiplied by the ~185K temperature rise from its 1 atm boiling point to room temperature plus its 511 kJ/kg heat of vaporization, 1 kg of liquid methane can take away ~900 kJ of heat.

This solves the heat dissipation problem very simply, and could be the preferred method if the mass of propellant needed is not too high.

I'm going to guesstimate that somewhere in the general neighborhood of 1.5 tons (give or take a ton) might be the cut off where SpaceX might prefer a more complex solution that saves mass.

So what can we do with 1.5 tons of methane? Here's a graph of days vs thermal load:



As you can see, even at 8-10 days, we're down to 1.5-2kW. This is not going to be enough and is not scalable to a sustainable design. 4 astronauts alone generate nearly 0.5kW of body heat, and we don't have enough margin for all their equipment. Then add longer term stays, extra crew... won't do.

On to greener pastures...

Combination solar-panel-radiators

This is counterintuitive. Solar panels want to stay in the sun, and radiators want to stay in the shade. But what else are you going to do when the Sun moves around you in a big circle (from your perspective at the lunar South Pole) and you've got a circular surface to cover, and you want to minimize moving parts that can break, so you don't want to rotate your solar panels and radiators?

First, let's analyze those solar panels. We can evaluate their solar exposure as if it was a flat vertical panel with an area of 76m^2 facing the sun -- that's 9m diameter x 9.4m height for the vertical cross section multiplied by a factor of 0.9 to account for the part with the elevator and windows, which seems to be about 3m wide, or ~10% of the circumference. When we get away from the poles, dropping in latitude, we also have to take into account the solar altitude angle and reflected light:

generated_power = photovoltaic_efficiency * solar_irradiance * (
cos(solar_altitude_angle)*vertical_cross_section * +
sin(solar_altitude_angle)*lunar_albedo*total_panel_area/2)

That 1/2 factor for reflected light is the field of view factor for vertical solar panels receiving light from a virtually infinite horizontal surface.

I'm assuming the solar panels will not be cooled, because this would add greatly to the thermal load on the radiators. This will drive solar panel temperatures to the neighborhood of 350K. Specifically, it would be 356K in peak sun with PV efficiency 20%, reflectivity of 0.2, and emissivity was 0.9. This 0.9 emissivity figure may seem optimistic, but apparently, it's quite achievable -- https://www.sciencedirect.com/science/article/abs/pii/S0927024819300819.

This is not too harsh of an environment for appropriately designed solar panels to operate in, but it will lower photovoltaic efficiency, so I'll go with 20% efficiency for a moderately conservative estimate. This gives us peak power of 21kW. That's plenty.

Now's let's examine the ambient thermal environment affecting our radiators on the shady side. The external heat source we have to worry about here is the combination of the sunlight reflected from the surface of the Moon and the infrared radiated by the surface of the Moon. Since there's no atmosphere to temper it, surface temperatures during the long days will quickly rise, such that the sum of reflected + radiated will be about equal to incoming solar irradiance, or:

sin(solar_altitude_angle)*solar_irradiance.

Since the surface takes up about half of the field of view from the vantage point of the radiators (the half below the horizon), incoming radiation on the shady side will be about half that, or:

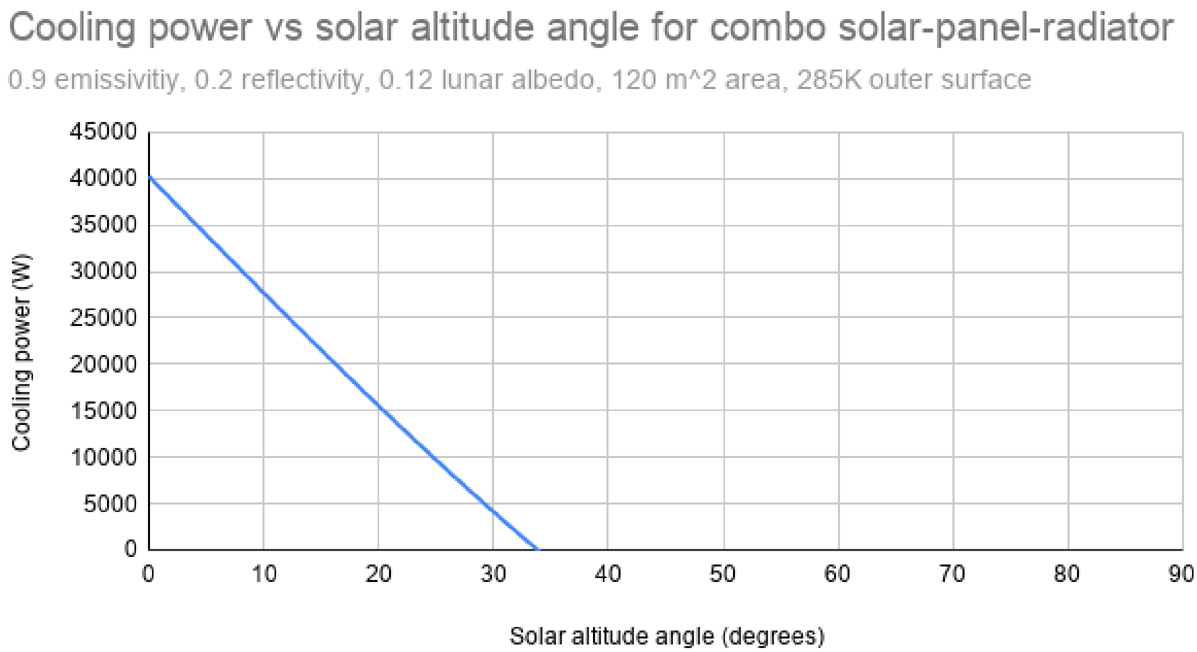
sin(solar_altitude_angle)*solar_irradiance/2

Heat flux into the radiators will be:

(lunar_albedo*(1-reflectivity) + (1 - lunar_albedo)*emissivity)*sin(solar_altitude_angle)*solar_irradiance/2

This is worst at high noon at the equator, when the solar altitude angle is 90 degrees. This is enough to drive our combo radiators, to ~330K, too high to be useful as radiators. Given how long a lunar day is, This would likely necessite using a different cooling mechanism in these conditions or avoiding these conditions altogether.

With passive cooling and a temperature drop of 10K from ambient to outer walls, here's a graph of cooling power vs solar altitude angle for this system:



Note that the highest solar altitude angle is high noon, and is about 90 degrees minus latitude for a planetary body like the Moon that doesn't have much of an axial tilt. We can see from this graph that this system will work well at latitudes above 60 degrees, but at lower latitudes, it can only handle relative short stays at times other than midday.

Will this be acceptable for NASA? Maybe. It's certainly good enough for a polar Moonbase, as well as for boots and footprints missions anywhere else.

A few final issues to address here:

1. How do you make sure to only use the radiator surfaces that are in the shade? The answer is to circumferentially segment the radiator, to have an insulating layer between the radiator pipes and the inside of the ship, and to only run coolant through the segments that are in the shade (easy to determine automatically, since these are the segments that will not be generating nearly as much power).

2. Are the solar panels thermally conductive enough for there to not be a significant temperature drop across them? Yes. SpaceX will likely be using thin film solar cells, but even if we were looking at the equivalent of a few millimeters of glass between the radiators and the outer surface, the temperature drop across the panels would be on the order of 1K.

Radiators Elsewhere

Where else might there be radiators in the ship shown in the rendering? Behind the white paint. Specifically, in the cone above the cabin.

A standard Starship has a liquid oxygen tank at the tip of the nose cone, where it serves to balance the center of gravity for a belly flop descent through an atmosphere. Lunar Starship will not perform an atmospheric belly flop and has no need for this. Instead, it has a docking port at the tip, and it's safe to assume that the cone volume between the docking port and the solar panels is habitable space.

For a Lunar Starship, the oxygen header tank can go inside the main oxygen tank, or even potentially left out altogether. Leaving it out would dramatically increase the propellant boil off rate, but it could still work for stays of up to a few weeks, and the absence of the header tanks would partially offset the extra propellant mass. The simplicity might be worth it, at least for initial variants.

Back to the radiators...

Based on measurements of the rendering and Starship's 9m diameter, the painted section of the nosecone appears to have a 8.3m base diameter, 1.8m tip diameter, and a 7.5m height. Approximating it as a conical section yields an area of ~157m^2. In reality, the curvature will make the area somewhat larger, so this is a conservative estimate.

Average heat flux from direct sunlight is:

(1-reflectivity)*solar_irradiance*solar_cross_section/area

Instead of trying to calculate the projection of a cone, which itself is an approximation, I'll use the quadratically weighted average of these two approximations for the solar cross section:

For low solar altitude angles, a triangular cross section approximation:

solar_cross_section[low_altitude_angle] ~= area * cos(solar_altitude_angle+theta)/pi

For high solar altitude angles, a flat disk approximation:
solar_cross_section[low_altitude_angle] ~= (pi * base_radius^2) * sin(solar_altitude_angle)

Heat flux from light reflected by the surface is:

(1-reflectivity)*lunar_albedo*solar_irradiance*sin(solar_altitude_angle) * field_of_view_factor where field_of_view_factor is (pi/2-theta)/pi.

Heat flux from IR radiated by the surface (at max steady-state surface temperature) is:

emissivity*(1-lunar_albedo)*solar_irradiance*sin(solar_altitude_angle)/2 * field_of_view_factor

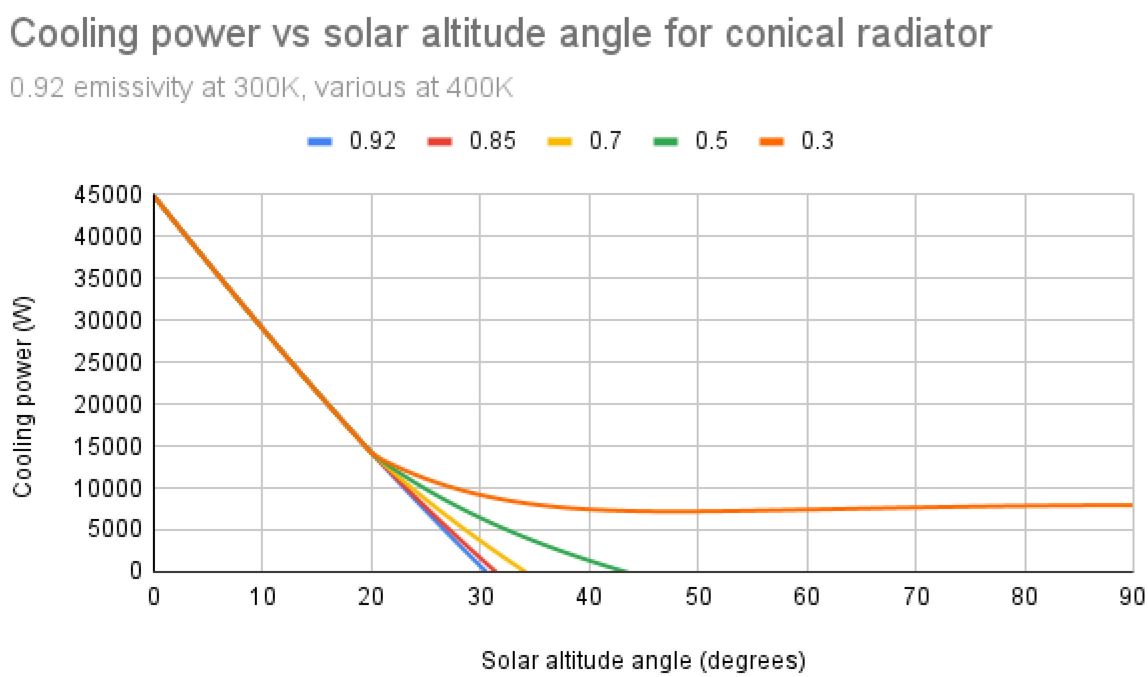
Subtracting all these from heat flux radiated out at wall temperature and multiplying by area gives us the cooling capacity.

Unfortunately and surprisingly, it turns out that the performance of this system is slightly poorer than that of the combo solar-panel-radiator setup at high solar altitude angles. The effective radiator area is somewhat larger than that of option (2), but while the reduced absorption of IR and reflected light from the solar surface (thanks to the cone angle and reflectivity) is more than countered by the limited but still significant absorption of direct sunlight.

The conclusion is the same: with passive cooling, it is good for indefinite stays at high latitudes, but only for short (multi-Earth-day) visits at lunar dawn to other locations, similar to Apollo missions.

With one caveat. So far, we've been assuming that the emissivity of the white paint at our desired wall temperature (~285K) is the same as its emissivity at the temperatures of the lunar surface, which can reach as high as 400K.

In theory, it could be made lower at those higher temps, for improved radiator performance. I don't know what the emissivity for PSBN paint is at 400K, though it's apparently 0.15 around 5800K (absorbance at solar surface temperatures). Here's a graph of conical radiator cooling power vs solar altitude angle for steady-state conditions with a lunar albedo of 0.12, lunar emissivity of 0.9, and a series of hypothetical paints with 0.85 reflectivity, 0.92 emissivity at 300K and various values of emissivity at 400K, approximated with a linear drop in emissivity from 300K to 400K:



To enable passive cooling at all solar altitude angles, though, we need a very low emissivity (around 0.3 or lower). This seems unrealistic.

The performance of option (3), then, is similar to that of option (2).

Active Cooling

What if NASA did want to send Starship on multi-week or multi-month missions to lower latitudes? With the vehicle shown in the rendering up top, without additional visible radiators, this would require active cooling -- running heat pumps to drive heat from the cabin to higher temperature radiators.

This is doable. But first, let's question why NASA would want to do such a thing. Without getting too off topic, it becomes apparent after thinking about the lunar day/night cycle that non-polar multi-month crewed operations doing substantial scientific research would likely need a base with a far more robust power system than what a lander alone can be expected to provide over two continuous weeks of darkness every month.

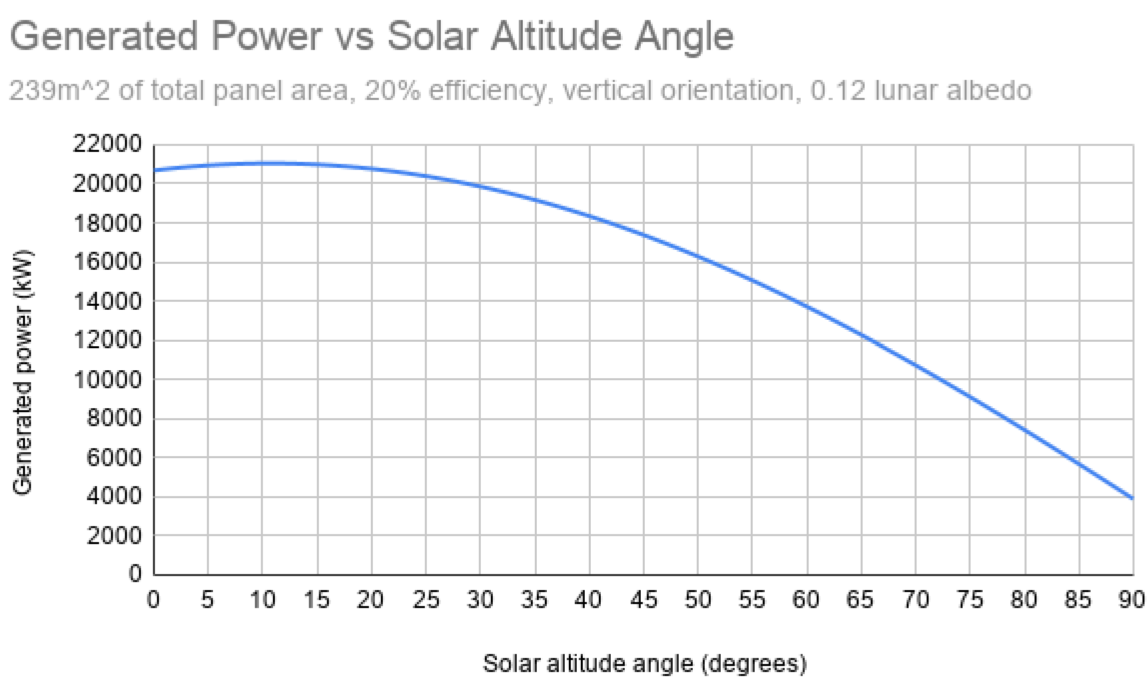
This means that if/when such a mission becomes desirable, a reasonable design constraint would be that the lander should be usable as an emergency shelter and as an emergency escape vehicle, but not as a base of operations for long duration non-polar missions.

This will mean that the lander should be able to keep the crew alive and cool at all times, but it dramatically cuts down on minimal power requirements. This is helpful for the cooling requirements, as well.

The performance of option (2) (radiators in the nose cone) with emissivity going from 0.92 at 300K to 0.85 at 400K is very close to the performance of option (3) (combo solar-panel-radiator) (a bit better at low solar angles, a bit worse at high solar angles). I'll use the former for this analysis, but note that the conclusion of this analysis will apply just as well to option (3) -- if option (3) can do it, so can option (2).

I'll use steady-state IR emission for the lunar surface for a conservative estimate. In actuality, the surface temperatures and IR emission curves for the surface will be smoothed out a little by the heat sink effect of the regolith, such that peak emission never quite reaches steady-state values, and also occurs a little past high noon, when there's more solar power available to help with cooling.

At this point, it makes sense to plot the power generation curve to see how much solar power is available for cooling and other equipment.



It's worth noting that the solar panels have near peak performance throughout the solar altitude angle range for which passive cooling will work -- throughout the lunar day above 60 degrees latitude, or for several Earth days at lunar dawn/dusk at lower latitudes.

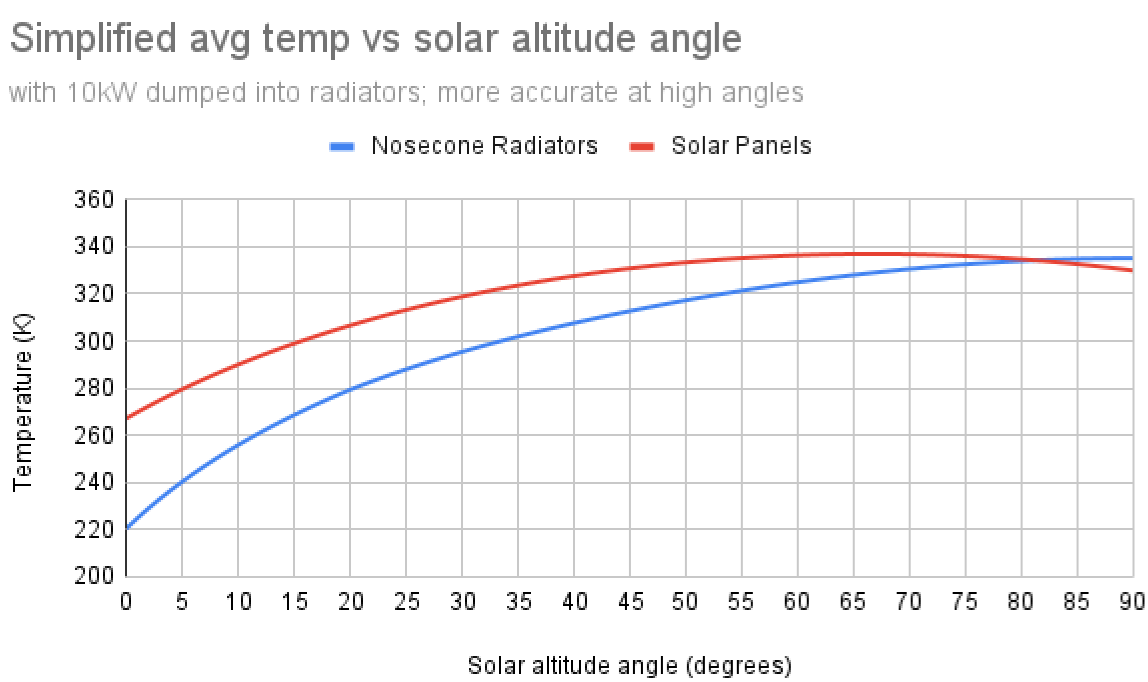
At high altitude angles, generated power drops sharply. In fact, the graph is not continuous

when plotted through the day, with generated power dropping most rapidly near high noon, then flipping and rising rapidly past high noon.
We see that we have 3.9kW of electrical power generated at the minimum. Let's budget 3kW of that for minimum continuous power requirement not including active cooling. This may not seem like a lot, but it's actually quite generous, seeing as how it basically just needs to cover minimal electronics, lights, comms, and air circulation. It's also over an order of magnitude more than what the Apollo Lunar Module had with less than 20kWh of battery capacity with a design life of 75 hours.

We also want the skin temperature curve to see how much of a temperature difference there will be driving heat into the cabin conductively. For the latter, I'll calculate average temperatures for the two regions (solar panel and white paint) as if the heat flux was uniform across each surface.

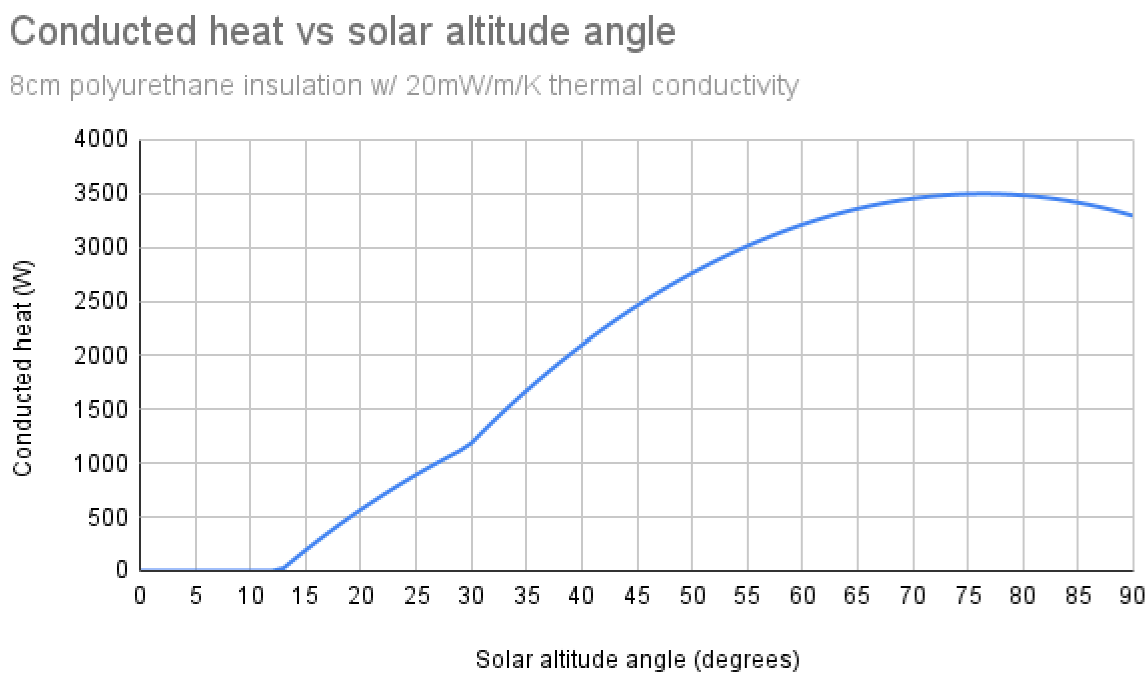
This is an accurate simplification for high solar altitude angles where we'll have peak thermal load. For low solar altitude angles, the heat flux will be highly uneven, and the average temperature will be lower (because of the T^4 relation of radiated heat to temperature), but there will be more thermal conduction because hot spots will exceed cabin temperature even at low average temperatures. This effect will be far more prominent for the solar panels than for the radiators.

I'm also factoring in a conservative estimate of 10kW of heat dump into the radiators.



There will of course be some kind of insulation for the crew cabin. Let's try 8cm thickness of

polyurethane foam with 30kg/m^3 density and 20mW/K/m thermal conductivity. The height of the cabin section covered by solar panels appears to be around 4.7m. Including the bottom surface, this yields a cabin surface area of ~354m^2, such that we need ~850kg of insulation. This seems reasonable for a 80-100 ton ship.
Conservatively estimating with the simplifying assumption that the bottom surface of the cabin will reach solar panel surface temperatures, we get this graph for heat conducted into the cabin:



We didn't factor conduction as a cooling source for the solar panels. We also haven't factored in heat sink effects in the insulator (or the cabin). This makes our skin temperature estimate and heat conduction estimates more conservative.

In the case of the radiators, we'll be pumping heat back, so we'll factor in conductive cooling there when confirming that our 10kW estimate for load on the radiators is above the maximum real load for the minimum operational scenario we're evaluating.

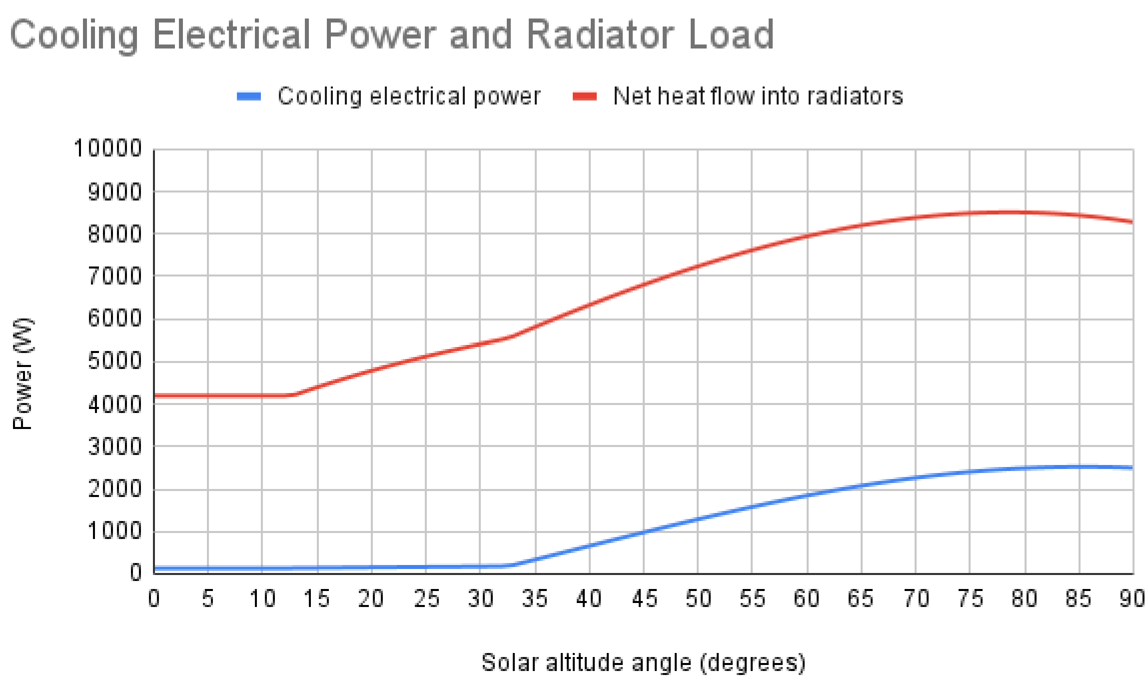
Conversely, I'm ignoring the windows, which have a potential to be a significant source of heat transfer. My assumption here is that in minimal operating conditions at high temperatures, the windows can be covered on the inside with reflective screens and insulating foam.

Heat pumps have a theoretical maximum coefficient of performance (COP) that describes the maximum ratio of heat pumped to power expended. This value is cold_side_temp/(hot_side_temp - cold_side_temp). In practice, highly efficient heat pumps apparently achieve approximately half this COP (https://en.wikipedia.org/wiki/Coefficient_of_performance) for a 35K difference over a 273K base temperature. I'll estimate the COP[cooling] for Starship's cooling system as 40% of theoretical max.

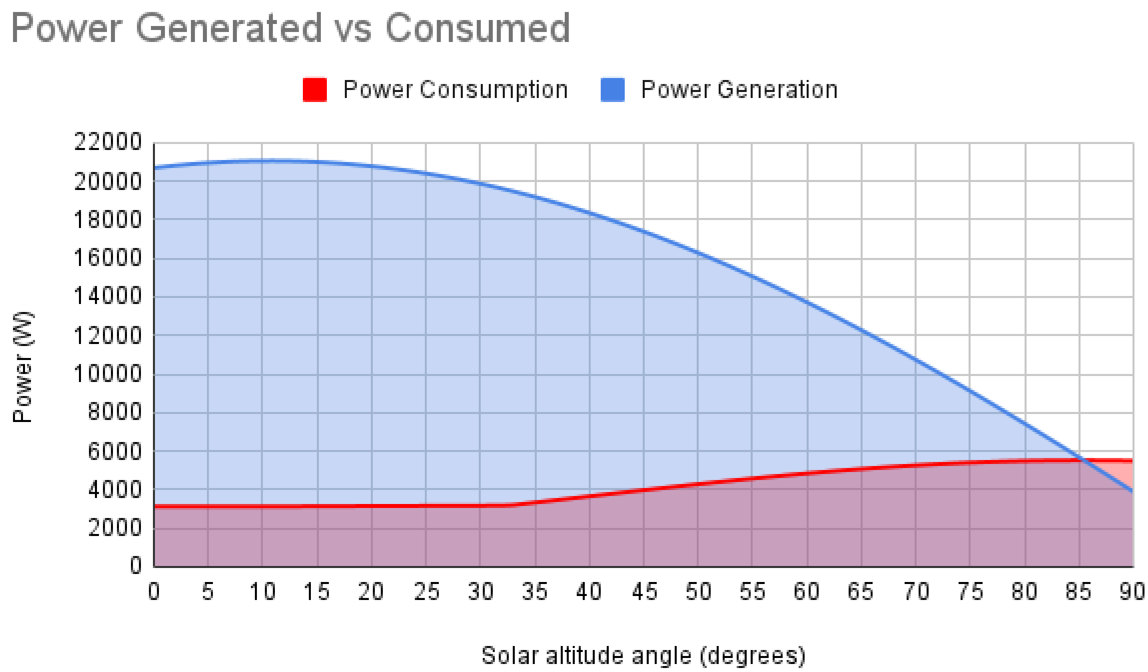
The heat the cooling system needs to pump out will be the heat transferred into the cabin via conduction + body heat generated by the astronauts (107W per person at 2200kcal/day) + heat generated by the chemical reactions in the CO_2 scrubbers (26W/person for lithium hydroxide for 1.05kg CO_2/day) + the 3kW we budgeted for electrical equipment besides the cooling system (this is conservative, because some of this equipment will likely be operating uncooled outside the crew cabin).

The net heat load on the radiators will be the heat that's pumped + electrical power used by the cooling system - the heat conducted from the radiators into the cabin.

For a generous crew size of 8 (twice the maximum currently considered for Artemis), we get:



Heat flow into the radiators stays well under the 10kW we budgeted. Electrical power needed for cooling is also quite manageable, staying under 3kW, but this does briefly drive total power consumption beyond what's generated by the solar panels. Here's the graph for that:



This works out to about 17.4kWh over the course of a lunar day at the equator -- the hottest scenario we need to worry about.

Batteries are the most obvious solution, though it works out that fuel cells or generators using onboard methane and oxygen can be mass competitive for a high single digit number of cycles (and depending on the use case, we'd have 1-2 cycles per lunar month). Let's go with batteries for simplicity and for an upper bound.

Even with a whopping 750% excess capacity (which will come in handy in case of solar panel failure, battery failure, or landing in a particularly dark location), we're looking at 150kWh of battery capacity, which at a battery energy density of 250Wh/kg works out to 600kg of batteries, and higher energy density batteries are already entering the commercial market. Again, a reasonable figure for a ship of this size.

A tangent: these batteries won't last very long powering 3kW of electrical equipment during lunar night, but if being used as emergency shelter, one of three options should be available:

1. Cut power even more (air circulation, periodic comms, and a few Ws worth of lighting are pretty much the only absolute necessity).
2. Abort to orbit.
3. If abort is not an option, and this is going to be a long-term stay, waiting for rescue, it should be okay to use up ascent propellant in fuel cells / generators.

What it comes down to is that with active cooling using radiators either behind the solar panels or in the nose cone, thermal management is manageable during multi-month stays at any latitude.

In Orbit

You might ask "what about in orbit?"

Low lunar orbit is very similar to the surface in terms of IR emitted by the Moon and reflected sunlight, but it has two distinct advantages. The biggest is that a spacecraft can choose its orientation. The second is that a "day" in low orbit is only about two hours, so periods of high thermal load from the surface are very brief. Insulation, combined with the heat capacity of the ship and cabin, will serve well to smooth out temperature extremes. Thermal regulation in low orbit is without question easier than that on the surface.

The other orbit in question, NRHO, where Lunar Starship will likely spend most of its time (at least when not on the surface), is even easier from a thermal management perspective. There's much less in the way of radiation from the lunar surface to worry about. Starship can simply orient itself optimally with respect to the Sun and it'll be more than fine. As noted above, a low solar altitude angle (equivalent to facing the Sun sideways), provides around 20kW of electrical power without adding much in the way of thermal load. If that's more electrical power than needed or desired, Starship can turn its tail partially sunward, reducing generated power and further reducing thermal load at the same time.