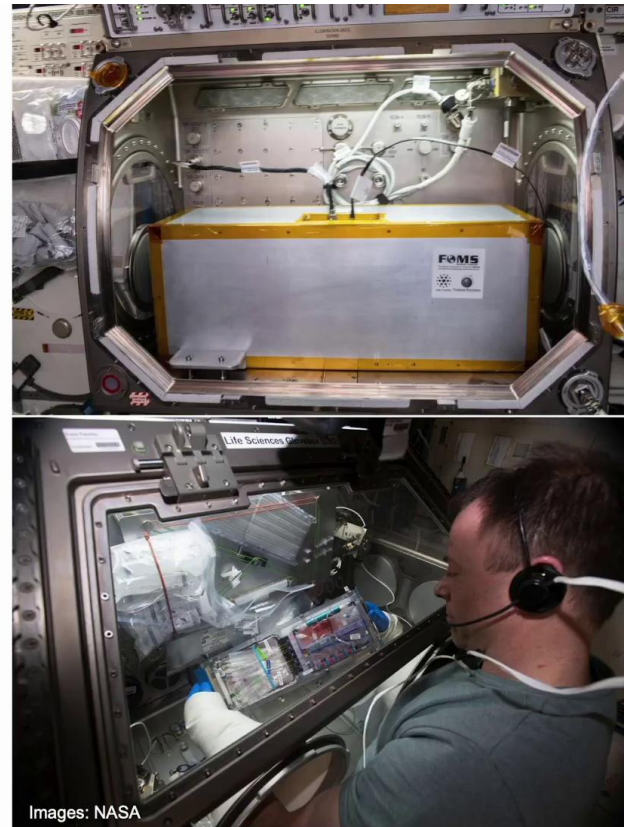




# Manufacturing in space



Welcome back. In this lecture, we will talk about manufacturing in space. Now that sounds really futuristic, right? And in a way, it is. It is an example of a space business that is really only starting to emerge now. Different from, for example, satellite communications or remote sensing, which have been around for decades in one form or the other. It is emerging now because some of the key trends we have seen in previous lectures substantially that space is getting so much cheaper both accessing space and operating in space. Nevertheless, we do not yet have any production facility, no factory or anything like this, producing anything at scale in space. This is yet to come, and several companies are working on that. We have, however, conducted many experiments in space that are relevant to production in space. And that is what you see on the pictures on this slide, both are on the International Space Station. On the upper right, you have what we call a glovebox for the manufacturing of special fibre, fibre optics. On the lower right, another glovebox, this one for life sciences. And materials and life sciences are arguably the two key use cases for in-space manufacturing. And we will talk about that a few slides on. First though, I should delineate the scope of this lecture.

Notes

Summary



# Manufacturing in space



- **Manufacturing in space can be**
  - for in-situ use (in space) vs.
  - for use on Earth, in terrestrial markets
- **Focus on locations in LEO (e.g. ISS)**

Now when we talk about manufacturing in space, we can actually divide that into two classes. First, you can actually manufacture things in space for use right there in space. You do it because it may be too complicated or slow or costly to bring things along in a rocket from Earth, especially when we're very far from Earth in places like the moon or Mars. We can and we do regularly resupply the International Space Station, but you can imagine the moon and Mars logistics, that gets much more complicated. Even if you're close to Earth in orbit, it may still make sense to manufacture things there rather than bring them from Earth. For example, there's a company called Made In Space, which is developing a satellite in conjunction with NASA that can 3D print its own thrusters along which you could then deploy solar cells. And the advantage here is that it's easier to fit a 3D printer and the raw materials into a rocket fairing than an unwieldy big finished satellite structure. In any event, this space for space manufacturing is not the topic of this lecture. We will focus on the second type of space manufacturing, and that is manufacturing in space for use here on Earth.

Notes

Summary

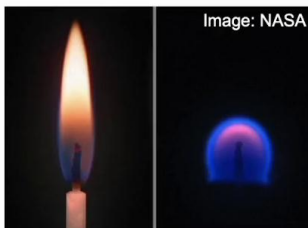


1m 30s

# Why use space as a location for manufacturing?

## Special conditions found in space

- Microgravity
- Hard vacuum
- Other – e.g. radiation, temperature



## trigger special phenomena, e.g.

- 3D growth
- No convection
- No buoyancy
- Ionization by radiation
- Physiological impacts on organisms

## which enable / facilitate e.g.

- Crystal growth
- Emulsions, foams
- Binding of materials (e.g. via CVD, ALD, laser annealing, MBE techniques)
- Study and use of organisms exposed to space

You go to space, you manufacture something, and you bring it back to Earth for consumption by customers here. And that also means that plans for this type of manufacturing usually envision it taking place in places close to Earth, specifically in low Earth orbit. Let's take a closer look. Now why would we even want to produce something that we want to use on Earth in space? Doesn't that seem unnecessarily complicated? Well, the answer lies in the special conditions we find in space, namely microgravity, a hard vacuum, and all sorts of radiation that is around there. Now why do those conditions matter? Well, those conditions, especially microgravity, have consequences which are interesting. And those are the ones you see listed here. And you can see one impressive example, a demonstration of such an effect, which is comparing what the flame looks like under 1G conditions on Earth on the left, and it's the sort of flame we're all familiar with. And then look what a flame looks like in zero-G. Now those secondary effects, so to say, they mean, in turn, that you can do some things in space which would be much harder to do on Earth, or even not possible at all. And those you can now see in the last column.

Notes

Summary

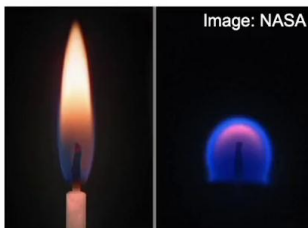




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And just to explain a few terms here, and you might notice anywhere, an emulsion is basically a mix of two liquids that usually are separate in phase, and it's easier to create emulsions and mixing liquids that don't usually mix on Earth in space. The same holds for foams, and a foam is a mix of a gas with another material that's either in a liquid or a solid state. And there's some other abbreviations here, and I won't go into detail, but basically CVD, ALD, MBE, those are all methods to combine materials, and it goes beyond the scope of the course. Just as an example, CVD, that means chemical vapour deposition, and ALD is atomic layer deposition. Okay, I had mentioned before that the two main use cases for manufacturing in space for Earth are materials and life sciences. So let's take a closer look at each one of those.

Notes

Summary



3m 54s

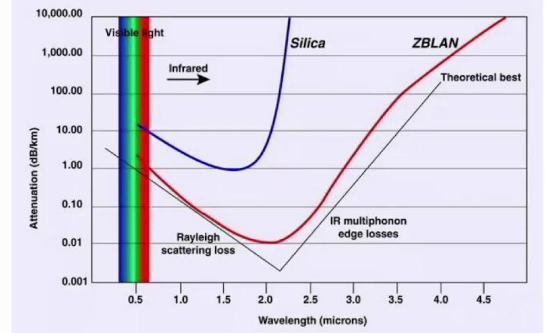
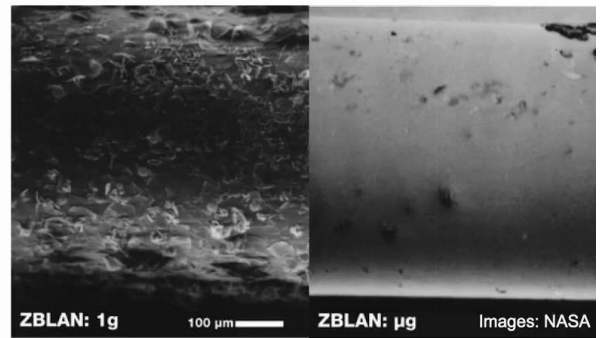
# Key use case categories: materials

## ▪ Examples of materials

- ZBLAN optical fiber
- Alloys, composites, ceramics, glasses
- Synthetic diamonds
- Graphene
- Biofilms
- Emulsions

## ▪ Example industries

- Semiconductor and other advanced electronics
- Telecommunications
- Renewable energy (solar cells)
- Food industry



Let's start with materials. One type of material we know makes sense to produce in microgravity from the experiments we've done is a special type of optical fiber called ZBLAN. And look at the picture on the top right. On the left side, you have a closeup, a microscopic image of ZBLAN produced under 1G, that is terrestrial conditions. On the right side, you have ZBLAN produced under microgravity conditions. And I think it's quite visible to the eye that the ZBLAN that was produced under microgravity condition is much purer. This has certain consequences which are shown in the graph on the bottom right, effectively means that this micro-G produced ZBLAN has fewer signal losses, and that's obviously something that is desirable and for which customers may be willing to pay a premium. Now, ZBLAN is by far not the only material that it makes sense to produce under microgravity conditions. We're listing some more here on the left hand side. And again, all of those take advantage of some of these in-space conditions and effects that we have seen on the previous slides, things like special alloys, composites, ceramics, even synthetic diamonds. Biofilms, emulsions, we already talked about.

Notes

Summary



4m 43s

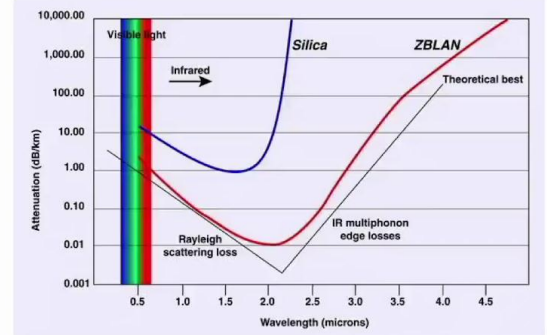
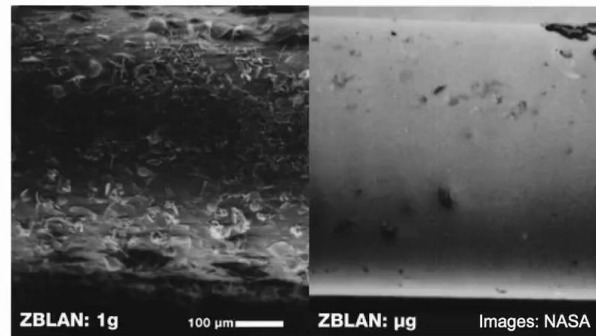
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## ■ Example industries

- Semiconductor and other advanced electronics
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- Food industry



And one important aspect here is that many of these materials have potential target customers in existing very large sectors on Earth, like the semiconductor sector or telecommunications. So those are huge potential target markets, which may, of course, help to make those space businesses economically-viable businesses. Okay, we could spend a lot of time here, but let's move on to life sciences.

Notes

Summary



5m 55s

# Key use case categories: life sciences

## ▪ Drug development

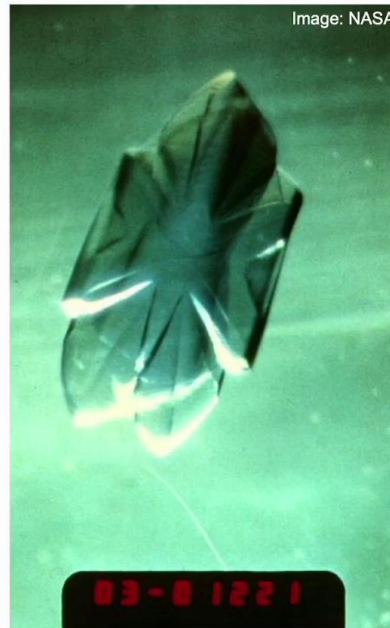
- Protein crystallization
- Human and animal model studies
- Organoids for testing
- Delivery systems

## ▪ Other therapies

- Monoclonal antibodies
- Replacement tissue and entire organs

## ▪ Orthopedic devices

## ▪ Agricultural use cases – e.g. crops



Protein Crystal Growth Isocitrate Lyase



ISS-aged French wine

There's also a lot of things you can do where you use the space conditions with regard to life sciences applications. As we mentioned before, things naturally grow in three dimensions under microgravity. And that, for example, allows you to grow organ tissue and eventually even entire organs without using what we call scaffolding on Earth. Basically, on Earth, under 1G conditions, if you don't use scaffolding, the organ mass would just collapse on itself. We can also grow better protein crystals, which helps in drug discovery. And you can see a nice example here on the left-most picture. This is a very nice crystal of something called Isocitrate Lyase, and it's an enzyme that is important for some plants, fungi, and bacteria. And inhibiting this specific enzyme can, for example, treat tuberculosis. And in order to design this inhibition, you want to know the structure of the enzyme very well. And this is why I said that this can help us in designing drugs. Now certain things also happen to the human body in space, for example, aging processes, bone loss, even genetic changes. And that allows us to study these phenomena in space and use that research to help us address these conditions, and maybe find cures for them.

Notes

Summary



6m 19s



# Key use case categories: life sciences

## ■ Drug development

- Protein crystallization
- Human and animal model studies
- Organoids for testing
- Delivery systems

## ■ Other therapies

- Monoclonal antibodies
- Replacement tissue and entire organs

## ■ Orthopedic devices

## ■ Agricultural use cases – e.g. crops

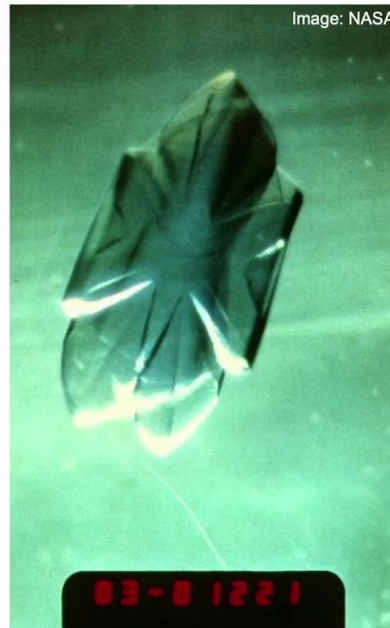


Image: NASA

Protein Crystal Growth Isocitrate Lyase



Image: Space Cargo Unlimited

ISS-aged French wine

This has already been happening. For example, research done back in the days of the space shuttle helped in the development of several osteoporosis, that is, bone loss drugs. And there are some other things listed here for completeness, for example, monoclonal antibodies and drug delivery systems. And again, we could spend a lot of time here, but we shall move on. Importantly, the life sciences use cases in space are not limited to humans, even though that's mostly what I've been talking about so far. You can also study seeds and plants, and their responses to space conditions. And that may help us to understand how to maybe make better and design better seeds, in the sense of more resilient seeds, which may help us with things like food production on Earth. There are company is looking at those applications. For example, there's a startup in Luxembourg called Space Cargo Unlimited that has recently taken some grape wine plants to the International Space Station, has already brought them back, and they're currently being analysed to see what the space conditions did to those plants. For good order, as you can see here on the right-hand picture is they actually also took some bottles of wine, some very nice French red wine Pétrus, to the International Space Station to see how the space conditions would impact the wine. And that wine is about to be auctioned off.

Notes

Summary



7m 28s

# Microgravity manufacturing platforms



## What conditions do you require?

- The specific space condition (e.g. vacuum)
- Volume (m<sup>3</sup>)
- Time in space
- Temperature and other env. variables
- Power consumption
- Human intervention or not?
- Flight profile (e.g. max. g forces)
- Others

Okay, let's say you identified a compelling material or life sciences product to produce in space. You now need to find some sort of platform where you can actually do that manufacturing. For example, a space station. In thinking about that, and ultimately, maybe even to compare platforms, you need to have a few variables in mind, which are listed here. Those include the specific space condition you need for your manufacturing, so microgravity or a hard vacuum. The volume you need, the time you need to spend in space, things like the temperature or maybe pressure, and other variables like that. Power consumption needs, always very important in space. Do you need astronaut help, that is, human intervention, or not? And you also should think about the flight profile, how much g force can your raw materials take on the way up and how much g forces can your finished product take on the way down.

Notes

Summary



8m 40s

# Microgravity manufacturing platforms



## Platforms available now or possibly soon

- ISS (but...)
- SpaceX Dragon free flyer
- Tiangong space station
- X-37B (but...)
- SNC Dream Chaser
- Space Rider (?)
- Custom spacecraft with re-entry capability, e.g. Space Forge, Varda
- Axiom station
- Blue Origin (?)



So let's now talk about some of the specific platform options that are either already available now or expected to become available in the not-too-distant future. And of course, the first one would be International Space Station. So our main platform right now, but it was never designed to be a manufacturing platform, it was designed to be a small-scale government laboratory. And hence, it's really not an ideal environment for manufacturing. There are astronauts around and there's, of course, environmental control systems which keep the astronauts alive, and that may actually introduce some contamination, which is not great for many manufacturing processes. And by the way, besides being inside the International Space Station, you can actually also be outside if you want things like a hard vacuum, for example, on something called the Bartolomeo platform. You could use SpaceX's Dragon capsule as a free flyer, and you can see it here in the bottom picture. China just sent up a space station, a new one, the Tiangong Space Station, and that may be interesting to use as a platform as well. Then there's something called the X-37B space plane in the US, but it's very secretive and is pretty much restricted to military use.

Notes

Summary



9m 35s



# Microgravity manufacturing platforms



## Platforms available now or possibly soon

- ISS (but...)
- SpaceX Dragon free flyer
- Tiangong space station
- X-37B (but...)
- SNC Dream Chaser
- Space Rider (?)
- Custom spacecraft with re-entry capability, e.g. Space Forge, Varda
- Axiom station
- Blue Origin (?)



In the middle picture, you have something called the Sierra Nevada Dream Chaser, and this is another space plane that's about hopefully, will come online very soon. And the Europeans also have a reusable capsule called the Space Rider. Then there are private companies, startups, working specifically on spacecraft platforms optimised for the manufacturing process. And clearly, such spacecraft must have a re-entry capability to bring finished product back, among other things. And that's not entirely trivial. You need things like a heat shield, recovery method. And that's what those companies are working on, companies like Varda in the US, or Space Forge in the UK. Axiom, another American company, is working on building a space station. Initially, they seem to be focused on the tourism use case, but there's no reason why they would not be able to re-purpose that for manufacturing at a later point in time. And Blue Origin, Jeff Bezos's space company, is also widely expected to ultimately build space stations, which could again, be used for manufacturing. There are some other potential platforms, but I think this gives you a good idea of what's currently out there and what might be out there in the near future.

Notes

Summary

10m 42s





# Manufacturing in space – as a business



## ▪ Business models

- Manufacturer (using somebody's microgravity platform)
- Platform provider
- Service broker
- Vertically integrated

## ▪ Need to understand the microeconomics



- All-in cost of producing e.g. 1 gram or kilogram of a material
- Achievable market price per g / kg

## ▪ Can it be simply done on Earth?

Okay, let's finish up talking about the business of manufacturing in space. What are the main ways for you to get involved in terms of business models? And you can see them listed here. You can be a business that has the product expertise and can handle every aspect that we got from designing the production process to actually selling the final product. You would then need to find a platform where you can execute a manufacturing. And that is, of course, what we previously discussed on the last slide. And it's, of course, also the second type of business model. You could just be a platform operator that rents out the platform to other people. You could be a kind of service broker which brings the first and second type of businesses together and helps executing the entire mission, and there's companies, startups out there that are focusing on that service. And lastly, as always, you could be a fully-integrated player that does everything. You have the platform, you take care of everything, and you design the production process, and you sell the product. It's imperative to understand the microeconomics of your proposed manufacturing business. After considering all of the variable cost, can you achieve a positive gross margin?

Notes

Summary



11m 48s

# Manufacturing in space – as a business



## ▪ Business models

- Manufacturer (using somebody's microgravity platform)
- Platform provider
- Service broker
- Vertically integrated

## ▪ Need to understand the microeconomics

- All-in cost of producing e.g. 1 gram or kilogram of a material
- Achievable market price per g / kg

## ▪ Can it be simply done on Earth?

That is, is the price, say, per gram of material to produce, is it higher than the total variable cost for that same gram? At the moment, this is probably only valid for a few very-high-valued products, but the cheaper space gets, the more products become economically viable in this sense. Lastly, you should always ask the simple question of whether you can not just produce your intended material right here on Earth with the same quality and desired specs. Nevertheless, as we have seen, it truly seems that there are some materials right now where it starts making sense to produce them in space. And as I mentioned, we expect that number to go up. So this is a very exciting business to watch.

Notes

Summary



12m 57s