# AEROSPACE ENGINEERING AND THE ENVIRONMENT

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Aerospace is a moving industry comprising aeronautics and astronautics. Humans were nomads in the remote beginning, settling down 10 000 years ago, but the need for travelling remained: for exploration, commerce, or survival. Transportation means have progressed a lot, from the horseback to planes, passing by boats, trains, cars..., but the need to be provisioned (food and drink), to be prepared for a possibly hostile environment (cloths), and to get rid of waste (cleaning), goes on.

Aerospace engineering has many types of environmental problems to solve, some of them intrinsic to the fly at high altitudes and beyond (and at very high speed), which must be solved before any attempt to go there (like cabin pressurization and air revitalization), and some other problems which impose non-immediate restrictions, but are important in the long term (like noise, air pollution, ionising radiation, space debris..). The two ways in the interaction, environment-to-vehicle and vehicle-to-environment, must be analysed (and not only the vehicle, but the whole aerospace infrastructure should be considered).

Many different aspects of the aerospace environment have an influence on aerospace vehicle design and operation, namely:

- The mechanical environment
    - Low pressure to vacuum (hypobaric environment).
    - The gravitation environment: from hypergravity (e.g. at launch and reentry, 3 g in STS, 5 g in Soyuz), to microgravity ($10^{-6}$ g on ISS).
    - Mechanical disturbances:
        - External perturbations: winds, aerosols (e.g. droplets, ice crystals, ashes), residual debris, micrometeorites...

        - Internal perturbations: vibrations from the propulsion system.
- The radiation environment
    - Electromagnetic radiations.
    - Atomic and subatomic particles.
- The chemical environment and its weathering effects; e.g. oxidation, corrosion, ionization, ablation; contamination by exhaust emissions and materials outgassing, fuel tank inertization...
- The electrical and magnetic environment, including light strike effects.
- The thermal environment; e.g. cold environment, solar heating, aerodynamic heating, effect of contrails in climate change...

Every industrial activity has its own environmental problems, not only during operation, but from design to dismantlement), with astronautics perhaps being at the summit of the problem, and a space suit the more drastic solution, although just achieved for a few hours.

As for most industries, aerospace energy use has a major contribution to environmental impact. Aerospace vehicles demand large power plants for propulsion (except orbiters), for navigation control (sensors, processors, and actuators), for communications, for thermal control, and for payload accommodation (environmental comfort for goods and people). Efficient energy management of the power plants (main and auxiliary), the electric and electronic systems, and the hydraulic and pneumatic systems, from the conceptual phase of design to operations and maintenance, is important not only environmentally, but for economic an safety enhancements.

For aviation, an industry that transported 2200 million passengers in 2010 and is expected to double every 20 to 25 years, environmental problems are becoming stringent (you may look at the Clean Sky initiative at http://www.cleansky.eu/):

- Fossil-fuel dependency. All present aircraft use crude-oil derivatives as fuel (notably Jet A-1). On-going research tries to bring biofuels aboard. The target for 2050 to reach a 50% share on biofuels has been stated.
- Greenhouse gas emissions. In 2010, aviation accounts for 3% of all man-made $CO_2$ emissions (expected to grow to 5% in 2050). Complete fossil-fuel dependency and low fuel efficiency must be ameliorated. Passenger-specific $CO_2$ emissions, some 100 g/(pax·km) for long-range jetliners (but some 250 g/(pax·km) for domestic flights), are similar to other means of transport: around 60 g/(pax·km) by train, 80 g/(pax·km) by bus, and 150 g/km by modern cars (130 g/km for new cars from 2012 in EU).
- Local physical, chemical, or biological pollution must be minimised (e.g. noise generation, exhaust emissions, disease spreading). And not only the effects on the outside environment but on the inside too (e.g. allow some local temperature control to each passenger by individual air nozzles, lower the typical 70 dB cabin noise level, avoid mixing breathed air with fresh air to avoid possible disease spreading, and so on).

We here restrict the attention to the control of the aerospace environmental for safe flight, leaving aside unwanted effects.

# ENVIRONMENTAL CONTROL SYSTEM IN AIRCRAFT

(Extracted from Environmental control system in aircraft.)

## Aircraft cabin air conditioning

Imagine you are in a close container; the first thing to care about is air for breathing (and air is not only the oxygen provider, but the pressure and temperature environment). Human comfort is best at 22±2 ºC, 90..100 kPa, and natural fresh air composition with 50..70% RH. The major difference between aircraft and ground air-conditioning is the wide pressure changes in the environment and inside an aircraft during a mission.

### Pressurization and oxygen control

An adult at rest normally breathes some 0.5 L of air in normal conditions 12 times per minute. This tidal volume may go up to 2 L in deep gasps, and the breath rate may go up to 120 breath/min on panting). Intake composition (fresh air) is 77% $N_2$ + 21% $O_2$ + 1% $H_2O$ + 1% Ar + 0.04% $CO_2$, and exhalation is 74% $N_2$ +17% $O_2$ +4% $H_2O$ +1% Ar +4% $CO_2$.

Indoors ventilation design standard is to supply 5 L/(s·pax) of air renewal with (conditioned) outside air, plus 5 L/(s·pax) of air recirculation (filtered). Notice the difference between room-ventilation airflow (>5 L/(s·pax)) and respiration airflow (0.5×12=6 L/(min·pax)=0.1 L/(s·pax)), because ventilation is needed not only for the lungs, but for heat and odours removal.

Ambient air at 10 km altitude is at 26 kPa and −50 ºC (too thin, and too cold). Both, pressure and oxygen fraction are important because what matters for the flow is chemical potential, depending on the product $x_{O2}p=p_{O2}$ (oxygen partial pressure). Safe range for prolonged exposure is $p_{O2}$=18..40 kPa. As atmospheric pressure decreases with altitude, either cabin pressure or oxygen fraction should be increased to keep $p_{O2}$ on range. Pilots on unpressurised cockpit need oxygen masks for $z$>3 km, and pressurised garments for $z$>15 km (to avoid ebullism, i.e. the boiling of aqueous fluids, which at 37 ºC boil at 6.3 kPa, 19 km ISA altitude, known as Armstrong limit).

Each passenger and crew compartment must be ventilated and each crew compartment must have enough fresh air (but not less than 0.3 $m^3$/min STP), with CO<50 ppm, $CO_2$<0.5% (it was 3% up to 1997), $O_3$<0.25 ppm, and particle filter for >10 nm (for virus; tobacco particles are much larger, some 10 μm). Cabin air is renewed every 2 or 3 min. The cockpit has a larger air supply to keep a little overpressure against the main cabin (to avoid gases in).

In the conventional air-cycle air-conditioning system, the whole aircraft is pressurised by bleed air (bled at 250 kPa from engine compressor, upstream of combustion chambers) supplied to the conditioning packs at some 450 K (180 ºC) with a pre-cooler, and controlled by outflow valves to keep cabin pressure above 75 kPa (equivalent to 2400 m altitude).

Pressure control is based on outflow valves (and safety valves):

- Safety valve overpressure is limited to $\Delta p \equiv p_{\text{int}} - p_{\text{ext}} = 65$ kPa for structural reasons.
- Safety valve depression is limited to $\Delta p = -7$ kPa to avoid structural collapse (controlled by a spring loaded flapper valve).
- Overpressure during normal operation is limited to $\Delta p < 55$ kPa by the main outflow valves (i.e. SLP cannot be maintained at $z > 6$ km).
- Sonic valves at lavatories and kitchens provide a constant independent outflow at those locations.
- A sudden change in cabin pressure $\Delta p > 3$ kPa (equivalent to $\Delta z = 300$ m near sea level) cause pain and vertigo.
- Rate of change in cabin pressure is limited to $\Delta p / \Delta t = 1$ kPa/min (equivalent to $\Delta z / \Delta t = 1.5$ m/s) to avoid ear problems (one may relieve it by swallowing).

Oxygen masks automatically drop down in case of sudden cabin depressurisation at altitudes above 5 km. Lung air is vented, and consciousness may be lost some 30 s after.

### Humidity

Human comfort demanding a relative humidity of 50..70%, but cabin air in airliners only have 10..20% RH on long flights, and just because of the water vapour released by passengers, $m_{\text{w,gen}} = 50$ g/(h·pax), since outside air is practically dry at the freezing environmental temperatures. There is also a reason to keep those very low humidity values inside the plane: to minimize problems of condensation and frost on the cold aluminium structure. New aircraft using more corrosion-resistant composites in their construction, are being designed to operate with a cabin relative humidity of 15..20%, providing more comfort on long flights.

In spite of the low cabin humidity, a mist may form by vapour condensation in the event of sudden cabin depressurisation.

### Thermal loads and design cases

Comfort air supply demands $T = 18..30$ ºC depending on heating or cooling needs, without thermal chocks, i.e. $T - T_{\text{cabin}} < 5$ ºC, and without drafts (i.e. $v < 0.2$ m/s close to people and <2 m/s anywhere). Outside humidity is very small at high altitudes, and is kept very low inside to minimize problems of condensation and frost on the cold structure (there are water sinks at the cabin wall bottom). Air enters at cabin ceiling, and exits at floor sides. Floor, lateral walls and ceiling are also heated/cooled to help comfort.

The thermal loads are:

- Heat loss through the fuselage (but it is an input on ground in summer).
- Heat release inside: avionics, passengers and crew, kitchen, lighting and entertainment.
- Worst hot case:

  - On ground at a hot and humid place, aircraft full, doors closed. Refrigeration must be able to cool from 47 ºC to 21 ºC in <30 min.
- Worst cold case:
  - On ground at a cold and humid place, aircraft empty, doors closed. Heating must be able to heat from –40 ºC to 24 ºC in <30 min.

To satisfy the air-conditioning needs in flight and on ground (we want a cabin air renovation flow of 5 L/(s·pax) at 75..100 kPa and 22 ºC), different systems can be used, e.g.:

- Up to 1950, only heating was available (from engine heat recovery, electrical heaters, or burners).
- A vapour-cycle system like in car's air conditioning (best with heat-pump capability), supplemented with a separate ventilation system. This is most used in small aircraft.
- An air-cycle system that provides both heating/cooling and ventilation. This is the standard in medium and large aircraft because of its compactness and reliability, in spite of its poor energy efficiency (its operation cost is typically 1 kW/pax).

The typical air-cycle conditioner pack works as follows:

- Air is bled from the main engine compressors, at around 250 kPa and hot (180 ºC, due to adiabatic compression). As pressure and temperature of bleeding depends on compressor stage and spinning rate, this pressure is regulated by having two or three bleedings at different stages and a mixing control valve.
- The hot bled air requires cooling, but a simple heat exchanger (HE) with outside air is not efficient (a big HE is needed to cool that amount of air from 200 ºC to 20 ºC, particularly at low altitudes). The air-cycle machine (ACM) is based on an inverse Brayton refrigerator. First, a HE drops the bled air stream from 200 ºC to 110 ºC; then, a compressor with pressure ratio around $\pi_{12}$=1.8 rises the air to 210 ºC, and a second HE lowers the temperature again to some 100 ºC. Afterwards, air passes through a turbine and exits at about 10 ºC, to be mixed with some cooled bled air at around 100 ºC to get the 15 ºC or so (it depends on operation phase) needed to keep a mean 22 ºC, when accounting for internal heat release (passengers and equipment), outside heat gain and loses, and air recirculation.
- Ram air is used as a heat sink. It is captured through a diffuser, and forced by a fan (driven by the ACM turbine) to go through the two heat exchangers mentioned above, and the exhaust nozzle.
- Two equal ACM half-nominal systems are implemented, to allow for one failure.

## Aircraft environmental protection system

### Against high temperature

Usually due to aerodynamic heating

- Airliners flying at $M \equiv v/c$=0.85 at 10 km altitude ($T$=–50 ºC, $c=\sqrt{\gamma RT}$ =300 m/s, $v$=250 m/s) suffer a dynamic temperature jump $\Delta T_{\text{dyn}}=v^2/(2c_p)$=32 ºC.
- The Concorde flying at $M$=2 at 17 km altitude ($T$=–57 ºC, $c=\sqrt{\gamma RT}$ =295 m/s, $v$=590 m/s) suffer a dynamic temperature jump $\Delta T_{\text{dyn}}$=174 ºC.

- Spacecraft during re-entry are exposed to very hot dissociated ionised air that may reach 10 000 K at the frontal shock wave layer (the rule-of-thumb is to assume the maximum air temperature in kelvins to be equal to the entry speed in meters per second); the outer skin must withstand up to 2000 K at their nose and other stagnation points, either by suitable refractory materials, or most often by ablation.

### Against ice formation

Protection against very low temperatures in aircraft is needed to avoid ice formation, and to avoid freezing of internal liquids (fuel, hydraulic liquid, lubricant oil, sanitary water…). Aircraft take-off is forbidden with ice or snow on wings and controls. An ice thickness of 1 mm on the leading edge may decrease lift up to 30%. All aircraft must be able to heat up the leading edge (by bleeding hot air, or electrically), or de-ice by other means (ancient rubber bands, or modern electromagnetic striction pulses).

Anti-ice protection is needed on:

- Structure
  - Wings, flaps, wind-screen, tail,
  - Sensors (pitot, static, antenna)
  - Water discharge (sanitary, condensates).
- Engines
  - Nose cowling: a streamlined metal covering, esp. one fitted around an aircraft engine.
  - Guide blades.
  - Propellers, if any.

Visual clues for ice formation:

1. Light icing: ice under the windscreen wiper blades.
2. Moderate icing: ice on the wiper nut.
3. Severe icing: ice on the central windscreen pillar.

Electrical ice detectors are based on magneto-strictive resonance change. A magnetic cylinder (6 mm diameter and 25 mm long) is axially vibrated with an oscillating magnetic field, and the extra ice mass lowers its resonant frequency. When $\Delta f$>150 Hz ($\delta_{ice}$>0.5 mm), an internal heater melts the ice and a counter is updated; after two heating cycles, the engine-anti-ice system is switched on; after 10 cycles, the wings anti-ice system too).

## ENVIRONMENTAL CONTROL SYSTEMS IN SPACECRAFT

Spacecraft missions and the space environment.

### Satellite thermal control

Heat transfer and thermal radiation modelling

## Space Station ECLSS

Physical-chemical methods of life support have been used as far back as the Mercury, Gemini, Apollo, and Skylab missions to maintain breathable air, clean water, and a safe environment. However, the importance of environmental control and life support systems (ECLSS) grow with standing time, so that they are the most advanced in space stations. Current practice to create a liveable environment in space for short-time crewed missions is to carry on board $H_2O$, $O_2$ and $N_2$ storage vessels, and get rid of carbon dioxide, water vapour and black waters. $CO_2$ can be removed by physical absorption, or by chemical reaction, usually with an hydroxide like in $CO_2(g)+2LiOH(aq)=Li_2CO_3(s)+H_2O(g)$, or better by revitalisation as already done aboard MIR: $CO_2(g)+2KO_2(s)=K_2CO_3(s)+(3/2)O_2(g)$; it seems also interesting for the future to combine it with hydrogen from water electrolysis: $CO_2(g)+2H_2(g)=C(s)+H_2O(l)$.

Different space stations may be considered:

- In orbit, like the present International Space Station (ISS).
- On the Moon and other celestial bodies without atmosphere.
- On Mars and other celestial bodies with some atmosphere.

The environmental control and life support system of the ISS, located in Node 3 (since 2005, formerly on Zvezda Service Module) has the following tasks.

- Air management
  - Maintain total cabin pressure. There are oxygen and nitrogen tanks attached to the outside of the ISS with gas lines running all throughout, not only for pressure control but for experiments aboard.
  - Maintain cabin temperature and humidity levels.
  - Ventilate, i.e. distribute and renovate cabin air through ISS modules.
  - Remove carbon dioxide from the cabin air. Two systems based on non-expandable absorbers (i.e. with regeneration) are used: the Carbon Dioxide Removal Assembly (CDRA, from USA) and the Vozdukh unit (from Russia).
  - Filter the cabin air for particulates and microorganisms.
  - Remove volatile organic trace gases from the cabin air.
  - Monitor (with mass spectrometers) and control (by gas supply or removal) cabin air partial pressures of nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapour.
  - Detect and suppress fire.
- Water management
  - In the Space Shuttle, waste water was vented out in a frozen form (solid wastes was compressed and stored aboard until landing). In the ISS most of it is recycled; urine is carried away through a hand-held aspirated funnel attached to a flexible hose ending in a rotating chamber that separates liquid and air.
  - Store and distribute potable water. For a crew of six, the annual need is some 7900 kg of water (55% for drink and food preparation, 28% for oxygen production, 11% for urine

    flush and 6% for hygiene). Only 1600 kg/yr of fresh water is uploaded, since the rest is recycled (nearly half and half from air condensation and urine).
  - Recycle wastewater to produce drinking (potable) water, from urine, from humid-air condensate, from oral hygiene and hand washing, and from the Space Shuttle's fuel cells when docked). This is a three-step process. The first step is a filter that removes particles and debris. Then the water passes through the "multi-filtration beds," which contain substances that remove organic and inorganic impurities. And finally, the "catalytic oxidation reactor" removes volatile organic compounds and kills bacteria and viruses. Two wastewater recyclers exist in the ISS (one from USA, the other from Russia).
  - Use recycled water to produce oxygen for the crew by electrolysis. Besides, even with intense conservation and recycling efforts, the Space Station gradually lose water because of inefficiencies in the life support system (the water recycling systems produce a small amount of unusable brine; the $CO_2$ removal systems leach some water out of the air), and air that's lost in the air locks takes humidity with it. Additional water might be produced from $CO_2$ waste (using some $H_2$ from the electrolysers) in a Sabatier reaction, $CO_2+4H_2=CH_4+2H_2O$, perhaps recovering the hydrogen by methane pyrolysis, $CH_4=C+2H_2$, and thus minimising the waste to dump.
- Solid waste management
  - The first space toilets were installed in Soyuz (1967-) and Skylab (1973-1974, in orbit until 1979), mainly to obtain precise samples of urine, faeces, and vomit, for examination on Earth. Before, only nappies were used by space crews.
  - A fan-suction toilet (called WCS: Waste Collection System) was available in the Space Shuttle (1981-2011) middle desk.
  - There were two space toilets (ASUs) on Mir (1986-2001). There was also a shower, but the functionality was very poor.
  - Presently there are two toilets on the International Space Station (similar to the Space Shuttle's WCS, in Zvezda and Tranquility modules), plus one in the Soyuz capsules attached (at least one always available for crew rescue).

Operation of life support systems, including thermal management, is centralised in the Environmental and Thermal Operating Systems (ETHOS).

## Space suit ECLSS

A space suit (first used in 1961) is a complex system of garments and equipment designed to keep a person alive and comfortable in the harsh environment of outer space (and usually to provide mobility too), i.e. the vital protection against vacuum and other mechanical and non-mechanical stresses (thermal, radiation…). Space suit proper is required for extra-vehicular activity (EVA), but different space suits can also be worn inside spacecraft for safety redundancy in some mission phases (launch and re-entry).

Fig. 1. Claude Nicolier repairs HST in STS-103 (1999).

A space suite for extra-vehicular activity must provide:

- Body pressure, at a stable value above the minimum of 18 kPa for blood oxygenation. USA space suits are regulated to 30 kPa (the Shuttle and the ISS are at 100 kPa). Russian and new NASA suits are pressurized to 56 kPa, shortening the pre-breathing period from few hours to <20 min (presently, NASA astronauts sleep for 8 h at the airlock at 70 kPa before going out EVA). Mind that 100 kPa overpressure is the same as for a pressure cooker. In 1971 the crew of Soyuz 11 died when their spacecraft depressurised during re-entry.
- Breathing control ($O_2$ supply and $CO_2$ and $H_2O$ removal). As USA space suits are regulated to 30 kPa, they use pure oxygen (a tank with 0.54 kg $O_2$ at 52 MPa), not air. The astronaut must pre-breathe pure oxygen for 1 h before donning (suiting up), to eliminates the nitrogen from the blood and tissues. Lithium hydroxide canisters in the backpack remove carbon dioxide.
- Thermal control. A blackbody suit for EVA at low Earth orbit might reach 100 ºC on the sunlit and −100 ºC in the shade. Since it is very difficult to control heat removal by radiation, all TCS are based on heavy insulation from the environment, and metabolic heat removal by convection to a water-boiler evaporative cooler (there is not enough surface are to use a heat radiator). At the beginning, fans/heat exchangers were used, to blow cool air through an umbilical, as in the Mercury and Gemini programs). Nowadays, since the Apollo program, temperature is regulated by a liquid cooling body garment, heavy insulation on feet and hands, and additional heating in the gloves; the garment has a plastic tube sewn between two a nylon layers, holding some 0.25 kg of water, being fed at constant rate from a 4.6 L tank in the backpack, with manual regulation of the water inlet temperature. To prevent microbial growth in this water loop, iodine ions or silver ions are added. Suits are externally white or metallised to avoid solar heat gains. If metabolic heat is not removed, the sweat produced by the astronaut will fog up the helmet visor, and cause the astronaut to become dehydrated. The cooling water loop transfers heat to a separate water loop fed from a 3.8 kg pressurised water tank that ends at the ‘sublimator‘, an evaporative cooler opened to outer space through a porous plate that regulates water flow according to heat flow up to a maximum dissipation of 600 W (water in the sublimator freezes when heat flow decreases). Overheating caused several crises on the first space walks in the

Voskhod and Gemini programs (astronaut Eugene Cernan lost several pounds during his spacewalk on Gemini 9).
- Mobility (see suit types, below).
- Communication (radio, visual, and electrical). The astronauts wear headsets with microphones and earphones. The helmet visor is made of polycarbonate; over the helmet, there is a solar reflector cap, a clear impact-resistant cap, two blinders, 4 head lamps (to see into the shadows) and a TV camera. There is a wire connector between the suit and the backpack, for power lines, and signal lines (radio-comms, and bio-instruments for monitoring of the astronaut's vital signs: respiration rate, heart rate, temperature, etc.).
- Electricity to power all active systems (sensors, controls, actuators, and displays), from batteries in the backpack. There are several types of batteries used to power the suits' equipment: lithium-ion batteries power up the suit, a nickel metal hydride battery is used for the lights and heated gloves, and nickel cadmium batteries are used to power the drill (e.g. 11 zinc cells connected in series may provide up to 27 amp-hours).
- Urine and faeces collection nappy (from Latin *mappa,* small cloth: a disposable multilayer cloth filled with cellulose and a chemical absorbent, sodium polyacrylate). Current EVA last many hours, and it takes too much time to pressurize and depressurize both the spacesuits and the airlocks/spacecraft, astronauts cannot simply go inside the spacecraft and use the toilet. A 1.9 L drinking water bag is available inside the upper side of the suit, with tubing up to mouth reach. There is also a slot in the helmet for a rice-paper-covered fruit-and-cereal bar that the astronaut can eat, but it is rarely used (to avoid crumps).
- Radiation protection for UV, subatomic particles and micrometeorites.
- Mechanical protection to bumps, punctures, and dust (particles on Mars are very small, like talcum powder).
- Propulsion (if not tethered), by means of compressed nitrogen rocket manoeuvring devices.

The backpack of a spacesuit is the Portable (Personal) Life Support System (PLSS, http://en.wikipedia.org/wiki/Primary_Life_Support_System). The entire space suit (for EVA) is also known as Extravehicular Mobility Unit (EMU).

## Space suit types

- Hard-shell. Early space flight suits (from 1930s high-altitude pilots to 1975 Apollo-ASTP) were hard-shell suits with bearing joints (like old sea-bottom divers), both for emergency and for EVA. Little manoeuvrability.
- Gas pressurised flexible garment with some rigid parts (helmet, part of torso with all connectors, waist seal, and rear entry hatch if any). They are hard to manoeuvre; 80% of astronaut work is spent against the pressurised gas and elastic garment. The explanation is as follows: at rest, a perfect flexible non-elastic garment, inflated to a pressure $p$, has maximum volume, $V$; any flexible deformations at constant area reduce the volume and increases the pressure, so the gas gets a work input of $-\int p\mathrm{d}V>0$. Any elastic contribution requires additional energy expenditure. Locomotion on Earth requires some 0.6 J/(kg·m), i.e. some 40 W for a 70 kg person walking at

1 m/s, and it seems to be just the same for displacements on the Moon ($g$=(1/6)$g_0$), under microgravity ($g$<$10^{-6}g_0$), and at Mars ($g$=(3/8)$g_0$): some 5 J/(kg·m).

- Elastic pressurised skin-tight garment with some rigid parts (helmet, and part of torso with all connectors) are under development. They have good manoeuvrability because they are smaller, have no gas, and the elasticity is along the skin neutral lines; i.e. the required body pressure is provided by a net of elastic fibres going along the lines of neutral deformation of the skin (if a circle is painted on part of the skin at rest, it becomes an ellipse when stressed, with two directions having no strain). They have no depressurisation problem (for previous types, a small puncture in the suit is mortal in 10..30 min, depending on hole size). And they are much cheaper (may be from \$10 million to \$0.1 million).

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