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Considerations for Passenger Transport by Advanced Spaceplanes

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One of the strongest incentives to space industry development in the 21st century is likely to be space tourism. At present the greatest handicaps to the exploitation of this opportunity are the prohibitive cost of access to space (few tourists could afford the ticket) and safety (astronautics remains an inherently dangerous occupation). This paper addresses both of these issues. First, the characteristics required of a vehicle suitable for carrying passengers into space are discussed in the context of the SKYLON spaceplane concept. Attention is focused on the design of the cabin module. Then the needs of the passengers are considered both from the perspectives of safety (the unique environmental hazards), health, and comfort. The paper concludes with a review of the key issues.

Keywords: Space tourism, spaceplanes, SKYLON, passenger safety

1. Introduction

Space tourism is now being openly discussed in the literature. To address this topic conscientiously, a review of the key issues involved in space passenger transport is in order.

2. Passenger Expectations

Imagine the space passenger arriving at an established spaceport, with a view to travelling to some orbiting habitat, either for business or leisure. This person is not a trained astronaut, but simply a reasonably fit and able traveller.

It is instructive to make a list of the key expectations in this person's mind:

- The flight will be safe, even allowing for partial engine failures and other minor malfunctions; that is, there will not be a disaster resulting from any identifiable single failure mode.
- The flight will be reasonably comfortable, even during acceleration and periods of micro-gravity.
- When staying in orbit, the habitat will provide appropriate work or leisure facilities, but will also provide partial, artificial gravity in "hotel" areas for sleeping and washing, etc.
- The return to Earth will be safe, making due allowance for re-entry deceleration.

The above list is included to show that much as today's travellers put their trust in an airline, so tomorrows will expect the same from the spaceplane operators. This "trust" is based on both the track record of the vehicle and the benign experience of other travellers.

The track record of the spaceplane will be based on the following parameters, which are the minimum necessary to achieve international certification.

- Normal flight operations are safe and incorporate adequate reserve factors.
- Safe, proven abort modes exist for all phases of flight, including partial engine-out sorties.
- Proven evacuation procedures exist for both emergency Earth landings and orbital rescues.

3. Vehicle Characteristics

At present, only vehicles that have "airliner-like" characteristics would fit the requirements listed. (This is largely driven by a study of the abort modes for every part of the flight profile).

The most critical areas for any aircraft are take-off and landing, so these need to be satisfied first. Then follows (unique to spaceplanes) safe re-entry corridors and adequate cross-range for landing.

The above, fundamental parameters will tend to eliminate vertical take-off machines where, in particular, a thrust reduction in the early climb results in disaster.

Reaction Engines Ltd. has been studying the SKYLON vehicle for some ten years, primarily for use as a commercial satellite launcher. However, when viewed in the light of these "passenger" requirements, the SKYLON vehicle appears eminently suitable. It is basically a hypersonic aircraft with hybrid engines that can continue to climb to orbit changing their mode of operation as the vehicle leaves the atmosphere. On return, because it is an aircraft, it has a high cross-range capability, terminating its flight by landing on a runway.

A full technical description of SKYLON and its propulsion system were presented in [1] and [2], and are not reiterated here. Figure 1 shows plan and vertical views of the complete SKYLON vehicle, with the cabin module installed in the centrally located payload bay.

4. Cabin Module

As part of the study of the potential use of SKYLON for passenger purposes, two key aspects need to be considered. The first is to produce a credible layout of a passenger cabin that satisfies the basic functions so far identified. This cabin is built to be interchangeable with the standard SKYLON payload container, thus allowing the vehicle to be readily reconfigured for freight or passenger payloads.

4.1 General Features

The payload bay of the SKYLON spaceplane is 12.7 metres long, 4.6 metres wide and 4.6 metres deep. When launching satellites, this bay would normally contain an interchangeable container. Thus the payloads remain sealed and clean in the container until the lid is opened, on orbit. When used for passenger transport, an alternative, pressurised container would be used that would be readily fitted between flights.

This "cabin module" would provide a breathable atmosphere (possibly at the same cabin pressure as current airliners) and contain additional life support systems for up to 30 or 40 passengers.

A general cross-section of the inside of the module is shown in fig. 2 and a possible cabin floor layout in fig. 3 (in plan and vertical views).

Under the floor, part of the volume is needed for life support systems, the remainder being used for both passenger baggage and supplies for the orbiting stations (or "hotels").

It should be noted, as shown in fig. 2, that the cabin module is of circular cross-section and self-contained. For flight within the atmosphere, the payload doors would need to be closed above the module, but these can be opened after leaving the atmosphere as discussed below.

4.2 Cabin Layout

The central feature is a passenger transfer airlock, to be used both for docking to the space station and for emergency, in–orbit transfer of personnel in the event of the vehicle becoming disabled, necessitating transfer to a rescue vehicle (possibly another SKYLON). The detailed design of this airlock has not been finalised as much will depend on the specifications imposed by certification requirements.

Normal, non-emergency, ground access is by means of two side doors in the module, as shown in fig. 4. These doors line-up with two exterior doors in the sides of the SKYLON fuselage. To cover the case of a runway overshoot, for instance due to brake failure, passengers would leave the aircraft by these doors and make their final descent to the ground by conventional inflatable chutes.

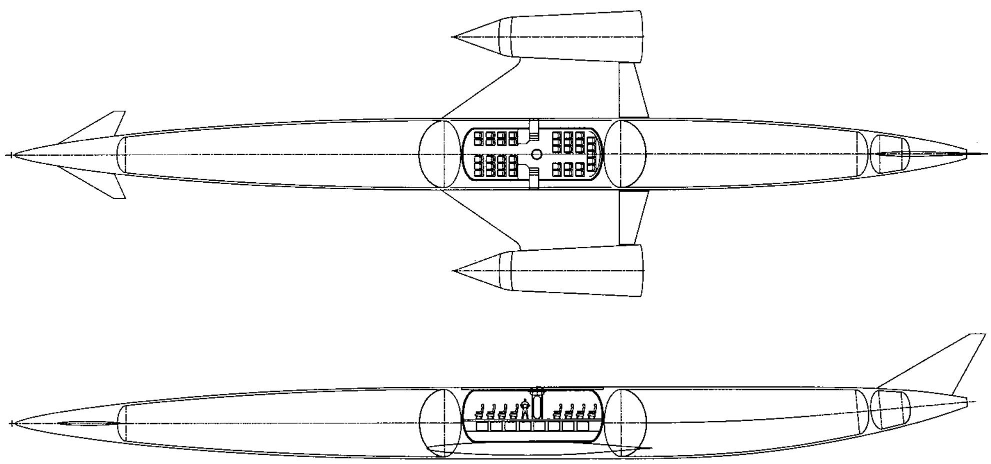

Fig. 1 SKYLON plan and vertical views showing Cabin Module installed in the payload bay.

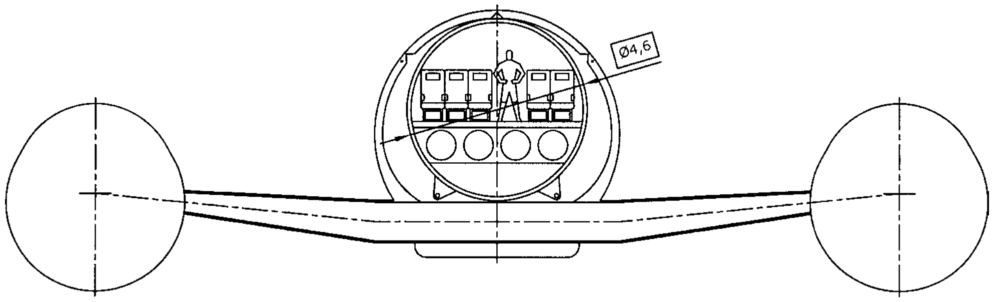

Fig. 2 Cross-section view of payload bay with Cabin Module installed.

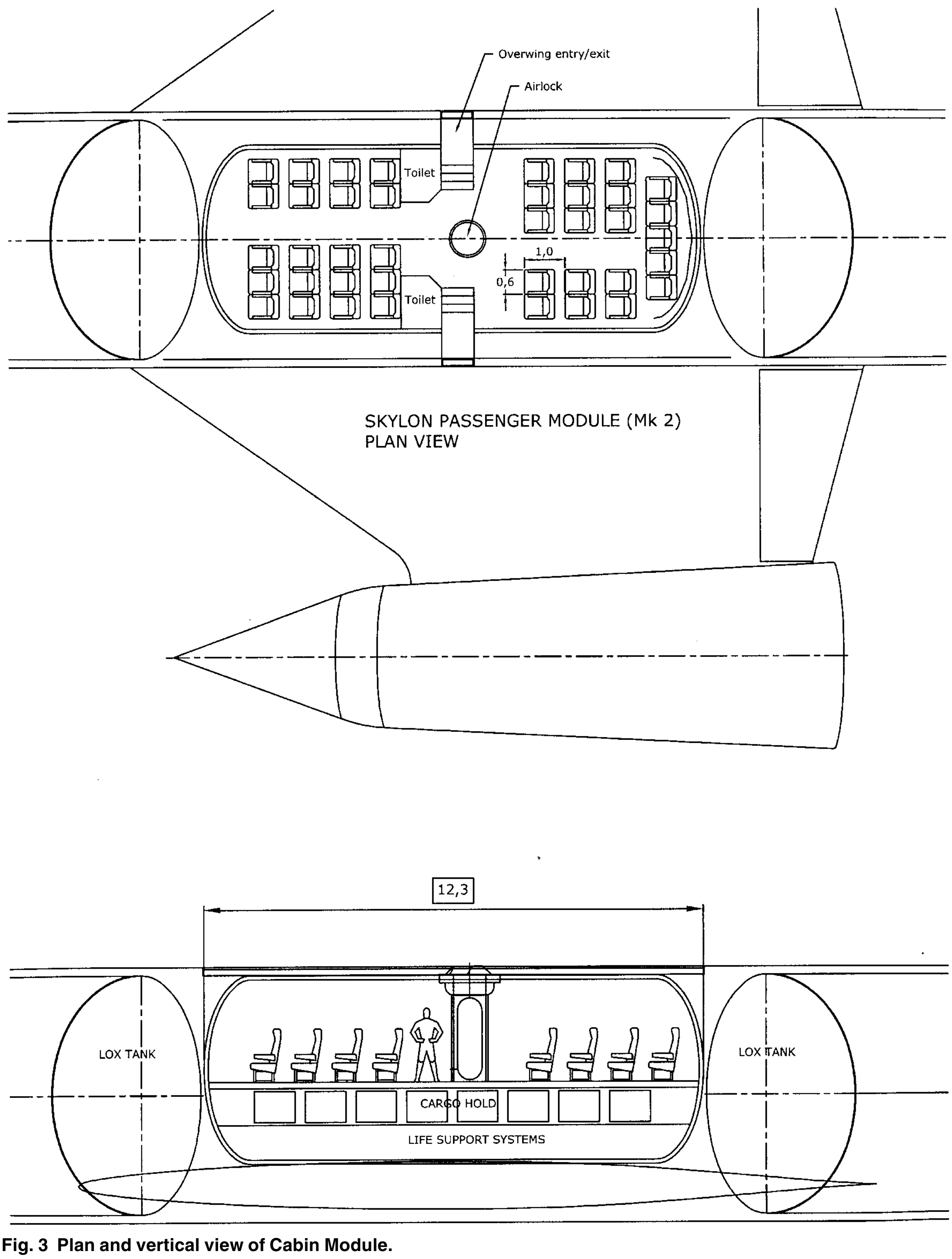

Fig. 3 Plan and vertical view of Cabin Module.

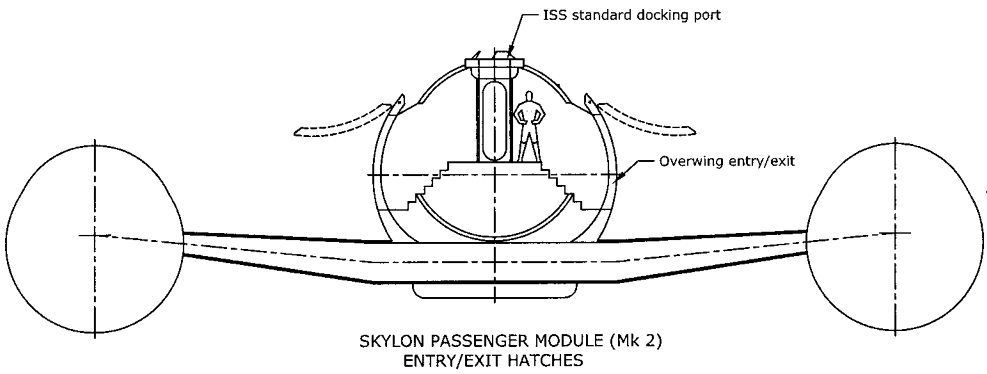

Fig. 4 Cabin Module entry and exit hatches.

In the cabin itself, there is provision for two toilet cubicles, possibly operating along the lines of those used on 'MIR'.

4.3 Special Features

It should be noted that, in order to provide maximum comfort during periods of micro-gravity, forced circulation of the atmosphere in the cabin is necessary, as normal convection cannot take place and a sitting passenger could slowly become surrounded by a "cloud" of exhaled carbon dioxide.

Discussions are taking place as to the merit of providing windows in the module roof so that during the coasting ascent, the SKYLON could roll "upside down", open the payload doors and allow the passengers to view the Earth as they attain orbit. Whilst this may appear unnecessary, it could possibly contribute to reducing the symptoms of space sickness by both providing a spatial reference and also a moving picture of Earth that would far surpass any artificial, screen version.

Other physiological aspects will be discussed in the appropriate section of this paper, but it is already realised that engineering effort will be needed to assist in providing an acceptable environment for the passengers. This is particularly important if, say due to a missed orbital rendezvous, further complete micro-gravity orbits have to be included before docking.

Passenger movement in the cabin, once in micro-gravity, would need to be permitted for human comfort and this requires the provision of a space-qualified toilet with a short recycling time between uses. At the present time, information gained from astronaut sources suggests that the Russian 'MIR' system is more "user-friendly" and recycles quicker than the American Shuttle/ISS system, but clearly, much development needs to be done in this area.

In terms of protection of the passengers from orbital debris, micrometeorites, etc. the basic SKYLON airframe will give sufficient shielding. However, if the "roof-windows" were adopted, then some form of triple layer design, like the Shuttle cabin windows, would need to be developed.

It is also estimated that the normal structure would give adequate radiation shielding for the comparatively short flight times of a typical transfer, dependence being placed on the orbiting habitat for long-term shielding.

The second aspect to be considered is an evaluation of the levels of acceleration, both horizontal and vertical with reference to the cabin/vehicle longitudinal axis, that would be experienced by the passengers. These data are presented for SKYLON in figs. 5 and 6 showing ascent and re-entry profiles respectively.

The general levels of acceleration are seen to be low, with the exception of the portion that corresponds to engine transition from airbreathing to pure rocket mode. This profile was generated in order to provide optimum launch performance for commercial satellite payloads.

It is obviously possible to change the rocket thrust level such that not only would the terminal acceleration be reduced, but also the rates of change of acceleration could be smoothed for passenger payloads. In particular, the normally abrupt change from rocket thrust at shut-down to zero gravity during coasting would need to be modified, as this would be the point of maximum "re-arrangement" of body organs.

It should, however, be noted that higher accelerations combined with high rates of change of acceleration are commonplace in advanced fairground rides. Legislation exists to limit these values, but the maximum levels for "thrill"' generation

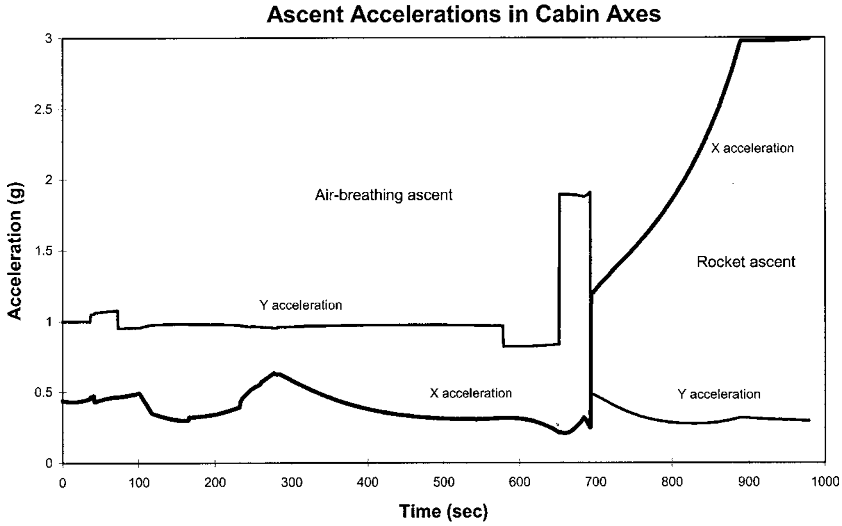

Fig. 5 SKYLON nominal ascent acceleration profile.

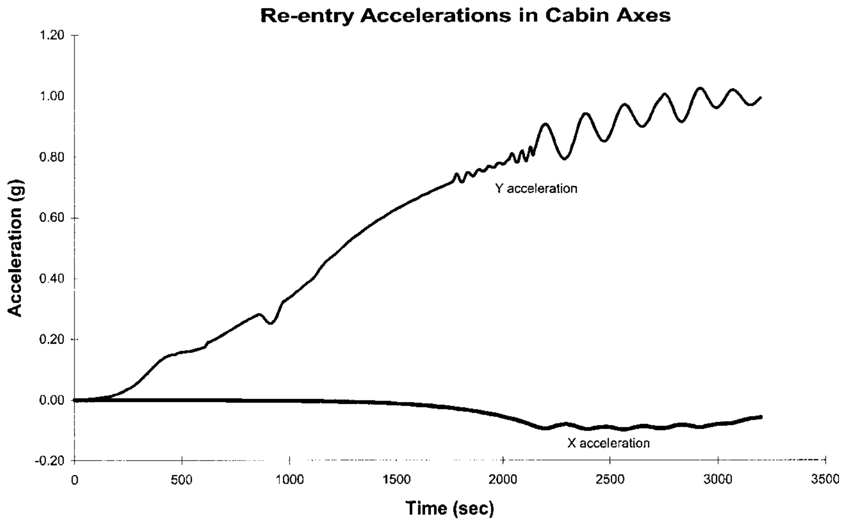

Fig. 6 SKYLON nominal re-entry acceleration profile.

can considerably exceed those envisaged for routine passenger transport.

In the period of flight after engine cut-off and generally in periods of orbit synchronisation (with the space-station), there will be significant periods of micro-gravity. This may result in several important physiological effects for the passengers and these will be considered later.

During re-entry, there should be less discomfort, as the vehicle will only leave the space station at the correct time for re-entry to a nominated spaceport on Earth, except in emergencies.

5. The Space Passengers

5.1 General Considerations

When considering the possibility of space tourism it is all too easy to envisage space passengers travelling in a manner very similar to present-day air travellers. You turn up at a spaceport, just as at present at an airport, check in baggage, relax with a drink or meal before boarding your space vehicle, and then settle back to enjoy the flight. Along the way, you might expect some refreshment during the flight, and an opportunity to off-load some of that refreshment! You might even expect to buy duty free goods! The reality will be far, far different, at least well into the foreseeable future.

The space environment is overwhelmingly hostile to life. Add confinement and isolation in a fragile habitat - whether a space transport vehicle like SKYLON, a space station, or a space hotel - a vulnerable life support system, and the remoteness of help and rescue, and you have the ultimate tourist challenge. Spend any significant period of time in this environment and you start losing bone and muscle mass, your cardiovascular system starts to “de-condition”, you develop space sickness that may last several days, and you are exposed to a radiation hazard orders of magnitude greater than on Earth. Then there are the psychological and sociological problems; you won’t be able to suddenly decide you have had enough, and go home!

Despite those problems, there is another far more positive aspect. All astronauts and cosmonauts have described space travel as an overwhelming, yet marvellous experience – psychologically and emotionally, as well as physically; the sight of the Earth from low Earth orbit (LEO), the blackness of space, the stars – they are all reported to be awe inspiring, but humbling. And once the first few days have passed, the novelty and opportunities provided by living in micro-gravity can be thoroughly enjoyed. Indeed, some lucky ones experience no space sickness at all, and adapt very quickly. There can be little doubt that there are many people who will be prepared to accept the risks and privations of a trip into space, just as they have done historically when travelling to far-flung corners of the Earth.

5.2 Passenger Consent

Similar to any commercial aviation venture, a passenger "Bill of Rights" prudently scores out the expectations for safety through all phases of transport and must include the conventions for emergency escape and recovery. Most people rarely give a second thought to the operational risks involved in commercial aviation, but the concept of low Earth orbit brings the requirement for awareness to a level much higher than simply reading the safety card in the seat pocket in front of you.

5.3 Pre-flight Training

It is reasonable to provide passengers with a condensed training program to familiarise them with the physiological effects of the flight conditions and emergency procedures for departure and re-entry. The relatively simple concept of egressing a jumbo jet is foreign to most travellers, yet we demand attentiveness to exit position and operation during departure briefings. The window of opportunity to egress an aircraft en route to LEO is narrow, and passengers need to be familiarised with practical methods of protection and escape. Other issues arise in the design. When does a viable exit in a transatmospheric vehicle become unusable? What are the realistic parameters for escape through each of the flight transitions of the near-space plane?

The crew must be thoroughly trained in physiological support and environmental controls. For effectiveness, the select crew should accomplish their own training in a reduced gravity environment-it does the passengers little good if the crew is incapacitated in flight! The amount of time required for reconditioning between missions must be a cornerstone of crew scheduling and training to prevent the myriad of physiological changes from threatening health and well being. Cabin crew training should include all the conventional requirements for basic life support (BLS) and be supplemented with additional advanced techniques if the responsibility for passenger safety and well-being is to rest with the crew.

5.4 Cabin Air Pressure: Provisions and Losses

Space travel is a vastly different proposition from air travel. Some lessons can be learnt from present day supersonic air travel. Concorde flies at a mere 60,000 ft (about 11 miles high). Although nearly twice the altitude of subsonic aircraft, it is still over 20 times lower than a low Earth orbit (LEO) space station. Although the cabin altitude of Concorde is similar to that of subsonic aircraft (6-8000ft), the consequences of loss of that cabin pressure are far more serious. Oxygen provides sufficient protection at the cruising altitude of conventional aircraft – hence the simple provision of oxygen masks if there is a sudden loss of pressure. However, in Concorde oxygen alone is insufficient; at 60,000 ft consciousness would be lost in a matter of seconds even if pure oxygen were breathed. Rather, protection against sudden loss of cabin pressure is built into the design of Concorde: a substantial reserve capacity to provide cabin air whilst the aircraft descends, and small windows, for example.

A similar approach may have to be adopted for SKYLON, even though the consequences to passengers of a sudden loss of cabin pressure would be far worse than for Concorde – indeed, probably fatal. The only certain way to protect passengers against a decompression occurring in a space environment would be to provide all the passengers with a full pressure suit. Enormous cost and labour intensive maintenance schedules would make full pressure suits logistically impossible for such a commercial venture. So SKYLON must be designed in such a way as to minimise the risks of decompression. This is not such an impossible task; no decompression incidents have been reported on Concorde. Nevertheless, there would be a big psychological difference between our Concorde and SKYLON passengers; the former know they stand an excellent chance of surviving a sudden decompression; the latter would know they stood no chance!

Cabin air at the right pressure is provided in aircraft by compression of outside air. In space there is no air, and so a spacecraft must carry a means of producing breathable air. In the Space Shuttle this is achieved by carrying liquid oxygen and nitrogen, and mixing them appropriately; carbon dioxide is removed by lithium hydroxide. SKYLON must carry its own life support system.

5.5 Radiation

There is another problem facing our intrepid space farers – solar and galactic cosmic (CG) radiation. In a sense this is even more serious than decompression because it is insidious.

Solar and CG radiation both vary with altitude, inclination and season. Concord is exposed to a higher dose of radiation than aircraft that fly at a lower altitude. Spacecraft that have a low inclination orbit have a lower level of exposure than high inclination orbital craft, due partly to an area known as the South Atlantic Anomaly (SAA). The Sun has a solar cycle of activity that peaks every 11 years. This cycle gives rise to fluctuations in the level of solar radiation that LEO spacecraft are exposed to, but the Sun can produce solar flares that have the ability to expose a spacecraft and its occupants to a lethal dose of radiation.

Exposure on Earth to radiation is very strictly controlled- justified, quantified and qualified. While the effects of radiation from Earth sources are well known, the effects of both solar and CG radiation have still not been fully explored and the long-term effects of high-energy radiation exposure are still under investigation. A European Community directive will place control measures on the exposure of aircrew and passengers, to both solar and CG radiation exposure while flying [3].

The methods employed to measure and quantify radiation on Earth (dosimetry) are well known and used widely. To quantify and qualify radiation in LEO alternative materials and technologies will have to be implemented. The exposure of members of the general public to radiation to which there is no control may have adverse effects.

These problems are obviously compounded for the crew who might be expected to fly many times a year. Doses recorded in astronauts to date are below accepted limits – although levels tend to be considerably higher than for Concorde aircrews. The point, however, is not that these doses are “safe”, but that all radiation can damage cells, and therefore exposure to any radiation should be minimised. So passengers undertaking that “once-in-a-lifetime” trip into space aboard SKYLON should be safe enough (unless they have the misfortune to be caught by a solar flare!). But what about the crew who might be expected to fly many times a year?

5.6 Gravity – Too Much and too Little

Too much gravity is an experience enjoyed transiently by many people on some of the more spectacular roller-coaster rides. The return fare into space will enable the effects of a substantial increase in body weight to be experienced – and over a rather longer time period than on a roller–coaster. This will present little problem to individuals who are fit and healthy. But what of those who are not so fit, or who have a heart condition of which they are perhaps unaware? Space tourism is not going to be possible for everyone – indeed, probably for far fewer people than currently undertake air travel. There will need to be agreed passenger selection criteria based on reasonable risk and known limitations.

However, the problem of too much gravity may turn out to be rather less serious than the problem of too little gravity. There is a down side to the fun and frolics of space travel; that is the problem of space sickness which afflicts about 50% of those experiencing “micro-gravity” for the first time. It occurs early into the space flight, is extremely distressing, and can result in frank vomiting – not pleasant in an environment where everything floats! Individual susceptibility cannot be predicted, at least presently, although anti-motion sickness drugs can help. Space sickness is made worse by head movement, and consequently keeping as still as possible helps. For this reason it may be preferable for SKYLON passengers to remain firmly strapped into their seats for the duration of the flight. This may be acceptable for a sub-orbital, or a single orbit flight, which might last a couple of hours at the most. However, for a trip to a LEO space station a protracted period in orbit may be necessary before docking, so basic human needs will have to be catered for. Learning to move around in the absence of gravity is difficult enough. But going to the toilet? Even astronauts can still find that a difficult task to master.

5.7 Eating and Drinking in Space

While some foods are available in a natural form (e.g. biscuits, nuts, sweets, tinned foods), many foodstuffs are prepared for eating before launch, and either dehydrated, vacuum packed, or sterilised by irradiation. Meal preparation in space involves re-hydration and heating as appropriate. Eating is very similar to on Earth, except that in space there is a tendency for food to just float away - which can be messy. Drinks, of which there is a wide selection, are taken from closed plastic beakers into which a straw is punched.

5.8 Waste Disposal

Getting rid of the inevitable consequences of eating and drinking in space - urine and faeces - is certainly one of the least glamorous aspects of living in space. And, throughout the entire manned space programme, it has been one of the most difficult to resolve. Fortunately, the days of "nappies" and plastic bags are long gone, and the Shuttle has a real toilet. However, the toilet is flushed by air, not water. The air is stirred by a fast-rotating centrifuge, which seems to break up faeces and fling them against the inside of the toilet bowl where they form a fixed, odourless film. Urine is collected in a funnel under light suction. When the toilet is "closed" after use, the contents are exposed to the vacuum of space, causing instant drying.

5.9 Personal Hygiene

Transient hygiene requirements will be less complicated than the long-term designs for living in space. Washing, showering and shaving can all be easily accomplished in space. Hand washing is accomplished by placing the hands in a plastic basin through two sleeves. Water (hot or cold) sprays over the hands, leaving the "wash-basin" via a vacuum pump. Showering is accomplished in a special cubicle, with the water supplied from a hand held unit, which drains under suction through holes in the floor of the cubicle. Drying is achieved using a towel as normal, but taking care that the body is restrained using footstraps. Similarly, restraint is necessary for dressing - otherwise the display of acrobatics will be impressive. Shaving is best carried out using soap and water, as electric shavers fail to collect all the cut hair, which then floats around. Several Skylab astronauts preferred to grow beards. Teeth are cleaned using edible toothpaste. "Clean" waste is collected, stored and returned to Earth.

5.10 Sleeping in Space

Despite the excitement over a flight into space, some passengers may want to get some shut-eye during the short hop to space. Strictly speaking, in a weightless environment there is no real need for a sleeping bag, or a bed, and some astronauts have been quite happy to find a quiet corner and an anchor point, and then simply nod off. Passengers in a craft such as SKYLON would be anchored to their seat with devices not unlike conventional restraints found in airliners. The anchor point is important, otherwise subtle body movements enact in the manner of a rocket, propelling the sleeper around the spacecraft - with possibly harmful consequences. Incidentally, it is important to keep the arms restrained too! More than one astronaut has been momentarily confused by the image of two strange objects floating in front of their face - their arms!

5.11 Relaxing in Space

Weightlessness offers all sorts of opportunities for novel forms of relaxation. Ball games take on a new perspective in the absence of gravity, both in the throwing, and in the catching. Space wrestling and chess can provide an interesting diversion from the mandatory exercise programmes. Darts is also a popular game in space, and hilarious if the dart thrower is not secured, as throwing initiates rotations around the body's centre of gravity. Board games can be played, provided pieces are securely anchored. Then there is always reading, writing, or the most popular pastime of all - just looking out of the window. Psychological factors will need to be taken into account. There are few people who do not find being confined in a small, probably windowless space, and being in an environment over which they have no control, at least mildly disquieting. Views of the outside world may well have to be limited to that provided by TV monitors. Then there is knowing that if there is an emergency, you stand little chance of surviving. The first space tourists will need to be a hardy, brave, and carefully selected group of people.

5.12 Exercise in Space

Except for very brief visits into space, exercise in space will be essential - to at least reduce the rate at which muscle loses mass (atrophies), and to prevent fainting on return to Earth. But, even though cosmonauts exercise for up to 2½ hours each day, exercise is far from being a completely effective counter-measure to space deconditioning – it does not prevent the loss of calcium from bone, for example. Exercise can take several forms: isometric using spring-loaded devices, cycling on a stationary bicycle, or running on a treadmill held down by "bungi" straps. The only real problem about exercising hard is the accumulation of sweat. Because sweat can't run down the body in a weightless environment, it builds up as a thick layer of water that can only be removed with a type of vacuum cleaner. Good ventilation is essential in the exercise area.

6. Summary of Considerations

The main points arising for the future safe and "comfortable" transport of fare-paying passengers to orbit are thought to be as follows:

1. From an overall consideration of the vehicle requirements and taking note of likely certification rules, the resulting spaceplane will have "airliner-like" characteristics.
2. Horizontal take-off and landing, as originally envisaged for HOTOL and later embodied in SKYLON, would appear to be the only system that can safely cater for all abort scenarios.
3. Whilst initially the volume of passenger traffic would be small, by having a vehicle with both freight and passenger capability the operators can adjust their timetables to suit the developing market. In this respect, the use of interchangeable container-like modules, as in the SKYLON vehicle, gives the operator maximum flexibility and also means that only one basic spaceplane design needs to be developed.
4. The SKYLON acceleration graphs show that the levels experienced by passengers are generally very low, far less than is allowed by present law in fair ground rides.
5. During the transit flights, the effects of micro-gravity have not been quantified for non-astronaut personnel. As the need for passenger transport develops, serious consideration of suitable pre-flight training must be undertaken.
6. In terms of certification issues, a UK-Japan workshop held in London highlighted the need for early involvement of the relevant certifying authorities, initially by the formation of a multi-disciplinary committee. At the present time, the Japanese appear to be ahead of the UK in these matters.
7. The above workshop also concluded that there were no serious technology gaps, but further examination of radiation effects would be needed
8. The passenger carrying spaceplane concept, in conjunction with known projects for orbiting habitats, provides an excellent basis for international collaboration.

7. The Way Ahead

- Certification issues must be addressed as a matter of high priority. In the UK, since April 1999 decisions were taken to form a body charged with the overall co-ordination of UK efforts in this field. This is under the auspices of the BIS and involves both private enterprise and relevant Government bodies. It will also serve as the interface for international collaboration, for example with America and Japan.
- There are also numerous outstanding physiological problems to be investigated. There is a real risk that advances in space technology will enable space tourism to "take-off" before crucial human factor and medical issues have been properly addressed. A concept vehicle like SKYLON provides a first opportunity to address these issues.
- Reaction Engines is re-examining the detail of the SKYLON design in the light of the recent investigations of requirements for passenger transport presented in this paper. For example, two aspects under review are the vehicle ascent/descent trajectory profiles and the cabin module-vehicle integration.

8. Conclusion

If it all sounds very difficult, even improbable, it is salutary to think back to the first passenger airlines. Many of the human factor problems facing those early pioneers must have seemed as intractable as those that now have to be faced by a nascent space tourist industry. They were not insoluble then, and they are not now. However, if the space transportation industry is going to be ready for its first fare-paying passengers, whether in five or fifteen years time, then these issues need to be addressed today.

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