An Underground Isolation Laboratory for Human Space Mission Simulations

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The European Space Agency (ESA) is evaluating an underground isolation laboratory for simulating long duration human space missions with 6-person crews confined to the laboratory for periods of 100 days and perhaps substantially longer. ESA is evaluating a remote location over 200 metres underground in an existing tunnel network in Belgium with the intent of increasing the laboratory's physical isolation. This paper describes a design for the laboratory that fits snugly into a portion of the tunnels, making the most of the confined and limited volume available. The tunnel system is operated by Studiecentrum voor Kernenegie – Centre d'Étude de l'Énergie Nucléaire (SCK-CEN) at Mol in Belgium. SCK-CEN originally built the tunnels for subterranean geological studies concerned with the underground storage of radioactive nuclear waste (though no such waste was ever stored there). An end gallery in the tunnel system is available for the isolation laboratory.

Many challenges exist in utilizing the tunnels for this purpose: delivery of all construction elements must take place down two lift shafts with construction and installation by hand; the end gallery site has one entrance/exit, raising crew emergency evacuation and safety concerns; the end gallery volume is below an accepted human habitability standard for long duration missions; there is minimal residual volume available for environmental control & life support (ECLS) systems. Despite these challenges, it is possible to achieve a feasible design utilizing modular and repetitive construction elements, a choice of open or closed ECLS systems and an interior accommodation and outfitting approach with life-cycle adaptability, all at relatively low cost. The laboratory has the potential to provide Europe with its own long duration spaceflight simulator to support international human missions to deep space, such as the "flexible path" exploration missions currently under study at NASA. The project design and engineering team comprised 4CON Space Ltd. (Paris), Altus Associates (Los Angeles), RFR (Paris), EADS-Astrium (Bremen) and Davis Langdon LLP (London).

I. Introduction

THE European Space Agency is considering the development of an underground isolation laboratory for simulating long duration human space missions. The simulated missions would involve 6-person crews confined to the laboratory for periods of 100 or possibly 150 days. ESA is studying a remote site over 200 metres underground in an existing tunnel network in Belgium with the intent of increasing the laboratory's physical isolation from the surface. The tunnel system is operated by Studiecentrum voor Kernenegie – Centre d'Étude de l'Énergie Nucléaire (SCK-CEN) at Mol in Belgium. SCK-CEN originally built the tunnels for subterranean geological studies concerned with the underground storage of radioactive nuclear waste under Belgium's nuclear energy programme. Subsequently, the storage of nuclear waste in the tunnels never occurred, though geological research into the long-term behaviour of the soil continues in tunnels. SCK-CEN has proposed to ESA that an end gallery in the tunnel system is converted into the isolation laboratory.

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II. Background

In the isolation studies field, ESA conducted or participated in the 1990s in simulated long duration missions and isolation studies performed in different chambers and facilities at various locations. The ISEMSI-90 study used a chamber provided by the Norwegian NUTEC company in Bergen. The EXEMSI-92 study was carried out at the German space agency DLR in Koln and the HUBES study of 1994/95 used a simulated MIR space station at the Institute of Biomedical Problems (IBMP) in Moscow. ESA carried out an analysis of the results of these three campaigns in the study GLOBEMSI-96[1]. The scientific aims of the campaigns were to obtain information on the psychological and physiological effects of long-term isolation and confinement on a small crew under conditions simulating those on a space station. The experimental protocol involved a variable architecture of 4, 2 or 1 main chambers, a variable crew size of 6, 4 and 3 crewmembers and variable isolation durations of 28, 60 and 135 days.

ESA also commissioned the HUMEX[2] study in 1999/2000 on human survivability and adaptation to long-duration missions. This comprised a critical assessment of the limiting factors for human health and performance and highlighted a number of key issues including radiation and bone fracture health risks, psychological risk from isolation and confinement and the need for bioregenerative life support. Among the conclusions was an identified need for ground-based simulation facilities. In 2003 ESA also carried out the REGLISSE[3] review of European ground laboratories and infrastructure to support space exploration. The review proposed facilities for medical and psychological research, life support and exobiology and an ideal scenario for a European facility.

At the present time ESA participates in the MARS-500 study at IBMP in Moscow which seeks to simulate a typical Mars Mission of roughly 8 months of outbound travel time, 1 month on the Martian surface and another 8 months on the return leg. ESA has therefore carried out or participated in several initiatives for simulated long-duration missions. However, the agency has realized that single isolated campaigns of the type referred to above are not the best way to conduct mission simulations as comparisons between campaigns are tenuous and results tend to be anecdotal and unrelated to coordinated research[4]. The proposed underground isolation laboratory offers a solution by providing ESA with its own permanent facility for simulating long duration exploration missions based on a coordinated and controlled programme of research.

III. Tunnel System

The location proposed -for the isolation laboratory was in an underground tunnel system in Belgium. Figure 1 below shows photographs of the existing tunnels in the vicinity of the end gallery – the site for the laboratory. The tunnel operator SCK-CEN built and has operated the tunnels as an underground laboratory named HADES. HADES was developed for research into the ability of the local geological environment to provide long-term storage of radioactive nuclear waste but the tunnels have never been used for that purpose. The tunnels reside in a geological layer of clay called Boom Clay. Boom Clay is a dense clay that originates in the Tertiary Period from 36-30 million years ago. It occurs at a depth of about 190 metres under the SCK-CEN site and has a thickness of about 100 metres. Boom Clay is considered an ideal environment for storing nuclear waste due to its long-term geological stability.

Figure 1. Photographs of Underground Tunnel Site for the Laboratory

The tunnel system comprises two vertical lift shafts 220m deep connected by a horizontal gallery – the connecting gallery – 150m long which extends beyond one lift shaft to form an end gallery 34m long and 3.5m diameter. The intention was to install the isolation laboratory in the end gallery, which is a cul-de-sac. The lift shafts vary in size and transportation capability. The only access to the end gallery is directly through the base of one lift shaft when the cage doors are open or by squeezing through a narrow gap around the lift shaft base. Figure 2 below shows a cutaway diagram of the tunnel configuration with the laboratory shown in yellow, and a cutaway view of the tunnel lining structure in the end gallery, top right.

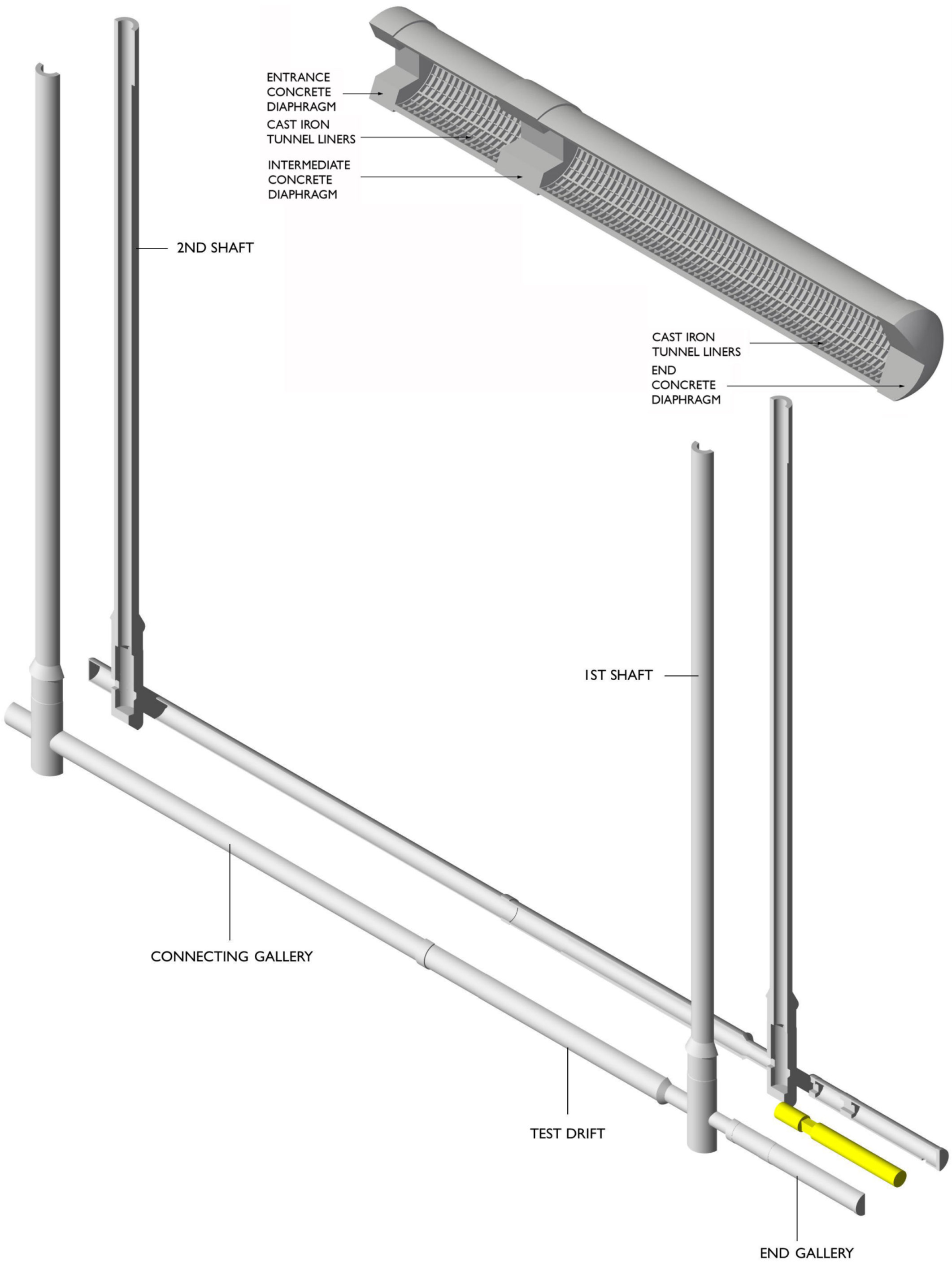


Figure 2. Cutaway Illustrations of the Underground Existing Tunnel System

IV. Objectives and Scope

ESA anticipates that isolation laboratory operations objectives would be to investigate the psychological effects of isolation and confinement, the factors that influence these effects, the beneficial role of habitation design, the testing of medical monitoring and the maintenance of environmental control & life support (ECLS) systems. The project aimed to incorporate these objectives in the development of a set of preliminary requirements, a laboratory design and engineering concept and an assessment of the feasibility of locating it in the tunnel system offered by SCK-CEN.

The scope of the project encompassed a literature and analogue review, preliminary requirements definition, an ECLS system concept, a safety and regulations review, an architectural design concept, a structural engineering concept, an outline development plan and a cost estimate.

V. Requirements

The preliminary requirements divide into three groups based on project life-cycle phases. The three groups cover design, construction and operation. This division helps to categorize requirements according to their application and relevance, bearing in mind that those dealing with construction concern contractors while those dealing with operations concern scientists and experimenters.

The requirements for design would guide the project as it continued into the design development and detail stage. The requirements for construction would evolve into a description of the laboratory's construction as part of the contractor bidding process if it proceeded to the construction stage. The requirements for operations would be of value to scientists and experimenters interested in performing simulated missions if the project reached the operational stage.

The requirements would expand and evolve as the project continued through further phases, particularly if site conditions and operational objectives changed. They are to be viewed as interim requirements that reflect the particular circumstances of the tunnel location in general and the end gallery in particular at the initial design stage.

VI. Regulations

Locating the isolation laboratory in an underground tunnel system would be subject to legislation, directives and regulations covering a range of health, safety and construction issues. A review process identified relevant examples. The Charter of Fundamental Rights of the EU[5] is concerned with human dignity, freedom, solidarity and equality that emphasize fair and just working conditions for all. The Declaration of Helsinki[6] covers ethical issues and applies to research involving human subjects where their well-being is more important than scientific objectives. There are several EU Council Directives that address health and safety and oblige an operator to avoid or minimize risk, replace the dangerous by the non or less dangerous, ensure good workplace design, provide hygiene, emergency services and evacuation safety and limit working time. The ESA Charter and Convention[7] commits ESA to observing local regulations that include public health and labour provisions. ESA's own safety and security regulations[8] deal with occupational safety, health, security and accident prevention.

Present throughout all the legislation and regulations is the need to ensure human health and safety in built environments. Precaution against fire, evacuation, control of hazards and risk reduction are ESA safety objectives. Local Belgian building regulations would apply to the laboratory design and construction, to the extent possible in the underground location. These typically cover structural stability, fire protection, emergency escape, construction materials, construction workmanship, sound insulation, ventilation, room height, hygiene, sanitation, waste disposal, energy conservation, accessibility and electrical safety.

There is also a basic need to provide emergency evacuation in the event of danger such as fire or smoke. This is normally provided in buildings and facilities by two means of escape - two separate escape routes – and these are often mandatory in building codes. While other parts of the tunnel system such as the connecting gallery could offer two means of escape, the end gallery cannot because it has only one entrance and exit point. The far end is a cul-de-sac. The end gallery proves to be the least safe part of the tunnel system in which to locate the laboratory from an emergency evacuation viewpoint. This fact would certainly need to be taken into account in a detailed analysis of the operational safety of the laboratory if it proceeded in the end gallery location.

VII. Volume

The internal volume of the end gallery is considerably less than the habitable volume allocation established by the United States and Russia for actual and simulated long duration missions. The habitable volume baseline for the NASA Mars Reference mission[9] was $90m^3$ per crew member while the MARS-500 simulation facility in Russia offers 91 m^3 per crew member. At the time of writing (January 2010), the 6-person crew on the International Space Station occupies a gross pressurized volume of about 765 m^3 or 127 m^3 each. The end gallery volume available for the isolation laboratory is 197.1 m^3 or just 32.9 m^3 for each of the six crew members. This is slightly more than a third of the US and Russian standards. A further problem is a split in the end gallery volume caused by a narrow passage that divides it into two chambers. The volumetric inadequacy of the end gallery posed a challenge for the design and outfitting of the laboratory. It is not possible to include the full range of accommodation that the laboratory needed to perform fully comprehensive mission simulations. Certain omissions are and would be inevitable. Figure 3 below gives an accurate idea of the maximum size of the isolation laboratory in the end gallery, compared to the size of International Space Station configuration. The laboratory is shown in yellow.

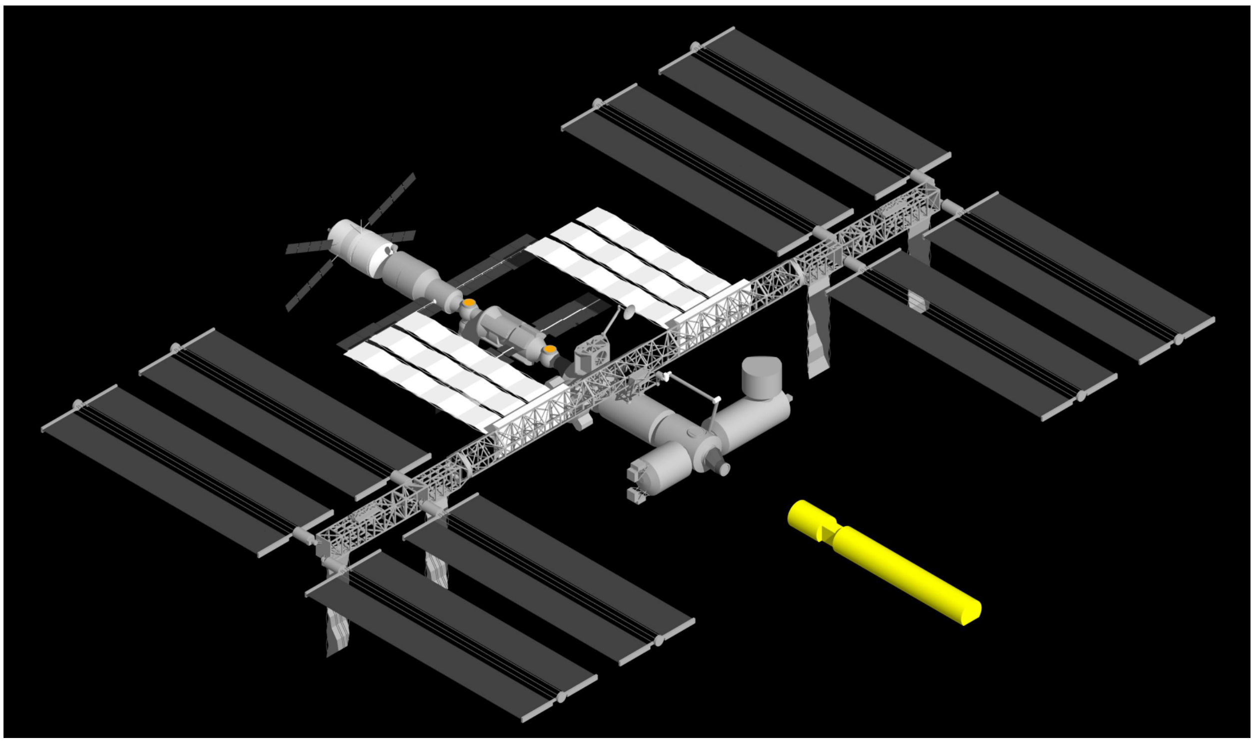


Figure 3. Size Comparison of the Laboratory and the International Space Station

VIII. Architecture

Despite the difficulties, a feasible architecture has emerged that makes the most of the limited volume available. In cross-section, the height chosen for the laboratory floor level ensures optimum floor width, maintains proper headroom close to the curved wall and provides adequate volume for sub-floor ECLS systems. Figure 4 below shows four options for the floor height, of which Option D is the optimum in terms of headroom and floor width.

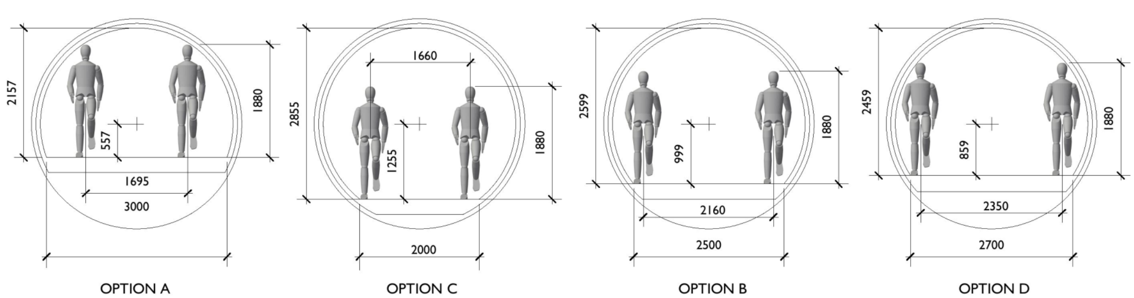
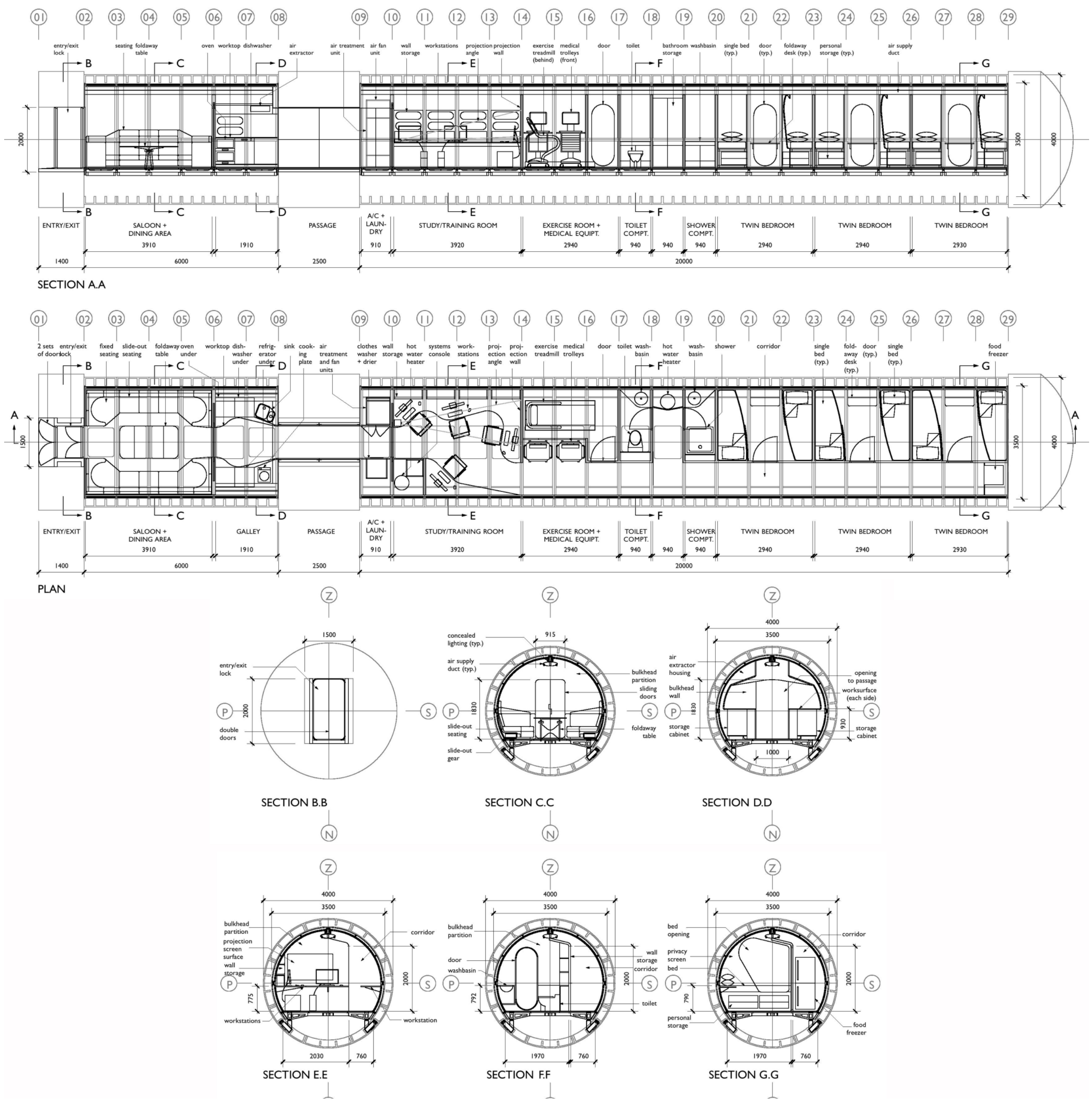


Figure 4. Cross-Section Options for Floor Height, Floor Width and Headroom

In plan, the architectural layout follows a logical sequence of activities based on a community-privacy gradient that separates noisy, communal areas from quiet, private areas. The single entry/exit point leads to a saloon used for crew meetings, meals, conferences and leisure. The saloon is the principal communal area of the laboratory. Together with the kitchen, it occupies the small gallery chamber, using the narrow dividing passage to advantage as an acoustic and visual buffer to separate it from other quieter accommodation.

The narrow passage leads to the large gallery chamber. This begins with a study and training area containing four workstations in a loosely planned arrangement designed to contrast with the uniform geometry of the cylindrical volume. It is the only communal working area possible in the limited volume. A small scientific laboratory could replace the workstations but there is not room for both. Figure 5 below shows a plan and sections of the architectural layout.

Figure 5. Plan and Sections showing the Laboratory Architectural Layout



The workstation area leads to a side corridor that provides circulation to all other areas. The side corridor liberates the centre of the cylindrical volume for activities that need compartments where maximum headroom can help to combat spatial confinement. First along the corridor is a crew exercise compartment with a full-size treadmill and adjacent storage for two mobile medical workstations. Beyond is a small side corridor leading to two bathroom compartments that are also limited by lack of room. One has a toilet, the other a shower and both have washbasins.

Beyond the bathrooms towards the far end of the laboratory are three sleeping compartments. Two crew members must share each of these to minimize their floor area and enable them to fit into the plan. The compartments can provide some privacy with the bunks built in into semi-private carrels. A double bed arrangement is possible for married or partnered crew members.

Critical to the accommodation layout is an unobstructed route to the single exit. This is vital for rapid crew evacuation in an emergency. The accommodation standards and architectural layout of the laboratory are inevitably compromised by the limited volume of the end gallery. Nevertheless, a workable architectural arrangement for 6 persons is just possible. Figures 6, 7 and 8 below shows cutaway isometric views of the architectural layout.

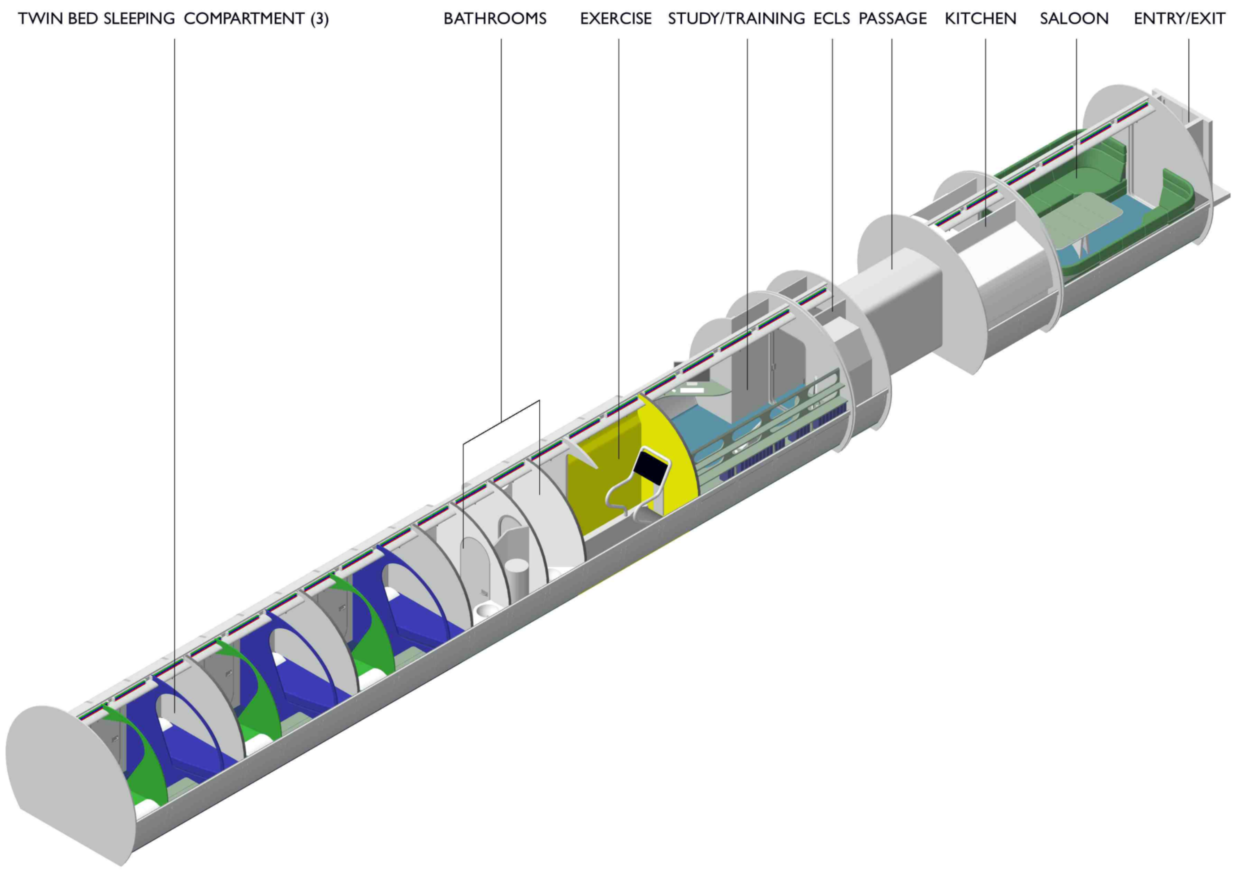


Figure 6. Cutaway Isometric View showing the Laboratory Architectural Layout

IX. Structure

The tunnel system in general and the end gallery in particular present challenges to the isolation laboratory's construction. The only means of delivering construction materials is by two lifts which are both quite small. Only manual delivery of all materials along the tunnels is possible as there is no mechanical lifting system. The laboratory structure must therefore be built from a large number of elements that are small enough to travel down the lifts and along the tunnels, and light enough to be carried by four people. Additionally, there is minimal room underground for a staging or storage area for arriving materials. As a result, there is great emphasis on prefabrication and modularity. This simplifies the assembly process in the restricted gallery environment, maximizes dimensional accuracy to fit close against the curved tunnel lining and standardizes prefabricated element shape and size for economical manufacture.

Figure 9 below shows the preliminary structural design of the laboratory. The structure becomes a kit-of-parts that is carefully tailored to achieve a close fit inside the end gallery. Four prefabricated parts form a complete enclosure segment in cross-section. These segments repeat down the length of the laboratory in one metre increments to match those of the tunnel itself. Steel foundation bearings with rubber blocks transfer the weight of the laboratory structure to the cast iron tunnel lining and provide acoustic isolation from noise from elsewhere in the tunnel system.

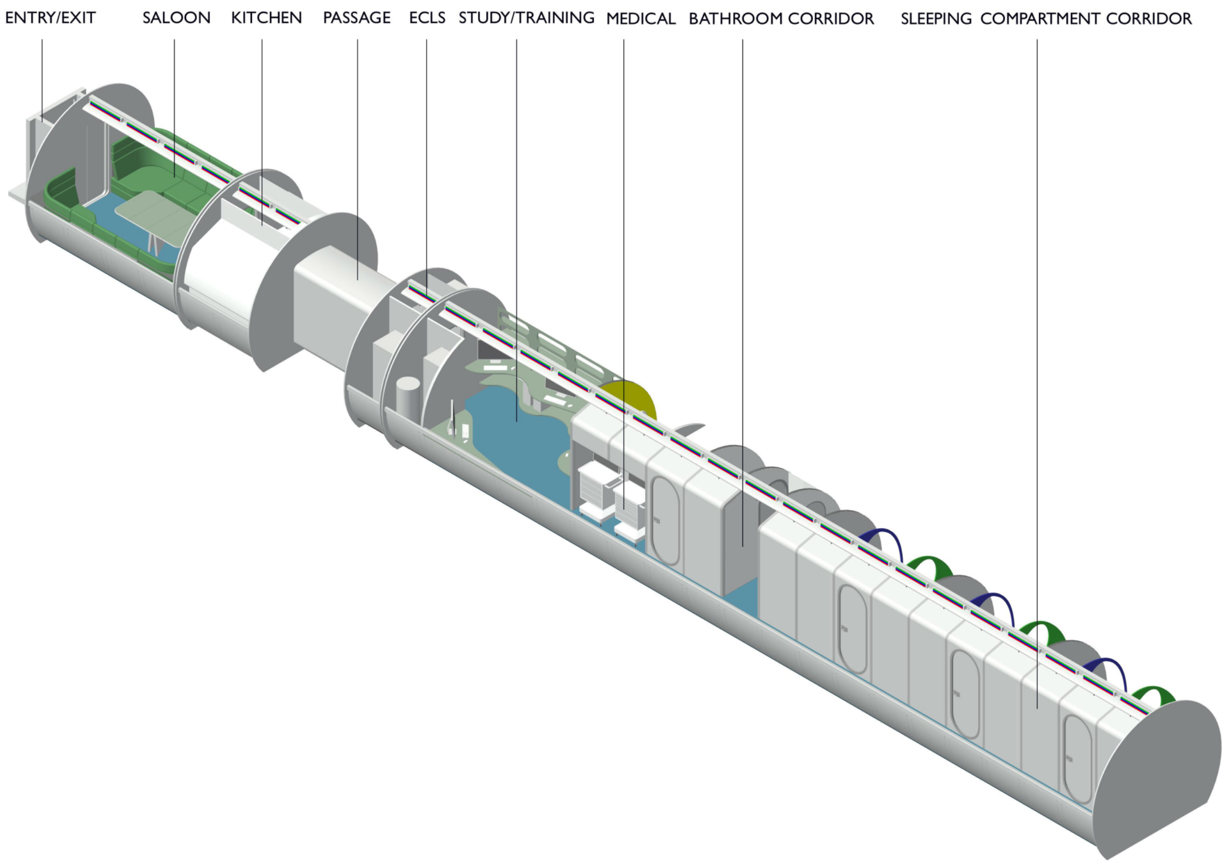


Figure 7. Cutaway Isometric View showing the Laboratory Architectural Layout

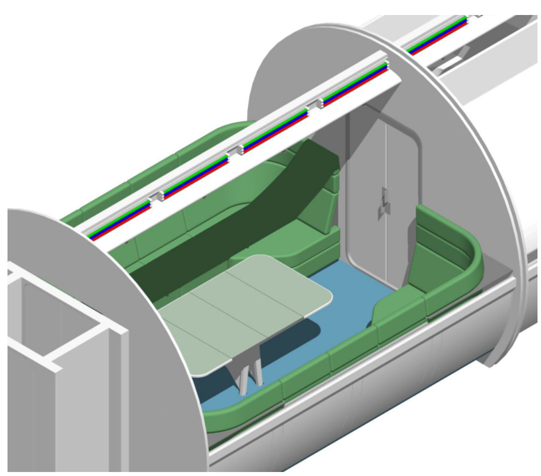


Figure 8. Close-Up Isometric View of the Saloon with Fold-Away Table

All construction materials must be lightweight, fire resistant, corrosion resistant, durable, non-toxic and easy to fabricate and assemble. For these reasons, aluminium in several manufactured forms is the chosen material for the prefabricated elements. The ECLS system requires that the laboratory is airtight. Compressible seals around the edges of the prefabricated floor and ceiling elements provide this as they bolt together. The structural design ensures that internal partitions, bulkheads, doors, appliances and fittings can be removed and relocated without interfering with the continuity of the laboratory enclosure. This provides for life-cycle adaptability and reconfigurability to suit evolving mission requirements and crew circumstances.

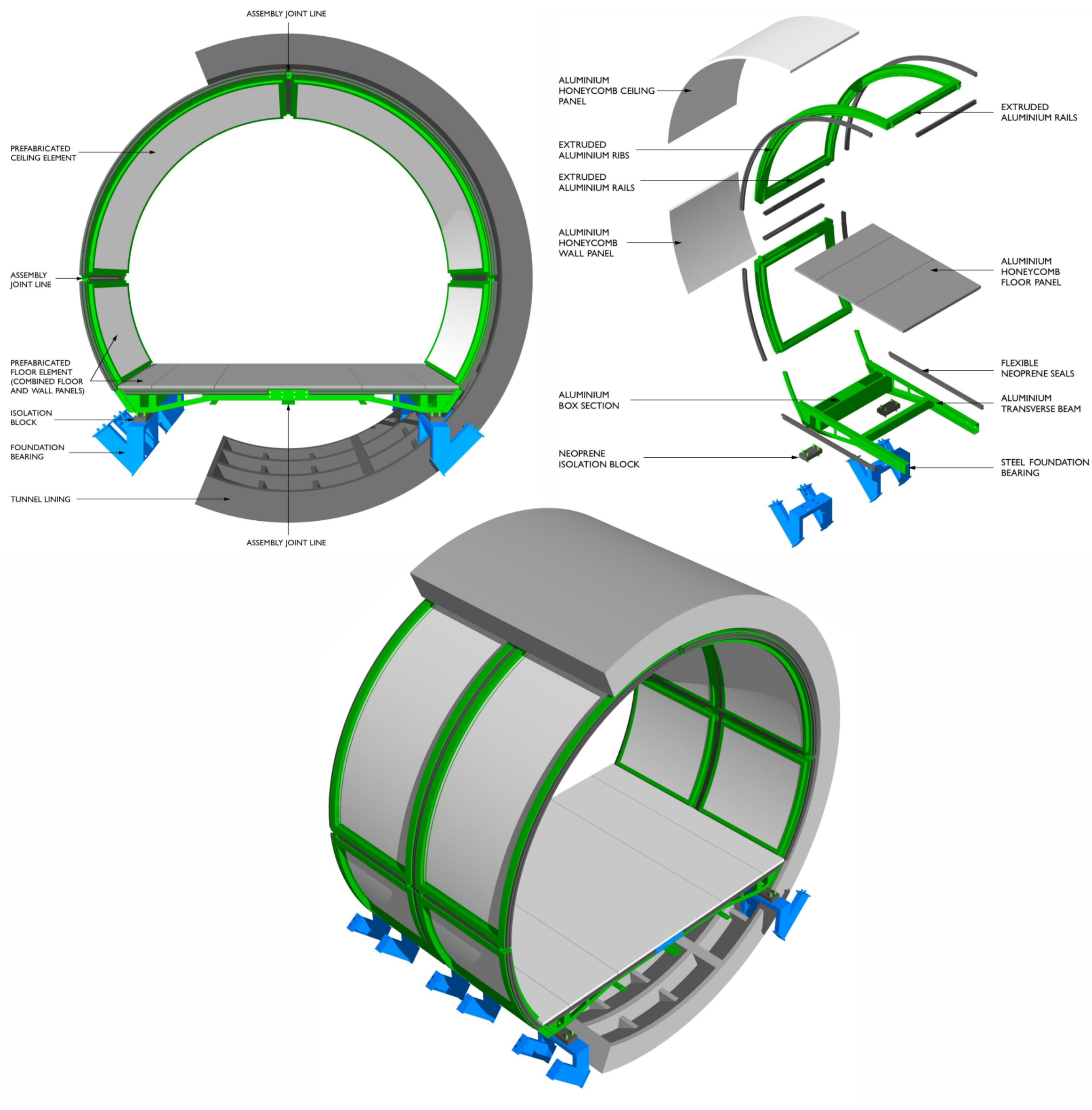


Figure 9 Illustrations of the Laboratory Structural System

X. Environmental Control & Life Support System

The isolation laboratory requires its own life support systems to provide crew habitability and maintain crew health and sustenance during the missions. This cannot be provided by the present tunnel system which only has air ventilation. Tailored ECLS, hygiene and food systems achieveseveral objectives. First, they provide a breathable air supply with the right oxygen content, at the right temperature and humidity and with contaminants and odours removed. Secondly, they provide a fresh water supply and long-term food storage. Thirdly, they include amenities for personal hygiene and a solid and liquid waste disposal system. ESA requires that the ECLS systems use terrestrial hardware, that ECLS space technologies apply only if fully developed and tested, and that operational validation of ECLS hardware is not a goal. The ECLS design uses a mixture of ECLS hardware based on building and submarine technologies. The ECLS installations occur primarily in the laboratory sub-floor zone with the distributed ECLS systems running from one end of the laboratory to the other. They are laid out and positioned according to their connections to appliances and equipment above, with bulky items like storage tanks placed on the module centreline where the sub-floor volume is deepest.

There are three engineering concepts for the ECLS atmospheric system with different degrees of recirculation and closure. The first concept is a fully open system with conditioned air supplied from the surface down a lift shaft duct, circulated through the laboratory and then vented into the tunnel system. The second concept is a partially closed system with air continuously revitalized, recirculated and augmented by a small amount of conditioned make-up air from the surface to replenish oxygen. In the third concept, the atmospheric system is closed with manufactured oxygen supplied to the air revitalization and recirculation system. Conventional sewage drainage is not possible far underground and a gravity-based composting toilet is included with a separate urine collection and storage system to extend the composting capacity to 100 days. A more advanced vacuum composting toilet system may be possible but the end gallery narrow passages obstruct straight and level pipe runs, resulting in multiple bends. Grey water recycling -will not fit in the sub-floor zone as there is not room for it. Grey water is therefore periodically pumped to the surface. The food supply and the food waste are stored in separate sub-floor compartments.

XI. Lighting

In the highly confined environment of the isolation laboratory, lighting becomes an important feature in improving and enriching crew member perception of the enclosed volume. Crew members should be able to exert total control over their illuminated environment and choose from multiple lighting effects and combinations suitable for day and night use. Lighting is a human factors issue that is as important as privacy and health but, in contrast to the leading role of lighting design in passenger aircraft cabin interiors, its qualitative role in crewed spacecraft design has usually been ignored. The isolation laboratory, therefore, presents an opportunity to optimize the role of lighting and treat it as an important research topic.

Figure 10 below shows three modelled examples of lighting effects in the laboratory's saloon and the potential for varying the appearance of the interior volume. On the left, overhead concealed white lighting behind the ventilation duct is turned up to maximum to illuminate the curved walls brightly, augmented by adjustable task downlights to illuminate the table. This lighting condition is used during the day for meetings, work, training and other task-based functions. In the centre, the overhead white light is dimmed down during meal times and coloured light added for effect. The task downlights are also dimmed to give a warmer lighting effect on the table. Changing lighting at meal times helps to emphasize meals as special events during the daily cycle. On the right, at night the character of the lighting changes completely to simulate a night-time environment. All the bright downlights and concealed lighting is turned off with illumination provided by cool colours and plenty of shadows to create perceived depth. In the distance, a brighter light can add interest.

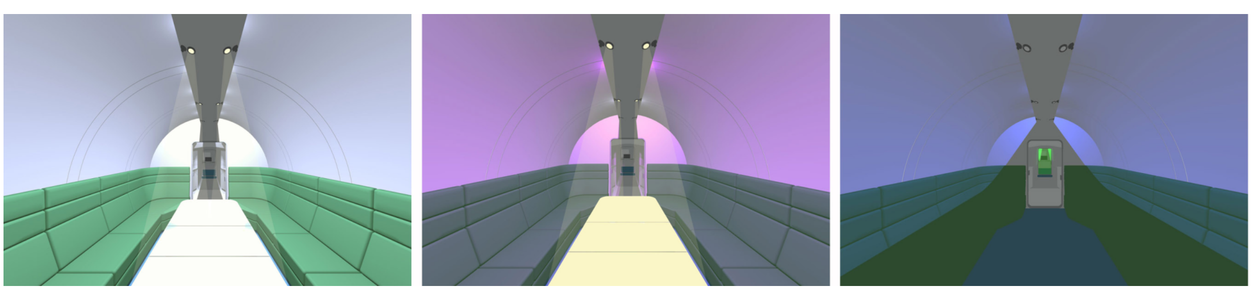


Figure 10 Examples of Internal Lighting Effects

XII. Operational Control

A surface facility controls and monitors the isolation laboratory's ECLS and other systems and observes and communicates with crews. These functions can be co-located in an operations control centre. The control centre location must be next to the lift shaft and tunnel control room operated by SCK-CEN. This will ensure control coordination and synchronization under normal operating conditions as well as in emergency situations. SCK-CEN staff will control the tunnel system up to the exterior of the isolation laboratory enclosure while ESA staff will control the laboratory enclosure, interior and systems. This ensures a clear division of operational responsibility. The control centre comprises a conference and communications room for group videoconferences and teleconferences with the crew, and a separate control room with consoles and equipment racks for monitoring laboratory ECLS systems and observing the crew.

XIII. Cost

The estimated year 2008 costs of constructing and outfitting the isolation laboratory in the underground end gallery and the control centre at the surface ranges from **€2,957,000** to **€3,392,000**, depending on which ECLS system is installed in the laboratory.

XIV. Conclusions

The project examined the feasibility of a permanent isolation laboratory to be used by ESA to study issues related to the simulated mission confinement of a human crew in remote spacecraft and produced a fairly detailed conceptual design and engineering solution for the laboratory in its proposed underground tunnel location. The project was confined to the underground location and other potential locations or other types of simulator were not part of the study's scope. Crew occupations, tasks and timelines inside the laboratory were similarly beyond the project's terms of reference.

The problems of locating the laboratory in the end gallery of the tunnel system are serious. The viability of the laboratory there is at best marginal and at worst quite negative. The outstanding problems concern the end gallery's limited volume and its questionable safety in an emergency such as a fire. Specifically, the available volume per crew member is about one third of that considered by the US and Russia as necessary for long duration spaceflight. Also, because the end gallery has only one entry and exit point, only one escape route is possible in an emergency where at least two are normally mandatory in the design of surface scientific laboratories and other research buildings. Having said this, it is nevertheless possible to draw the following conclusions:

(a) The isolation laboratory can be designed, constructed and operated as an independent facility for the study of psychological, behavioural, social and habitation issues on simulated missions of varying length and crew mix;
(b) The laboratory's modular and prefabricated design is linearly adaptable to suit different laboratory lengths and is sectionally scalable to suit different laboratory diameters and geometries, driven by different location circumstances;
(c) Different types of environmental control & life support systems utilizing non-space hardware with different degrees of autonomy, closure and crew maintenance can be incorporated in the facility design and become an operational feature;
(d) A surface-based laboratory inside another building similar to the MARS-500 facility at IBMP in Moscow can eliminate the deficiencies of the underground end gallery and introduce adaptability and scalability into the laboratory's life-cycle;
(e) An alternative type of tunnel, such as a disused railway or road tunnel in good structural condition and close to or at the surface, would offer the same degree of isolation and an opportunity to correct the deficiencies and disadvantages of the underground tunnel location;
(f) It would also be possible to evolve the laboratory design into an underwater facility to maximize crew isolation and dependency on environmental control & life support systems, possibly locating it in shallow coastal European waters with good shore access. This approach would draw on the considerable experience gained over the years in the design, engineering and operation of underwater habitats for marine biology research from Conshelf 1 in 1962 to the present Aquarius facility off the Florida coast[10].

Project Team

The project team comprised the following organizations:

4CON Space Ltd. (project management and research)
Altus Associates (architectural design and ECLS layouts)
RFR (structural design)
EADS-Astrium (ECLSS research and concepts)
Davis Langdon LLP (cost estimation)

Acknowledgment

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References

[1]Tafforin, C., and Bichi, A., "Global Analysis of Scientific Data from the Three Experimental Campaigns for the European Manned Space Infrastructure," *SAE Transactions (ISSN 0096-736X)*, 1996, Vol. 105, SAE, pp. 536-545.

[2]European Space Agency, "HUMEX – A Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions," ESA SP-1264, November 2003.

[3]Comet, B., Manzey. D., et al, "REGLISSE – Review of European Ground Laboratories and Infrastructures for Sciences and Support Of Exploration," Compilation of Technical Notes 1-7. ESA. TEC-MCT/20004/3381/IN/CL. 30.10.03.

[4]European Space Agency, "Summary of the Isolation Study Strategy meeting." MSM/GA/2005-95. ESA Headquarters, Paris. 22-23.4.03

[5]European Union, "Charter of Fundamental Rights of the European Union." 2000/C 364/01. OJ. 18.12.2000.

[6]World Medical Association, "Declaration of Helsinki." The 18th World Medical Assembly, Helsinki, Finland, 1964. Amended by the 29th World Medical Assembly, Tokyo, Japan, Octover 1975; the 35th World Medical Assembly, Venice, Italy, October 1983; the 41st World Medical Assembly, Hong Kong, September 1989; and the 59th World Medical Assembly, Seoul, South Korea, 2008.

[7]European Space Agency, "Convention of the European Space Agency." ESA SP-1300, September 2005.

[8]European Space Agency, "Safety & Security Manual." AOS/4167/issue 2. ESTEC, Site Security and Safety Office. 01.24.1994.

[9]Hoffman, S.J., and Kaplan, D.I., "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team." NASA SP-6107. NASA, Lyndon B. Johnson Space Center, Houston, Texas. July 1997; and "Reference Mission Version 3.0. Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team." Exploration Office, Advanced Development Office. EX13-98-036. NASA, Lyndon B. Johnson Space Center, Houston, Texas. June 1998.

[10]Miller, James W., and Koblick, Ian G., "Living and Working in the Sea." Second Edition. Five Corners Publications Ltd. 1995. ISBN 1-886699-01-1.