Design of Space Music Hall as a Module of Low Earth Orbit Space Station

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In recent years, new space stations in low Earth orbit have been considered and developed by several private companies to replace the International Space Station (ISS). In the future, when more people will stay in orbit for longer periods of time, the following demands are expected to arise: (1) a place for orbiters to relax and unwind, (2) a place for communication, and (3) a place for new cultural activities of humankind. We designed a crewed module in space that functions as a place for cultural activities such as concerts and live performances. In this paper, the feasibility of these facilities is studied and its in-orbit operation planning is also considered.

Nomenclature

+TAR = Earth (the TARget) side of the Music Hall module
-TAR = opposite of the Earth side of the Music Hall module
A = Area of the window surface
ATCS = Active Thermal Control System
C = heat Constant of the module
C&DH = Communication & Data Handling unit
CHX = Cabin Heat Exchanger
CO2 = Carbon Dioxide
dB = decibel
ECLSS = Environmental Control and Life Support System
Fs = view factor
GS = Ground station
H2 = Hydrogen
H2O = Water
HEPA = High Efficiency Particulate Air Filter
IMV = nter-Module Ventilation
ISS = International Space Station
JEM = Japanese Experiment Module
kg = kilogram
kW = kiloWat
LEO = Low Earth Orbit
m = mass of the module
MISSION = Mission equipment
MLI = Multi layer insulation
N2 = Nitrogen
NASA = National Aeronautics and Space Administration
O2 = Oxygen
PA = Public Address
PCDU = Power Control & Distribution Unit
Ps = Solar constant
SIDE = target side of the Music Hall module
T = Temperature
t = unit time
VRA = Vent Relief Assembly
WS = Water separator for dehumidification
α = Alpha
ε = Epsilon
σ = Stefan-Boltzmann constant

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I. Introduction

ISS (the International Space Station) is the largest crewed LEO (Low Earth Orbit) space station in human history and has been in operation for more than 20 years[1] ,but it was announced that the ISS will cease operations around the end of 2030, as it has fulfilled many of its roles[2]. At the same time, however, several new LEO space station development and construction projects have begun to arise in recent years. For example, several U.S. private companies have begun to develop new LEO space stations, aiming to provide an orbital platform to replace the ISS[3,4]. It is considered that LEO is the easiest for private companies to embark on human space development because it can carry more weight than geostationary orbit, the Moon, or Mars, and because it is safer and less affected by radiation, and high-speed communications are possible. Given the fact that short space tours in ballistic orbit and personal travel to the ISS are already a reality, LEO space stations are likely to develop significantly in the coming decades.

Table 1.1. Levels of ECLSS mass loop closure

The contents of the first 3 columns are adapted from Wieland[5] and that of the last columns are referred from Ohkami et al[6]

Level of Closure	Description of Closure	Mission Scenarios/Duration	Class
Totally Closed	Closed except for losses due to leaks, EVA's, etc. (e.g., biological life support)	Lunar colony, Mars colony/permanent	1
Solid Waste Recycling	Recovery of solid waste (e.g., for use as fertilizer for plants)	Lunar base, Mars base/decades	2
Food Production	Fresh food grown to supplement stored food	Evolutionary S.S. Freedom/ decades, Mars mission/years (no resupply)	3
O2 Recycling	O2 recovered for reuse	S.S. Freedom/years	4
Water Recycling	Water recovered for reuse	S.S. Freedom/years	5
Totally Open, Using Regenerable Techniques	Reduced expendables (e.g., use of molecular sieve instead of LiOH for CO2 removal)	Skylab/months, extended duration orbiter, rover habitat/weeks	6
Totally Open, Using Nonregenerable Techniques	All mass brought along or resupplied with no reuse (waste vented or stored)	Mercury, Gemini, Apollo, Orbiter/days	7

Table 1.2. Stages of development of closed living spaces

it is organized from Ohkami et al[6]

stage	Stay index (persons/year)	class	cultural,social,economiccal situation	note
1	up to 3	6.7	None. Privacy is not considered.	man-tended,skylab,saryuto
2	3 to 30	5	Privacy is considered a little	MIRE,ISS
3	30 to 300	4	Privacy is considered public play space is added	Planetary Science Research Station Large orbit station
4	300 to 3000	3	cultural, medical facility emerge economic activity start	same as above + sightseeing
5	3000 to 30000	2	education facility	Permanent educational and tourist facilities

How the space station will develop and how the number of people staying on the space station will increase could depend on how advanced the technology of the Environmental Control Life Support System (ECLSS) is in space. According to Wieland (1994), the stages of development of the circulation system in closed space are classified as shown in Table 1.1. According to this, the current ISS is a physico-chemical ECLSS, since it performs “Water Recycling” and a part of “O2 Recycling” in the first column of the table. Moreover, Ohkami et al (2008) numbered this classification from 1 to 7 (we added to the last column of the Table1.1), and then classified the developmental stages of closed living spaces as shown in Table 1.2. According to this classification, the current ECLSS of the ISS belongs to the circulatory system of class 5, with about 7 people staying on the ISS, which means that the development stage of the closed living space is in the second stage. There is a strong link between the future development of the L EO space station, where more people will stay in orbit, and the achievement of Circulatory System Class 4, where oxygen is almost completely recyclable. This paper focuses on those periods in which this state of closed living spaces is reached.

As LEO space stations develop and more people (dozens or hundreds of people in total, including facility workers, visitors to hotels, researchers, etc.) live in orbit for a certain period of time in the future, the following demands for the life in orbit and human activities are expected to arise.

1. A place for relaxation: to release the physical and mental fatigue caused by the constant awareness of the dangers of space debris and radiation.
2. A place for socialization among people in orbit: to promote interaction among them, relieve loneliness and lack of communication, and facilitate their work and labor in a closed space.
3. A place for new cultural activities of human beings: a place to create a culture unique to space and to promote the development of human culture.

Now, the number of people staying in orbit and the number of days each person stays in orbit are limited. Therefore, the function of the living space does not need to be sophisticated. However, entertainment and cultural activities are essential for people who stay in orbit for sightseeing purposes or who work in orbit for long periods of time with vacations in between.

Here, we consider some previous examples of cultural facilities on the space station. First, the International Space Station has a Russian service module called "Zvezda". This module has crew members' sleeping quarters, a toilet and hygiene facilities, a galley with a refrigerator, and a table for securing meals while eating[7]. This module is considered to give ISS crews cultural exchanges among international crew members through meals. Second, as for cultural activities on the space station, several musical instruments have been played on the ISS. The acoustic guitar is a typical example, and keyboards, saxophones, flutes, and Japanese instruments such as the dragon flute and koto were also played by Japanese astronauts in the Japanese Experiment Module (JEM)[8]. These are the conditions in which cultural activities are practiced by utilizing the space of the existing module. However, no facility designed specifically for cultural activities has ever been launched in orbit. There is also no example of an established musician performing in space.

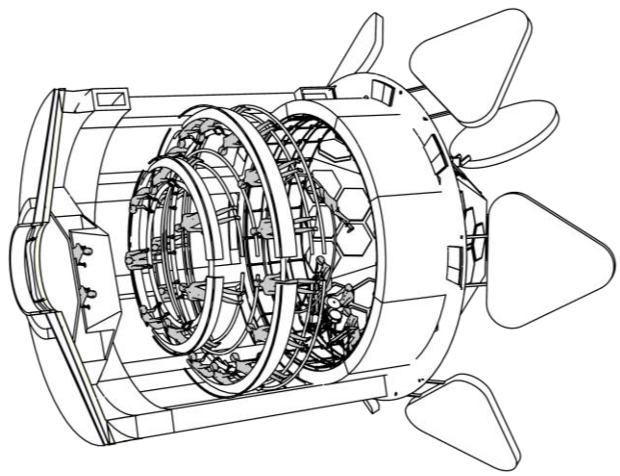

Figure 1.1. The picture of the designed module (The front walls are removed to show the inside)

In this unprecedented situation it is necessary to have an advanced conceptual design in order to realize an entertainment facility that can be enjoyed by many people and to prepare for the time when entertainment and cultural facilities in space begin to be seriously considered in the future. Therefore, we design a crewed module in the space station that functions as a place for cultural activities, generally called a "theater hall," and verify its feasibility on orbit by planning how to operate it. Through this verification, we consider how the "attractiveness and novelty unique to space" affects culture in space and use this as an example for future research on the formation of space culture and the actual design of similar facilities.

II. Mission Design

In this section, we will describe the process of concretizing the mission concept in the first stage of the design.

First of all, we defined theater space as "the presence of an audience and a stage”. This is because the concise definition could enable us to be more flexible in design without the common sense of ground facilities. Next, we define the characteristics of the low earth orbit as

A) Microgravity environment
B) Earth view
C) Closed environment
D) No sound propagates outside the module

Utilizing the advantage of (A) and (B), we postulated the potential to achieve the "attractiveness and novelty unique to space".

Second, we assumed that the module is a part of a huge space station complex with living quarters and research facilities and then defined the specifications of the space station. This space station will have the specifications shown in Table 2.1, and 30 to 300 people will stay there for long and short term stays for various activities such as scientific and technological research, sightseeing tours, operations, and other. The control system is assumed to be basically the same as that of the International Space Station, with scaled-up power generation and supply. The interface between the space station and each module is assumed to use the same common berthing mechanism as that of the ISS[9].

Last, the overall flow of this mission is then configured as follows and Figure 2.2, starting with the method of transport to LEO.

1. launch by rocket to reach the orbit of the station
2. rendezvous docking of the rocket to the space station
3. taken out by the space station's robotic arm and docked at the destination port
4. initial checkout, including antenna deployment
5. assembly of the seats and stage
6. operation (multiple modes)

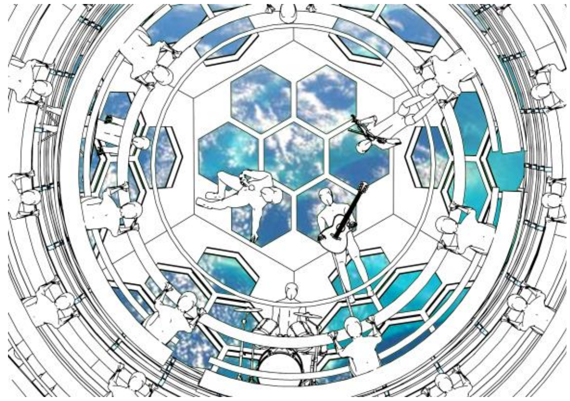

Figure 2.1. View of the Earth through the stage and window

Table 2.1. comparison of the assumed space station specifications with ISS

	ISS value[6]	Assumed value
orbit altitude	400 to 500km	
orbit inclination	51.6deg	
operation period	20year	20year or more
structure	Module docking	
number of modules	13	15 to 100
crew number	7	30 to 300
mass	420ton	3500ton
Total power consumption	90kW	750kW
Payload power consumption	30kW	250kW
area of solar panel	2500m^2	9000m^2
area of heat radiator	872m^2	2150 to 5100m^2
station keeping propellant	7ton per year	53ton per year

The rocket envisioned here must have the following capabilities capable of accommodating and launching the module, which has a diameter of about 8 meters, capable of rendezvous docking with the ISS, and capable of opening the hangar while docked to the ISS so that the robotic arm can remove the module. There is no rocket that meets these requirements as of February 2023, but SpaceX is developing a large spacecraft called "Starship," which has a diameter of 9 meters and is planned to have the capability to transport the module to the space station[10]. Therefore, assuming that a rocket that meets the requirements of this project will appear in the future, the module was designed with reference to some of the Starship's specifications. The operational period is assumed to be 20 years.

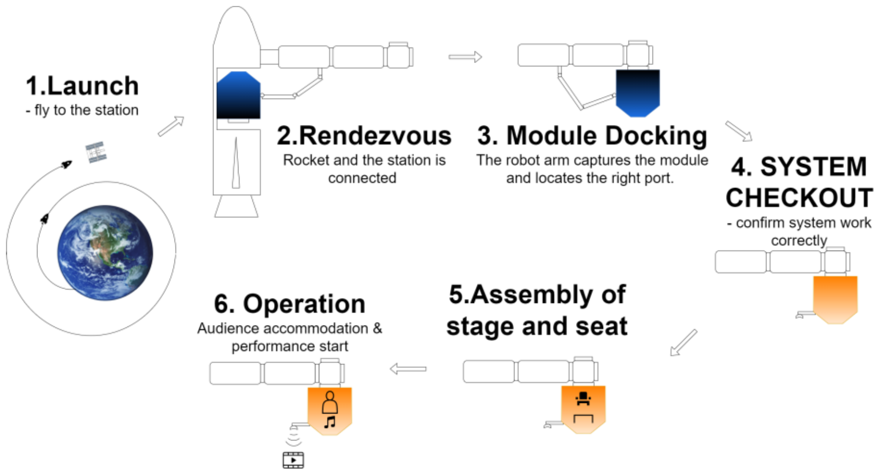

Figure 2.2. Mission sequence

III. Music Hall Design

In this section, we explain the design for the function of a music hall. As we defined in section II, the theater space essentially consists of an audience space and a stage and was designed especially for a microgravity environment. In addition, this module also required a special design for the sound and lighting equipment.

First, we introduce the design of the stage. The performance space must allow the performers to maximize their performance and fully deliver the intended dramatic effect to the audience. Based on the basic requirements of the performance space, we utilized the characteristics of microgravity space and adopted a design that "pinches the left and right edges of the theater on the ground and bends them into a cylindrical shape to close them". The stage is a circular space with a diameter of 5m and a length of about 3m, allowing the performer to utilize the space in three dimensions and to swim around the body while performing. Then, handrails are placed at appropriate intervals on the walls, and by using equipment such as poles, platforms, Velcro, and strings, the body and instruments can be freely fixed, allowing

Figure 3.1. Free performance style
performers can move around the stage

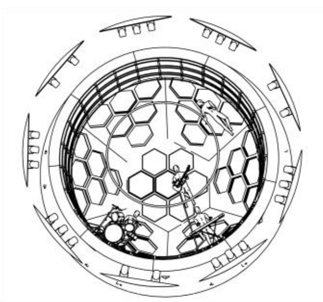

Figure 3.2. Band performance style
some performers are in a fixed position

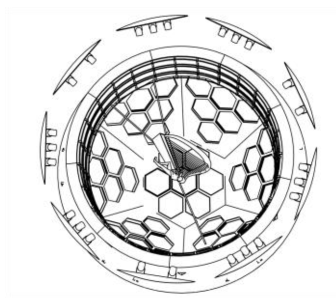

Figure 3.3. Harp performance style
music instruments are fixed, and a musician plays around it

for a variety of performance styles. The detailed configurations are shown in Figures 3.1 to 3.3. The back of the stage has a large window with a view of the earth, allowing the audience to enjoy the performance on stage and a view at the same time. The figure below shows the view of the stage from the audience seats.

Secondly, the audience seating was also designed to take advantage of the characteristics of microgravity based on the basic requirements and a three-dimensional circumference of the seats. In order to accommodate the audience as efficiently as possible, the seating arrangement consists of two rows: the first row seats 10 people on a circumference of about 3 m in diameter, and the second-row seats 18 people on a maneuver of about 5 m in diameter. By increasing the diameter of the circumference on each row, the audience can get a good perspective of the stage no matter where they sit and enjoy the artists' performances from various directions (see Figure 3.4). In a microgravity environment, even if you sit on a seat, you will float up due to reaction force. In addition, it is necessary to consider the natural posture in a microgravity environment (see Figure 3.6 and reference[11]). As a result, we configured the seating with curved seat shapes for the handrails, footrests, and waist area (see Figure 3.5) to achieve a support shape that allows the audience to stand naturally in place and properly direct their sight lines toward the stage. The support shape allows the audience to stand naturally in place and their line of sight to the stage. As for evacuation, as will be explained in detail in section D. Safety Management System, measures were taken to ensure that emergency evacuation would not be impeded by the smooth arrival and departure from the seats.

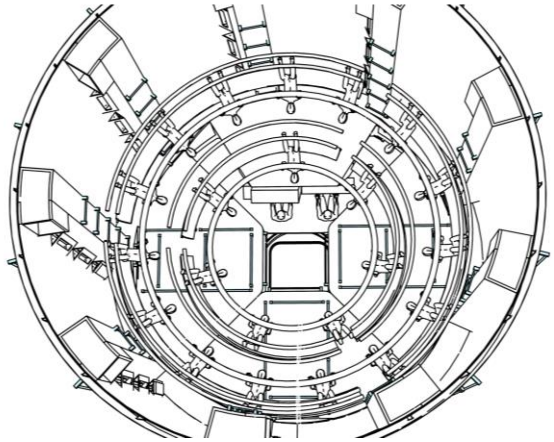

Figure 3.4. View of the audience area from the stage

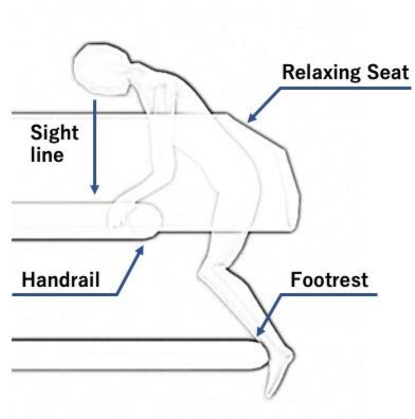

Figure 3.5. Design of the audience seat

Additionally, the sound and lighting equipment effectively utilized the three-dimensional characteristics of the space. Speakers are mounted around the perimeter of the stage, and lighting is mounted between the stage and the seating space, both in a circle. This allows sound and lighting to be delivered in all directions. In addition, a space PA table equipped with lighting and sound operation equipment was placed on the -TAR surface (Figure 3.7.), as it was considered necessary

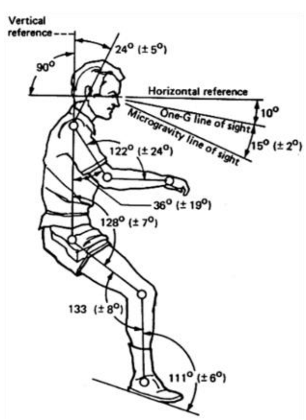

Figure 3.6. Neutral body posture[11]

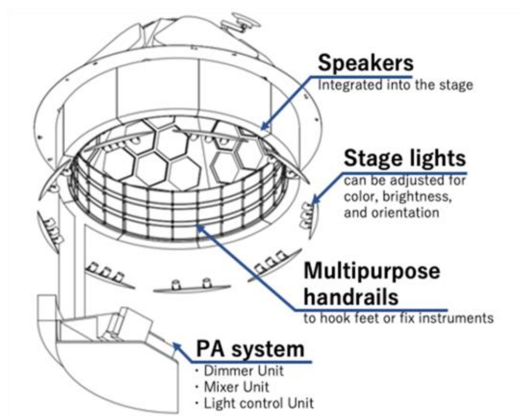

Figure 3.7. PA (Public Address) configuration

to have not only performers and audience but also staff and backstage personnel to make the theater work.

In conclusion, the above design features will enable performances in this module to realize three-dimensional performances that do not exist on the ground, taking advantage of the characteristics of microgravity, and the window behind the stage that provides a view of the earth will create a moving experience, making it a music facility with a special attractiveness that cannot be found in ground-based facilities.

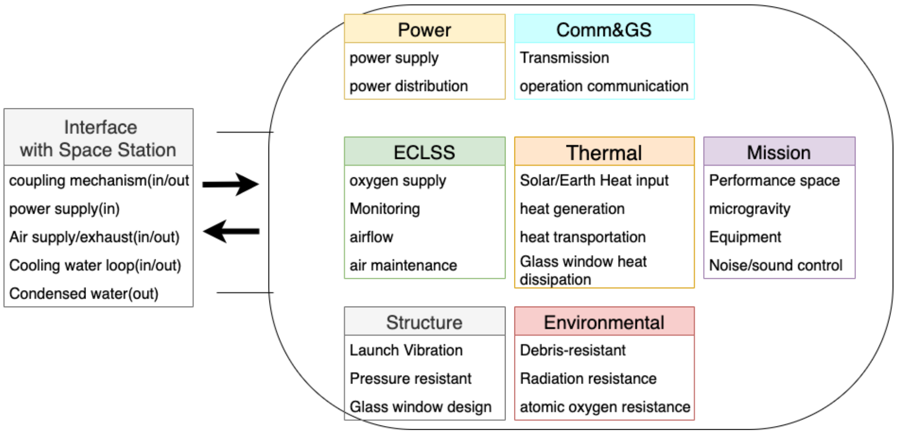

Figure 4.1. Subsystem Configuration

IV. Subsystem Design

In this section, a brief introduction to the subsystem design of the module is provided. Figure 4.1 summarizes the subsystem elements of the module. The design is based on the "JEM" module for the International Space Station, and detailed discussions are omitted where there are no new issues. On the other hand, since the module was designed specifically for a space music hall, it is necessary to examine the technical feasibility of a system that differs from existing modules.

A. Structure

The module consists of a cylindrical shell approximately 7.4 m in diameter and 8 m long (we call this section SIDE), a cupola section of 2.6 m in length(+TAR), and the section with a docking port to the space station(-TAR). Figure 4.2 shows the module accommodated in a rocket. Figure 1.1 also shows the overview of the designed module. While the module needed as large a size as possible to accommodate a wide performance stage space and a large number of spectators, the size and weight of the launch rocket fairing restricted the design. While the aluminum metal cylindrical shell structure has been used in modules for the International Space Station, inflatable structures (e.g., Bigelow Aerospace's "BEAM"[12]) and deployable structures (e.g., folding structure by Sogame[13]) have also been attracting attention in recent years. However, considering that the module to be used for this project requires overall rigidity due to the glass window and that the internal support structure in an inflatable structure would be an obstacle, an aluminum metal cylindrical shell structure with high reliability was adopted. According to the user guide[10] for the "Starship" launch vehicle, the maximum payload diameter is 8m. Therefore, this module

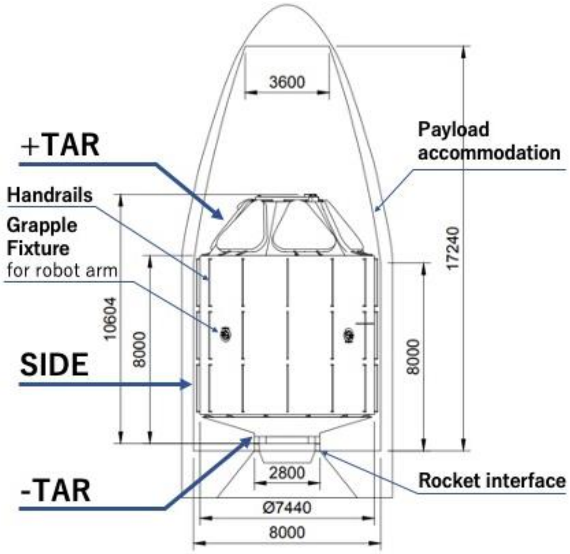

Figure 4.2. rocket accommodation of the designed module (the unit of length: [mm])

was designed to fit within the outer diameter of 8 m, including protrusions. Weight parameters of each section are shown in Table.5.1. Total weight is about 16 tons, and it is allowable in view of max payload weight.

Table 4.1. weight parameters[kg]

section	structure	equipment	total
SIDE	5454	3123	8577
+TAR	3808	34	3842
-TAR	2043	2008	4051
total	11305	5165	16470

The view of the earth while the audience listens to the performance is designed for +TAR as an entertainment element that cannot be realized in a music facility on the ground. To achieve this, the entire surface of the +TAR was designed as a window (see Figure 4.3 and 4.4). ISS has a window with a similar purpose called a "cupola”[14] and this design is based on this structure. Since the glass structure is vulnerable to debris impact, the window should not face the direction of the space station and should be covered with a rigid shelter when not in use. Furthermore, since the crew may be exposed to radiation from space radiation and heat inside the module may escape, the glass window should be fitted with a cover, and a motor should be used to drive and control the window so that it can be opened and closed. During the design study, there was concern about the lack of strength for deflection due to the size of the window being designed being larger than the "cupola". For this reason, the window was made of hexagonal plates in a segmented structure, which resulted in a highly design-oriented appearance (see Figure 2.1).

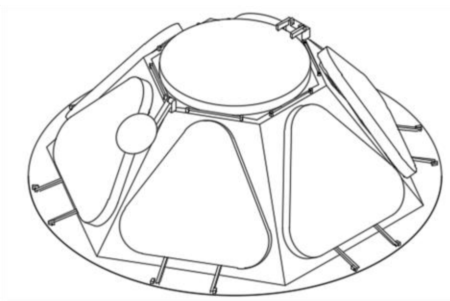

Figure 4.3. +TAR window close

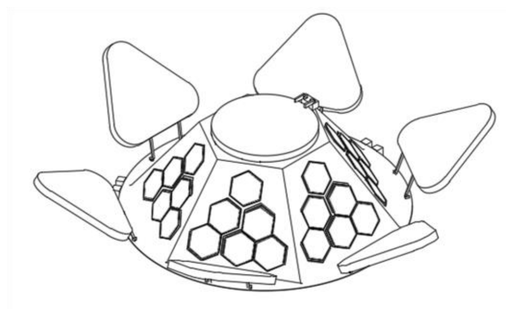

Figure 4.4. -TAR window open

B. Thermal control

In this module, we studied the thermal control system, which is important for hardware feasibility and human habitability.

The thermal control system for this module and its space station is assumed almost the same as that of ISS. The thermal environment conditions in the ISS pressurized space are shown in Table 4.2. The thermal requirements for a space station with a crew space are not only the allowable temperature range of the equipment, but also the temperature and humidity conditions of the cabin air where people can live, the surface temperature of equipment and walls to prevent burns and frostbite, and the prevention of condensation on windows and walls (above the dew point temperature) to prevent mold formation.

Table 4.2. Thermal requirements of ISS

	ISS requirement	unit
humidity	25 to 70	%
module temperature	18.3 to 29.4	℃
dew point	4.4 to 15.6	℃
surface temperature	4 to 45	℃

Like the ISS, the external surface of this module is covered with MLI to insulate it. Because the thermal radiation environment from space changes dramatically with time, it is difficult to maintain the above narrow temperature range with the thermal control based on surface optical properties, which is commonly adopted in satellites. The heat generated inside the module is collected by the cooling water loop, transported to the outside of the module by the heat exchanger, and dissipated by the radiator(see Figure 4.5). The radiators are not shared among the modules but are centralized by the radiators managed by the station. However, while a typical module is insulated by covering the entire surface with MLI, this module has a large window, through which heat is exchanged with the outside. Therefore, it was a concern whether a thermal balance could be achieved in this situation, and a single-contact thermal analysis for the module was

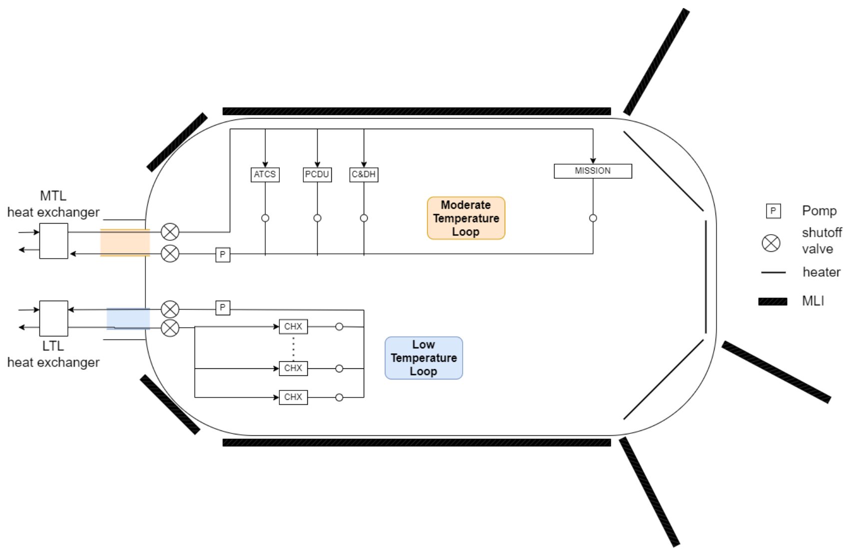

Figure 4.5. Overview of thermal control system of the designed module

performed. The thermal equilibrium equation was formulated as follows, where *Qs* is the heat input from solar radiation, *Qa* is the albedo heat input from the earth, *Qe* is the infrared radiation from the earth, q is the heat dissipation from the window, *We* is the internal heat generation, and Q is the amount transported from the cooling water loop. It is assumed that all heat exchange inside and outside the module, except for the cooling loop, is through a window with a representative cross-section area of A.

$$mC\frac{dT}{dt} = Q_s + Q_a + Q_e - q + W_e - Q \tag{1}$$

$$Qs = \alpha sFsPsA \tag{2}$$

$$Qa = \alpha sFaPaA \tag{3}$$

$$Qe = \varepsilon FePeA \tag{4}$$

$$q = \varepsilon\sigma T^4 A \tag{5}$$

Since the amount of heat transport by the cooling water loop can be freely controlled to some extent (but Q must be larger than 0), the operational condition is that Q must be larger than 0 at temperature equilibrium (dT/dt = 0). This can be summarized in the following equation.

$$(Q_s + Q_a + Q_e - q) + W_e > 0 \tag{6}$$

Table 4.3. thermal analysis results in each operational mode

Operation mode		Nominal		Performance		Performance(MAX)	
people		2		>10		30	
window		open	close	open	close	open	close
Heat input	Solar radiation[W]	0	0	0	0	0	0
	Albedo[W]	0	0	0	0	0	0
	infrared radiation[W]	13141	0	13141	0	13141	0
Heat output	Temperature[°C]	**4**	-	26	-	26	-
	Radiation heat[W]	-20949	0	-28435	0	-28435	0
Heat generation	equipment[W]	7519	7519	22384	22384	22384	22384
	human[W]	292	292	1460	1460	4380	4380
Q(water loop transport)[W]		**0**	**7811**	**8550**	**23844**	**11470**	**26764**

As a result of the study, it was found that the window has a basic tendency to dissipate heat. It was found that if the window is oriented toward space, the heat balance becomes negative and the temperature inside the module decreases. Based on these findings, it was decided that the window should be oriented directly below the Earth. This was also effective in reducing the crew's exposure to radiation. Next, the overall heat balance for each mode of operation was organized, considering the amount of heat generated by the number of people in the room and by the on/off of the performance equipment. Here, we assume an eclipse time, which is on the worst side of low temperature. The results are shown in Table 4.3. It shows that in steady-state mode, i.e., when no performances are taking place and there are few people inside, the equilibrium temperature may fall below the acceptable range. Therefore, it was found that it is necessary to keep the windows closed when no performances are taking place. On the other hand, it was confirmed that in other operational modes, the room temperature can be maintained by controlling the excess internal heating value to transport the appropriate amount of heat to the outside of the module by means of a cooling water loop.

C. ECLSS

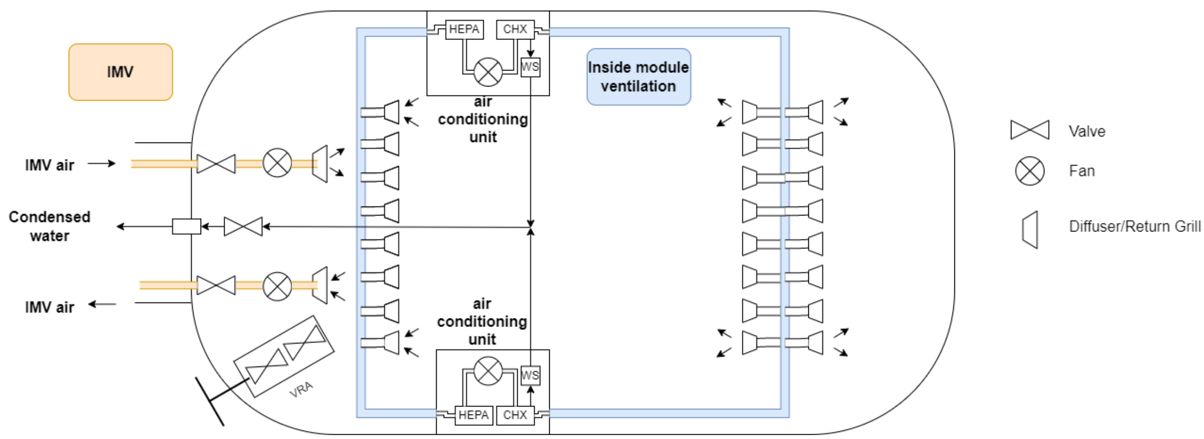

Figure 4.6. Overview of air management system of the designed module

In this module, we studied the air management system, which is an important component of the Environmental Control and Life Support System (ECLSS) required for a crewed module and achieved the requirement to maintain fresh air in the module. The ECLSS is an essential life support system for a manned module, consisting of water, air, food and waste management. However, because this module is designed to be an entertainment and cultural facility docked to the station, we rely on the station for food, water and waste management. Regarding the air system, we have identified the following two requirements: 1) to maintain a constant level of carbon dioxide in the module with fresh air from the station, and 2) to ensure that fresh air is continuously circulated in the module to provide a comfortable environment for the crew.

For the first requirement, to maintain a carbon dioxide concentration of 0.53% (the allowable limit for air in the module) with 30 people in the module and a CO2 emission of 0.022 m3/h per person, it was necessary to ventilate the module at a rate of 16.9 m3/h between the module and the station, based on the station atmospheric CO2 concentration of approximately 0.4% [15]. For the second requirement, we set the minimum air circulation velocity inside the module to 0.076 m/s, using JEM as a reference for a quiet module[16]. To ensure an even distribution of the air volume throughout the module and to prevent the air from being concentrated in certain areas, we arranged multiple fans on the circular axis of the cylinder to circulate the air within the module. With a cross-sectional area of 40.85m^2 and a minimum circulating air velocity of 0.076 m/s, the minimum air volume required

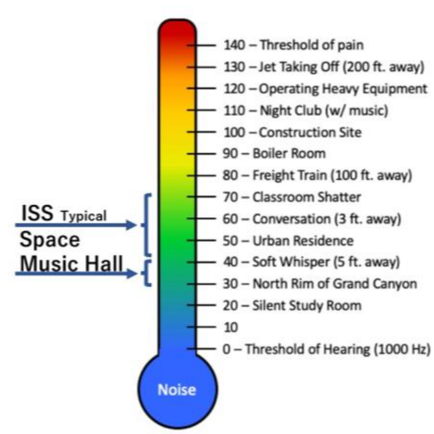

Figure 4.7. Acoustic noise level of ISS and the designed module

The picture is referred by Ref. 17

Table 4.4. quantities of sound absorbed material

place	sound absorbed material	size
inside the elbow	Glass wool & Punching metal	25mm thickness
inside the duct	Glass wool	36.2mm thickness
outside duct	lead	0.75mm thickness
sound absorbed box		800mm ×400mm ×1000mm box
inside the box	Glass wool & Polyethylene film	100mm thickness

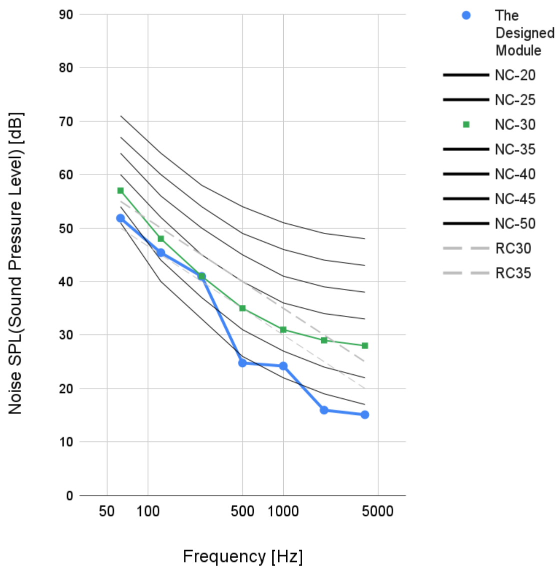

Figure 4.8. Noise characteristic of the designed module

was 3.1 m^3/s, which we achieved by installing nine sirocco fans with a minimum air volume of 0.4m^3/s around the circumference of the cylinder.

In addition, the noise generated by the internal circulation fans posed a significant challenge to musical activities, requiring soundproofing measures. Similarly, ISS has a large number of fans and pumps in constant operation that generate noise. Currently, the internal noise level of ISS is approximately 50-60 dB (Ref. 18), which poses significant challenges for astronauts, including the risk of hearing loss. Therefore, in the current design, the noise generated by the fans used for internal circulation was identified as the most significant noise source, and as a result, the fans were placed in a dispersed manner to reduce the noise level, and soundproofing measures were implemented around the fans and ducts. Based on Ref. 18, noise calculations were performed, and sound-absorbing materials such as lead, and glass wool were installed around the supply air fans and ducts in sufficient quantities (as specified in Table 4.4) to achieve a noise characteristic similar to that shown in Figure 4.8. To achieve a noise level suitable for a music hall, it was necessary to reduce the noise level to NC30 (as shown in Figure 4.8). This has been achieved with the current design, but further detailed design is required to address the noise distribution in the room and the sound absorption characteristics of humans.

D. Safety management

Crewed space modules require reliable safety management and operation. Catastrophic hazards that could result in loss of crew life or loss of the space station include, for example, fire, air contamination by toxic gases, and sudden depressurization due to debris impact. For these hazards, a two-failure tolerant safety design is required. For example, bumpers are installed on the outer shell to protect against debris impact, and emergency evacuation operations are implemented if the bumpers are not sufficient to protect against these hazards. Although the basic safety design of this design, such as bumpers, could be the same as the existing design, it was necessary to examine whether emergency evacuation would not be affected by the fact that a large number of people stay in a single habitation module.

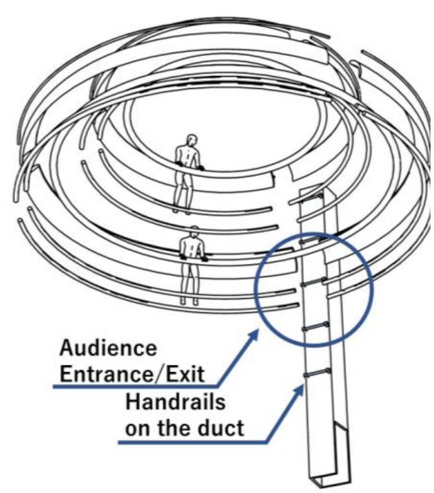

Figure 4.9. Configuration of entrance and exit for audiences

The design is required to ensure that in the event of a catastrophic hazard, the guests can immediately move to an exit and evacuate to a separate module. The module designed for this project has a capacity of 30 people, which is very large compared to that of the International Space Station. It also does not have a second exit that would be effective as a redundant system. Therefore, a handrail was installed on the wall to allow the crew to move smoothly to the exit, and a clear evacuation route for the audience and performers was also provided by using the handrail.

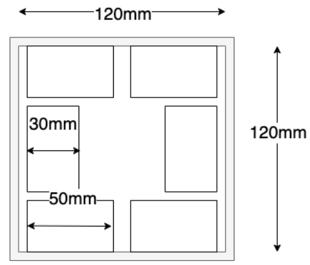

Figure 4.10. size of the port and area occupied by people passing through it

The evacuation time for dozens of crew members to evacuate outside the module was also studied. According to Ref. 20, it is estimated that it takes 200 seconds for the atmospheric pressure in the module of JEM to drop from 1 atm to 0.7 atm when a hole of about 10 cm is invoked by a debris. First, we calculated the time for one person to reach the port from the other side of the module. According to Ref. 21, the speed of grabbing and moving inside a space facility is estimated to be 1.5m/s~2m/s. Since this module is about 10m long, it is estimated that it would take about 10 seconds to reach the entrance/exit area if there is an appropriate guiding handrail. Next, we calculated the time how many people can pass through the port and how much time it takes. The size of the port is 1200mm x 1200mm square (this size refers to Ref. 22) and we assume that the size of the surface occupied by one person is 30cm x 50cm. Figure 4.10 shows that four persons and a maximum of six persons can pass through the port at the same time. If the time required for one person to pass through the port is 10 seconds, it takes $10 + 30/4 \times 10 = 85$ seconds to evacuate 30 persons. This is sufficiently smaller than the decompression time of 200 seconds to ensure safety.

E. Power and communication

The power consumption of the module is assumed capable of supplying the specified amount of power from the station's solar array paddles. The power consumption of the module's internal equipment is as follows for each operational mode. The required power for this time is almost the same as that of the ISS JEM (Ref. 23), and there should be no problem with the amount of power supplied.

Table 4.5. Power consumption (unit: wat)

Power consumption	Nominal	Performance
ECLSS	4260.6	4260.6
Thermal control	1044.4	1044.4
C&DH	760	760
Communication	524	524
MISSION	0	14865
Lighting	930	930
Total[W]	7519	22384

For the communication system with the ground, the concept was discussed. It would be very valuable to broadcast the performance of this module to the ground simultaneously. The problem with real-time video streaming is that the time available for communication with a single ground station is only about 10 minutes. This is because the station is in low earth orbit. Although it is conceivable that ground stations could be placed in various locations to provide constant communication, the most realistic concept for the future is to link to any ground station on the earth via a geostationary satellite or a low earth orbit communication relay constellation.

V. Discussion

In this section, we discuss how much of the feasibility of the proposed concept was achieved by the above design results. First, it is considered that the basic hardware design feasibility was fulfilled under the assumption of the space station's specifications. The interface configuration also meets the basic requirements. In addition, the design of life support control and safety management, which should be considered for a crewed module, are also sufficient for consideration in the conceptual study phase. Furthermore, the basic requirement for a music hall, "a space for performances and seating," has been achieved, and the introduction of a new performance style that takes advantage of microgravity and a concept for viewing the earth has also been successfully implemented.

On the other hand, it is necessary to discuss matters that could not be adequately considered in the design target of this research. First, from a cost perspective, it is not sufficiently clear whether the present design was feasible or not. Second, as for safety management, fire detection and extinguishing methods in the event of fire are considered important safety management issues but were not examined very much this time. For example, in the JEM module, air circulation is stopped in the event of a fire, and firefighting is performed in individually separated firefighting compartments (Ref. 24). This method cannot be applied to an open space like this where there are large numbers of people. Third, when it comes to the design of a music hall, design and evaluation of sound reverberation acoustics must be conducted as in the case of music halls on the ground. This can be verified on the ground using a mock-up. Finally, we made bold assumptions about the space station, rockets, and communication relay constellations. This allowed us to focus on the module design, but there is no doubt that these systems also need to be studied in detail.

VI. Conclusion

This study pointed out the possibility that low-Earth orbit stations will develop significantly in the coming decades and that more people (dozens or hundreds of people in total, including facility workers, hotel guests, and researchers) will be living in orbit for a period in the future. In this situation, it was considered that there would be a demand for entertainment and cultural facilities for those staying in orbit and for human activities, and that such facilities have not been sufficiently considered at this time. Therefore, we designed such a facility to study its feasibility, and to clarify its necessity and potential attractiveness. As a result of the design, the value of a music hall incorporating attractions not on the ground was embodied, and the basic feasibility of the subsystem was also verified. On the other hand, it was confirmed that this design includes many assumptions for the future and that these assumptions have not been fully verified. Based on the above, although this design is still a prototype and a first approximation, it could be a valuable first study in predicting future culture, such as the design of a performance space on the space station and a module where many people can stay.

Appendix

This section supplements the study of the business viability of the actual commercial operation of this space music hall. While the feasibility of the design and the cost of development are necessary, the business viability of such a facility must also be taken into consideration.

First, a simple calculation was made to determine the order of magnitude of the audience ticket price that would be required to generate a profit in excess of the cost of development and operation. The table A.1 shows the amount of cost that would be required to make the development and operation, the setting value used for calculation of sales, and total profit after operating this module for five years. The cost refers to that of JEM[i]. The number of launches per year and launch costs are tentative values that take future projections into account, and the validity of these calculations will be subject to further discussion. The number of participants in the on-ground streaming was referred from the number of participants in the streaming type of live performances of famous artists[ii].

Table A.1 Simple estimation of cost and revenue

	item	value	unit
cost	development+launch	2455	million dollars
	operation	82	million dollars/year
	total	2864	million dollars/year
set value	Orbit viewing ticket	1	million dollars/year/live
	Streaming ticket	100	dollars/year/live
	No. of lives	24	live/year
	audience in the orbit	20	people/live
	audience on the ground	100000	people/live
profit	ticket sales	720	million dollars/year
	total sales	3600	million dollars
	total profit	736	million dollars

Immediately it became clear that the number of audiences in orbit is so small that there is a limit to the amount of revenue that can be generated from their ticket prices alone. Therefore, it will be necessary to broadcast the performance (video and audio) in real time to those on the ground and receive a ticket price for participating in the streaming. Even if the ticket price itself is not that high, it is possible to generate revenue from an overwhelmingly large number of people. The following is a concrete estimate of the ticket price;

- Tickets for on-orbit viewing: 1 million dollars/person: about 20 people attending one performance
- Tickets for ground streaming: 100 dollars/person: about tens of thousands of people attending one performance

In this way, a business model that uses two methods, one that "delivers performances realistically on orbit to a small number of people for a high price" and the other that "delivers performance data to a large number of participants for a reasonable price," is considered to be appropriate.

Second, we will discuss the overall business framework of this space music hall. The stakeholders involved here can be roughly divided into the management and operation entity of the space music hall, the on-orbit artists, the on-orbit audience, and the audience participating in the on-ground streaming. The artists' labels and support staff are also largely included in the artists' side of the scheme.

Creating the framework, we thought it is important to allow the artists to make a profit as well as the management and operation entity. Performing in space is a publicity stunt and attracts attention, but if the launch costs and facility usage fees result in a loss, it will ultimately be a "one-time" event. Therefore, it is necessary to be compensated for one's labor in the same way as a regular job, from the time one goes to space to the time one returns, as is the case with today's professional astronauts. In the monetization model shown in Figure A.1, we considered a structure in which a percentage of ticket sales would be the artist's share.

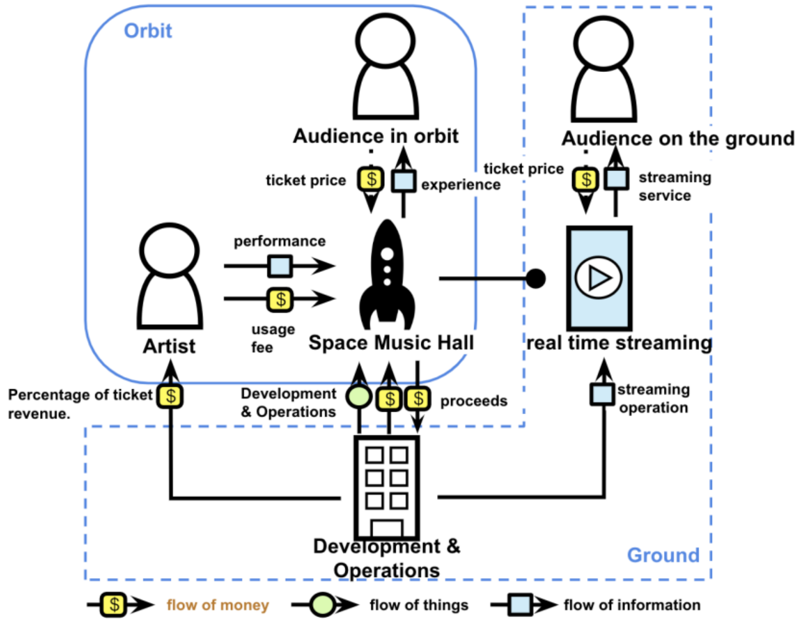

Figure A.1. Business framework of Space Music Hall

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