To cite this document: Amendola, Crescenzio and Lizy-Destrez, Stéphanie Panorama of ideas on structure and materials for the design of a multi-modular space station at EML2. (2013) In: 64th IAC - International Astronautical Congress, 23 September 2013 - 27 September 2013 (Beijing, China).
The goal of the article will be to come up with an optimized solution that can answer the question of how to build a space station (named THOR, Trans-lunar Human explORation): fit for Deep Space Habitat. The spacecraft's structure examined here is based around seven cylindrical habitable modules, each one fulfilling a specific function - leisure and daily life, experiments, Extra Vehicular Activity, Space Medical Center - and two extra spherical sections, used both for daily life activities and docking tasks.

Taking the challenges and constraints of deep-space environment into account and adding up the effects of solar winds in deep space environment, each module has been put through an accurate analysis to then be optimized during the conceptual design of the spacecraft. Some ideas for the propulsive system layout and overall configuration for the docking system have also been proposed.

To make the study at hand as thorough as possible, the research project focus on and examines a wide array of materials used to build spacecraft and stations: metal alloys, composite materials, sandwich honeycomb core, inflatable anti-solar-radiation (at the option of water storage inside), and see-through glass-like materials. Eventually, a conclusive part then try to sum up both structural concepts and material analysis for the final internal and external design of the spacecraft.

During the study, many questions about possible innovative solutions arose, and the final chapter summarize them all.

I. INTRODUCTION

Released in September 2011 by the ISECG (International Space Exploration Coordination Group), the Global Exploration Roadmap (GER) brings under light a way of exploring a large array of destinations situated beyond low-Earth orbit by following a “Moon”-“near-Earth asteroids” and “Mars” pathway. Strong emphasis is put on the need to come up with new and modern space station that would conform to the concept of “Deep Space Habitat”. In order to widen the human presence in the Solar System, this project shows some pioneering design ideas on materials and structures to build a seven-module manned space station located at Earth-Moon Lagrange point n. 2 (EML2).

Many materials and structural concepts will be proposed, all of which will be thoroughly analyzed in the present study, in order to meet all the challenges posed by space environment.

The choice of the Lagrangian point n. 2 is due to the many advantages of this location: easy access form both the Earth and the Moon with minimum launch window constraints, no artificial debris hazard, small fuel requirements for station-keeping and a location independent form country borders on Earth[11]. Moreover, EML2 location is an easily accessible place in Deep Space Habitat for crew and resupply cargoes, without any communication problems (continuous visibility, no delay, ...). As a consequence, it will be a perfect stopover for exploration, presenting high benefits in term of long-strategy and human factors [10].
The assumed space station architecture here examined is based on seven cylindrical habitable modules, each one fulfilling a specific function - leisure and daily life, experiments, Extra Vehicular Activity module, Space Medical Center - and two extra spherical sections, used both for daily life activities and docking tasks.

During the design of the space station, one section focuses on the materials examined in the project: Aluminum alloys, inflatable materials, Lexan-polycarbonate and, eventually, water. Their features have been analyzed in order to satisfy the constraints posed by loads and deep-space environment.

In order to prevent catastrophic failure of the station, each structural component has been tested and optimized. Both external structures and internal architecture have been designed bearing in mind the criteria imposed by a crewed spacecraft. An overall investigation of the docking configurations have also been performed: it consisted in designing and optimizing the anchor points between the spherical modules and the cylindrical ones.

Eventually, a conclusive part then confronts both module and material analysis. The goal here will be to come up with an optimized solution for internal and external layouts that can answer the question of how to build a space station fit for Deep Space Habitat, taking into account both structural and human constraints.

Nowadays, it is not possible to accurately plan the assembly of the seven modules of THOR spacecraft. This aspect strictly depends on external constraints (e.g. state of art for engines, docking system, trajectory optimization), that are still unknown. AT ISAE, studies are undergoing to develop some deployment and operations strategies ([10] and [11]). In any case, two solutions can be presented:

- set up at LEO;
- set up at EML2.

Each solution has its own benefits and drawbacks, and they will be summarized in the paper.

II. ARCHITECTURE

The design of a space station entails complex issues: it is not an easy task to put together such a structure while solving all the constraints at hand. What are the possible ideas for the configuration of a Deep Space station?

The THOR space station consists of 7 cylindrical and 2 spherical modules. The choice of using cylindrical elements recalls the Automatic Transfer Vehicle structure: in fact, each cylindrical module will have the same dimensions than the Automatic Transfer Vehicle (ATV). This choice solves the size issue for a future launch of the spacecraft with Ariane 5, because it is possible to refer to ATV for the overall structure design (Table 1).

<table>
<thead>
<tr>
<th>Cylinder</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>10 m</td>
</tr>
<tr>
<td>Radius</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>4 – 20 mm</td>
</tr>
<tr>
<td>Volume (void)</td>
<td>196.5 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sphere</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>4.5 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>20 mm</td>
</tr>
<tr>
<td>Volume (void)</td>
<td>254.5 m³</td>
</tr>
</tbody>
</table>

Table 1: Modules features

Each module has a specific function: in order to prevent the failure propagation in the whole spacecraft, their critical functions are segregate. Moreover, this solution allows to be more flexible for integration so as to not depend on the integration duration. A first design of the spacecraft is shown hereinafter in Figure 2. The mass of each module depends on its particular function and embedded components. The features must be progressively updated in function of the structural results obtained in the future works. The question that arises is how to optimize the choice of the internal configuration in order to get the best solution. Thankfully, the orientation and the configuration of the modules has already been planned in precedent work performed at ISAE University [11].

![Space Station draft](image)
Mass

Sheer mass is one of the sizing parameters for a space mission. Taking the ATV’s dimensions as reference, it is possible to have a first mass estimation of the space vehicle. The main difference with the ATV has to do with the presence of crew members (and all the technicalities it implies), a propulsive system and fuel: in fact, because of the longer trip, a more suitable engine is needed as well as a much bigger quantity of fuel, implying a full redesign of fuel tanks. Furthermore, the mission is totally different, and so the type of trajectory and maneuvers: this is why it is not more possible to have the same type of propulsive system.

In order to respect the constraints of mass and volume imposed by the Ariane 5 launcher, in the overall design the value of mass has been fixed to 21 t. Due to the presence of crew and engines/fuel, the ratio between the structural mass and the payload’s should change, in order to optimize the mission and to solve all the constraints imposed by Deep Space exploration.

<table>
<thead>
<tr>
<th>Mass Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem</td>
</tr>
<tr>
<td>Structure</td>
</tr>
<tr>
<td>Propulsion</td>
</tr>
<tr>
<td>AOCS</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>TT&amp;C</td>
</tr>
<tr>
<td>Thermal</td>
</tr>
<tr>
<td>Payload</td>
</tr>
<tr>
<td>Wiring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forecast mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mass</td>
</tr>
<tr>
<td>Dry mass (structure and systems)</td>
</tr>
<tr>
<td>Hypothetical fuel mass</td>
</tr>
<tr>
<td>Payload</td>
</tr>
<tr>
<td>Payload/Masslaunch</td>
</tr>
</tbody>
</table>

Table 2: Mass repartition

Because of the iterative method used to obtain the finale value of the mass, the foretasted mass factor must be constantly kept in mind and updated during the evolution of the project, to take into account possible launcher upgrades. The question at hand is the following: how is it possible to optimize the internal and external structure in order to get the lowest weight possible?

III. ENVIRONMENT

The space environment will impose specific constraints on the space station that must be taken into account in its design. Each the work situation that the modules will go through during their exploitation period will add up to the condition list: loads, Low Earth Orbit and, eventually, stationary position at Lagrangian Point n.2. Consequently, in what way the time spent in stationary position in each aforementioned situation will influence design?

Loads

The maximum loads carried during the spacecraft life-cycle[11] are the factors taken into account to design and scale the primary (the rigid frame) and secondary structures (junction between primary structure and other components), as well as all the other parts. Generally, the dynamic mechanical loads that occur on the spacecraft during the lifetime of a mission are:

a) handling loads; b) transporting loads; c) vibration tests required for the qualification of the structure; d) dynamic loads during launch; e) post-launch loads; f) loads/influences on the spacecraft in orbit (in-service loads)[17].

Launch is clearly the pivotal point in terms of loads. In fact, at the beginning of the mission, the whole structure is submitted to both longitudinal and lateral acceleration. Both static and dynamic loads can be caused by aerodynamics and propulsion. The apex of acceleration occurs at the end of the rocket-propelled phase. The acceleration increases because the mass of the launch vehicle decreases, while the overall thrust remains the same. The lateral steady-state accelerations are usually much smaller than the vertical acceleration in the launch direction[17].

The different launch phases are[1]:

- engine ignition and take-off;
- maximum dynamic pressure burst;
- EAP (Solid Propellant Boosters) pressure variations;
- EAP separation
- spacecraft separation (using pyrotechnic devices).

Each launch phase has different effects on the structure of the spacecraft.

During ground operations for an Ariane 5 campaign, the spacecraft is submitted to a temperature of
$23^\circ C \pm 2^\circ C$ and the relative humidity is $55\% \pm 5\%$\cite{1}. The most drastic condition that involves high temperatures and high heat flows take place after the fairing jettisoning.

**Low Earth Orbit**

The commonly accepted range for Low Earth Orbit is between 160 and 2000 kilometers. This orbit is unsuitable for many research aims. In fact, space debris, the heavy satellite traffic and the problematic conditions for materials (degradation, charging) prevents the long-time presence of human missions in this orbit, but it can still be considered an alternative to EML2.

Spacecraft generally have circular orbits: it means that the distance between them and Earth does not vary much through time. The LEO orbit has some advantages: it is rather easy to reach and cost is less expensive than other destinations. Of course, when the size of the spacecraft increases, the cost raises\cite{14}. Spacecraft lifetime in LEO orbit influences the structural requirements of the station: the time slot in which it can lay in this orbit can be of $2/3$ days, 1 month or much longer (up to 15 years). It depends on the space station integration strategy chosen during the study of the project. Indeed, the constraints change depending on the duration of the mission in Low Earth Orbit. Another important parameter that conditions both mission and design of the manned vehicle is the orbit’s altitude: temperature, the level of radiations and space debris have different effects, all depending on the distance separating THOR from the Earth.

Low Earth Orbit unfortunately also implies many obvious constraints:

- atmospheric drag;
- space debris;
- plasma environment.

The atmospheric drag is the result of friction between the spacecraft and the tenuous atmosphere\cite{14}. This phenomenon degrades the orbit. As a consequence the fuel consumption increases to maintain the spacecraft in its initial altitude, avoiding atmosphere re-entry that would insulates and degrades the materials.

Another crucial parameter in the scaling of the structures is the high rate of space debris, that depends on the traffic on spacecraft in the LEO. The presence of space debris ‘is an unsafe environment in the long term for crewed facilities’ \cite{12}.

A spacecraft at LEO (e.g. ISS) is exposed to an energetic-trapped electron dose due to plasma environment that deteriorates long-term durability of materials such as Teflon®, silicone, organic materials and other radiation labile ones.

All the elements described above are important factors that have to be taken into account while designing the modules. Furthermore, the amount of damages strictly depends on the time slot in which the spacecraft remains in Low Earth Orbit. The best solution should be to stay as briefly as possible, in order to avoid all the structural problems that hail from the
debris impact and the chemical particles. Nevertheless particular attention must be paid to the possibility of accidental issues that can lead to a longer stay period in LEO, for as long as 15 years.

EML2

The Lagrangian points are five positions in the Moon-Earth system, where the orbital motion of a body balances gravitational forces of the two massive bodies (Figure 5): as such, any object at a specific Lagrangian point reaches equilibrium by orbiting around it, and it has the centripetal force required to orbit around this point[11].

The EML2 is a position of unstable equilibrium, that lies on the Moon-Earth path, beyond the Earth. In this position, the Earth and Sun gravitational forces would balance the centrifugal effect on a spacecraft located here. The pull of both Earth and Sun allows spacecraft to have a higher velocity, and it can follow the Earth’s motion.

The equation below rules the motion of any object located at EML2:

\[
\frac{M_1}{(R+r)^2} + \frac{M_2}{r^2} = \left(\frac{M_1}{M_1 + M_2 R + r}\right) \frac{M_1 + M_2}{R^3}
\] (1)

Long-term human mission in Space actually requires shielding against different types of radiation, that long run damage the materials and destroy the human cells, leading to the death of the crew.

The THOR space station will orbit around EML2, on a Halo orbit that is large enough to maintain continuous visibility for communications with ground stations on Earth. As a consequence, the station will always present the same side to the Earth and always the same side towards Deep Space, even if all sides will face the Sun. This has an important consequence on thermal gradient. Anyway, the orientation of the spacecraft will change because the Earth position is changing during one year.

The equations of the spaceship motion - free to move three dimensionally - at EML2 are the following:

\[
\ddot{x} = 2\dot{y} + \frac{dU}{dx}
\] (2)

\[
\ddot{y} = -2\dot{x} + \frac{dU}{dy}
\] (3)

\[
z = \frac{dU}{dz}
\] (4)

\[
U = \frac{1 - \mu}{r_1} + \frac{\mu}{r_2} + \frac{1}{2}(x^2 + y^2)
\] (5)

\[
\mu = \frac{m_2}{m_1 + m_2}
\] (6)

where \(x, y\) and \(z\) are the coordinates of the ship, \(U\) is the potential of the system, \(\mu\) is the mass parameter and \(m_1\) and \(m_2\), \(r_1\) and \(r_2\) are respectively the mass and the distance from the ship to each primary, that are Earth and Moon[11].

The most important sources of perturbations are:

- solar pressure;
- high temperature gradient;
- plasma environment.

The first perturbation is due to the radiation pressure of the sunlight and the thermal emission of the sun falling on the spacecraft. One of the problems for the spacecraft is the great temperature discrepancy between the face exposed to the Sun and the one in the shadow. In fact, many materials (i.e. Lexan), are very sensitive to important temperature differences. On the average, a Sun-facing side of the spacecraft reaches a temperature of about 300K (26.8°C), while the shaded side is no warmer than 80K (−193.1°C). The plasma environment must be taken into account while analyzing EML2 environment. It causes the charging of the external structures of the spacecraft, due to the collection of plasma electrons and ions on its frame[6]: it leads to the attraction of debris and particles on the external structure.

The thickness of the plasma sheet changes in function of solar activity, and its orientation change in function of the time of the year.

The main damages due to high-energy particles would affect electronic components, degrade material and dark of optical glass. Therefore, any analysis has to take into account the possible attenuation of
energy due to the materials’ geometry and inherent properties.

The exposition of the spacecraft to the flow of radioactive particles depends on the trajectory chosen to reach the EML2 point. In order to prevent catastrophic damages to the spacecraft’s control system, an accurate analysis of the high-energy particle fluxes must be planned. The magnitude of the energy depends on the Sun’s cyclic energy variations (solar wind, solar ionizing radiations, solar magnetic fields) which has an average time slot of 11 years[6].

The radiation environment at EML2 is made of galactic and solar components[6]. The damages caused by the high-energy radioactive particles affect both electronics (processing and memory loss, devices detection failure) and materials; as above-mentioned, the main problems of materials exposed to radiations are 'embrittlement, loss of ultimate tensile strength, and increase in surface hardness'[6].

The presence of polymeric materials in the primary and secondary structure is largely influenced by the high-energy particles factor. In fact, their properties are altered by the capacity of the particle’s capacity to break long-chain chemical bonds. In this case, beyond the mechanical properties of the materials, thermal and electrical insulation properties are affected.

Despite distance, the Sun largely influences the thermal environment at EML2, in function of its cycle. Deep space behaves as a heat sink cavity and the operating temperature reached vary from 30 to 70 K.

At EML2, it is not possible to accurately evaluate the debris/meteoroid environment. In fact, a statistical approach is needed when studying this field. The main parameters of the meteoroid model are flux, directionality and velocity distribution. The model that actually describe the flux is the Grün Model[6].

For a comparison between the different perturbations Low Earth orbit and EML2 see Table 3: which ones are the most important?

Since the duration of stay is higher in EML2 than in LEO, the most sizing perturbations are: radiation pressure, temperature gradient and plasma environment. However, the other factors should not be underestimated: in the worst case, the spacecraft can remain at LEO up to 15 years. Moreover, some perturbations are time dependent - e.g. temperature gradient - and their magnitude increases with the duration of the mission.

**Solar Wind**

Solar wind is composed of protons, electrons and α particles. Evaluating the apex of solar activity is purely statistical: in fact, it cannot be predicted but it is possible to determine its phase during a certain activity period. In any case, Solar Cosmic radiations are composed of two parts: low-energy flow (or permanent solar wind) and high energy flow (particles released during solar flares, between $10^{21}$ and $10^{25}$ J).

Solar wind encompass three elements[2]:

- **Inter-stream**, the slow part of the flow ($< 500 \text{ km/h}$);
- **Coronal hole**, high velocity flow ($500 \sim 800 \text{ km/s}$), that can be observed during the declining phase of the solar activity;
- **Coronal mass ejections**, the part of flow characterized by presence of heavy metals, that follow each solar maximum activity.

The velocity of solar wind can be modeled in function of temperature; solar wind reaches the its asymptotic velocity at 1 AU. An important effect on the velocity is due to the Sun’s rotation. In fact, the flow can be accelerated or decelerated in function of the velocity of solar rotation[16].

In order to respect all the constrains created by to solar wind, great attention must be paid on to the choice of materials. In fact, during the life time of the spacecraft, the materials and all the electrical/optical components can be damaged by the presence of high-velocity particles, and specific treatments could be required in order to fulfill the design criteria imposed by the environment at EML2.

### IV. MATERIALS

The choice of a material is essential for the design of a space station. For the selection, many constraints have to be taken into account. Each material is characterized by its own mechanical, physical and chemical properties: a material is chosen according to its usefulness within the framework.
The technical requirements of a material structural design are:

- low density;
- high resistance to rupture;
- high tenacity to rupture;
- fatigue resistance;
- hardness;
- low coefficient of thermal expansion;
- low electrical conductivity.

High temperature conditions must also be taken into account: for example, during its lifetime a material operates in a range of temperatures between $-150^\circ C$ and $+120^\circ C$.

Keeping these requirements in mind, what are the materials that must be used in order to get the most efficient design?

The materials analyzed in this project are:

- Aluminum Alloy;
- Aluminum-Lithium Alloy;
- Lexan-Polycarbonate;
- Inflatable materials;
- water.

Each one must satisfy the challenges imposed by the space environments and the loads: it is not easy to find materials that can work and properly behave during the spacecraft’s lifetime. Both Aluminum Alloy have already been used in aerospace structures as well as water, while Lexan-Polycarbonate and inflatable materials are new possible ones under study nowadays.

**Aluminum Alloy**

Aluminum alloys have a key role in the building of aerospace structures. It has indeed very good mechanical properties and a rather low density. In addition, it has a well-known behavior in the spacecraft field, since it has already been used in the ISS and ATV designs.

The main features are listed below.

Most of the time, aluminum is anodized: this electrolytic process improves thermic endurance, corrosion and wear resistance and provides better adhesion properties for paints. This happens thanks to the increase in thickness of the natural oxide layer placed on the outer side of the external surface.

Anodized aluminum is used both for external structures (e.g. truss) and for debris shields.

**Aluminum-Lithium Alloy (8090)**

Among other advantages, the use of Al-Li alloy helps, weight maximization, which is most critical for space applications.

![Figure 6: Material Selection Criteria](image)

<table>
<thead>
<tr>
<th>Density</th>
<th>2840 kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>352 MPa</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>455 MPa</td>
</tr>
<tr>
<td>$E$</td>
<td>73.1 GPa</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>10%</td>
</tr>
<tr>
<td>Fatigue strength at $5 \times 10^8$ cycles</td>
<td>103 MPa</td>
</tr>
<tr>
<td>Shear module</td>
<td>27 GPa</td>
</tr>
<tr>
<td>Shear strength</td>
<td>b 285 MPa</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>0.864 J/g $^\circ C$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>120 W/m-K</td>
</tr>
</tbody>
</table>

Table 4: Aluminum Alloy (2219) Characteristics [3]

Figure 7: Nominal Composition of 8090 Al-Li Alloy [4]

It is a candidate material for the cryogenic tankage of booster systems: in fact, it has good mechanical
and thermic features when used to build as reservoirs for liquid oxygen and hydrogen fuel tanks.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2550 kg/m³</td>
</tr>
<tr>
<td>(\sigma_y)</td>
<td>210 MPa</td>
</tr>
<tr>
<td>(\sigma_r)</td>
<td>335 MPa</td>
</tr>
<tr>
<td>E</td>
<td>77 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.34</td>
</tr>
<tr>
<td>Thermal conductivity at 25°C</td>
<td>93.5 W/m-K</td>
</tr>
<tr>
<td>Specific heat at 100°C</td>
<td>930 J/kg-K</td>
</tr>
</tbody>
</table>

Table 5: Aluminum-Lithium Alloy Characteristics

Lexan-Polycarbonate

Lexan is a thermoplastic polymer: it can be easily worked, molded and thermoformed. Polycarbonate is highly transparent in visible light, with better light transmission than many other types of glass.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1200 kg/m³</td>
</tr>
<tr>
<td>(\sigma_r)</td>
<td>70 MPa</td>
</tr>
<tr>
<td>E</td>
<td>2.3 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.38</td>
</tr>
<tr>
<td>Thermal conductivity at 23°C</td>
<td>0.21 W/m-K</td>
</tr>
</tbody>
</table>

Table 6: Lexan Characteristics

This particular material, despite not presenting any high mechanical properties, plays a crucial role in high impact and temperature resistance. Its exceptional clarity, is also ideal to have a good visibility of the outer world. Lexan can be utilized as double glazing (at the option of water storage inside) for protection against break and cracking. It is additionally easily workable: in fact it can be thermoformed into complex shapes without losing its mechanical and thermic properties.

Inflatable materials

Nowadays inflatable materials are being used more and more: low cost, high mechanical packaging efficiency, low weight and the possibility of water storage are some of the advantages that make these materials sought-after solutions.

It is nonetheless useful to highlight some important handicaps when using inflatable materials: they are highly sensitive to wide \(\Delta T\) and there is a high chance of gas leakage due to potential holes caused by space debris.

To avoid thermal expansion due to temperature gradients, an insulativity system must be provided. The principal element of inflatable structures are the membrane materials, used at first for the lenticular structures.

Pure inflatable materials (very light and thin elastic films) can be used when subjected to very low loads \((\sigma_{\text{max}} = 7 \times 10^{-3} \text{Pa})\).

Obviously, a rigidization system must be present: high strength module after expansion, reversibility, high flexibility, low thermal expansion, resistance to the space environment and minimal change of shape after the rigidization process are some of the challenges that must be tackled[7].

However, the main advantage of this family of materials is that these structures can be easily packaged in very small volumes before launch phases[7].

The interaction between inflatable materials (always under a constant load due to their characteristics) and the space environment must however be taken into account: this is a significant constraint, and because of the novelty of the material, great attention must be paid while designing inflatable elements.

Water

The best way to be protected to a radioactive environment is the thick atmosphere that surround the Earth (particles of hydrogen and helium), but this is impossible to obtain in the spacecraft. So another ‘material’ that is really useful against radioactive streams is water, and it can be rather easily carried on board of a spacecraft. Moreover, the high shape adaptability of the water is a benefit for the design of the structures: in fact, it can be easily stored in the thin layers of the deployable structures or between the double glazing of panels (e.g. Lexan).

Of course, the anti radiation properties of water exponentially depend on the thickness of the layer.

The water has the best proprieties when used against Beta particles, X-ray and Gamma radiation. Even if this is not the only method for radiation shielding (e.g. liquid hydrogen, soil), it is less expansive and with lower density than all the other ones. Nevertheless, a great problem is the degradation of materials that can lead to effects even worst of the previous ones.

Comparison

Both Aluminum and Aluminum-Lithium alloy have already been used in the modern spacecraft: primary and secondary structures as well as all the rigidization components are made of these materials (high mechanical properties and low density). On the other hand, Lexan is a new material that presents low mechanical features but very high thermal resistance;
moreover, its transparency allows to use it for both windows and, in case, the cupola.

<table>
<thead>
<tr>
<th>Density</th>
<th>A.A.</th>
<th>A.-L. A.</th>
<th>L-P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2840</td>
<td>2550</td>
<td>1200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poisson’s ratio</th>
<th>0.33</th>
<th>0.34</th>
<th>0.38</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>73.1</td>
<td>77</td>
<td>2.3</td>
</tr>
<tr>
<td>(\sigma_r)</td>
<td>455</td>
<td>335</td>
<td>70</td>
</tr>
<tr>
<td>T. conductivity</td>
<td>120</td>
<td>93.5</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 7: Comparison between materials (units as tables before)

<table>
<thead>
<tr>
<th>Pro</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.A. Good</td>
<td>High density</td>
</tr>
<tr>
<td>mechanical</td>
<td></td>
</tr>
<tr>
<td>properties</td>
<td></td>
</tr>
<tr>
<td>A.-L. A.</td>
<td>Good</td>
</tr>
<tr>
<td>mechanical</td>
<td>High density</td>
</tr>
<tr>
<td>and thermal</td>
<td></td>
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<td>properties</td>
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<td>L-P</td>
<td>Temperature</td>
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<td>Low</td>
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<td>resistance</td>
<td>mechanical</td>
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<td>properties</td>
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</tbody>
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Table 8: Pro and Cons of materials

Because of the different characteristics of materials, it is not possible to state which one is the best in the spacecraft design. In fact, each material is useful in different applications, while it presents very low features in other aspects (Tables 7 and 8).

V. NATURAL FREQUENCIES

The natural frequency of a body describes its behavior in term of oscillation, when submitted to vibrations. The resonant frequency or resonance is a proper characteristic of a system, once identified its geometry and material: at this particular range of frequencies, even small periodic vibrations can lead to large amplitude oscillations, because of the vibrational energy stored into the body. It can be dangerous for the structure if resonance is reached during the mission: oscillations can lead to the failure of the structures.

When two bodies are joint, it is necessary to keep their natural frequencies as far as possible. So, the dynamic coupling between them - the spacecraft’s module and the launch vehicle in this case - is avoided.

The longitudinal stiffness requirements for Ariane 5 prescribe a lower limit of 27Hz for a spacecraft with a mass greater than 4500kg, and a lateral one of 7.5Hz; moreover, ‘no secondary mode should be lower than the first primary mode’[1].

The natural frequency of a SDOF (Single Degree Of Freedom) system is given by [17]:

\[
fn = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{g}{x_{stat}}}
\]  

(7)

where:

- k: stiffness
- m: mass
- g: gravity
- \(x_{stat}\): static displacement

If the static displacement \(\Delta\) is calculated per \(1m/s^2\), the approximation of the natural frequency is:

\[
fn = \frac{1}{2\pi} \sqrt{\frac{g}{\Delta}}
\]  

(8)

Given a cylindrical module with a total mass of \(M_{tot} = 21000Kg\) (21t), the shear force is \(D_s = M_{tot}\) and the bending moment is \(M = M_{tot}h\).

The natural frequency has been calculated when the spacecraft has been placed on the conical payload adapter that is clamped at the lower side of the cone.

The total static displacement (m), of the center of gravity, due to \(1m/s^2\) acceleration in the x-direction is[17]:

\[
\Delta = \delta + h\theta
\]  

(9)

So, the value of natural frequency obtained by the formula is: 58.44Hz.

The analytical computation has been validated through modal analysis using the software Ansys®14.5. Both upper and lower face have been fixed, as it will be during the launch. The values of the resonance frequency modes of the cylindrical module are 51.1Hz for \(t = 10\ mm\) and 58.98Hz for \(t = 20\ mm\). The values of the experimental analysis are very similar to the analytical ones.

For the spherical module, it is very hard to provide an analytical computation in order to get the resonance frequency. Hence, due to the reliability of the software, it is possible to give an overall approximation of the first mode’s value. The lowest thickness of 10mm has been taken into account, because it
represents the most sizing case. The value of the first resonance frequency is here \(110.54\) Hz.

The results satisfy all the challenges posed by both space environments and Ariane 5 requirements: resonance should be avoided, but more tests must be performed when the mass of each module will be updated.

VI. DESIGN

The design of a space station needs accurate planning: in order to obtain the final architecture all the above-mentioned constraints and challenges must be satisfied.

The three main functions of a space structure are:

1. integrity or resistance preservation;
2. rigidity;
3. stability.

The whole spacecraft consists of a primary structure and a secondary structure: the first one has to carry the loads and is the spacecraft’s frame, while the secondary structure sustains the primary one. It deals with the dynamic part of the loads and the overall stability.

Design criteria

The design criteria of a crewed spacecraft are both structural and psychological: it is very important not to underestimate the human factor in a long-term human space mission.

The leading design criteria are divided, in decreasing order of importance, into:

- general design requirements:
  - duration of mission;
  - influence of isolated and limited room on the crew;
- structural design criteria;
- material design criteria;
- adjacencies design requirements:
  - compatibility of adjacent modules and sequential dependency;
  - physical interference between modules;
  - environmental interference;
- orientation design requirements:
  - north-south orientation linked to horizontal and vertical reference plane;
- visual design requirements:
  - presence of windows for the psychological well-being of the crew members;
  - arrangement, color and design of walls and modules of spacecraft.

In what way all these parameters influence the structure of the space station? How should the structure be put together in order to satisfy all the aforementioned constraints?

VI.I External Structure

The structure of the spacecraft has a vital importance for the mission success. In fact, both primary and secondary structures have to assure their functions (strength, radiation isolation, thermal protection) for as long the vehicle has to be in the outer space.

While designing the structures, several types of loads have been taken into account (see III. Environment). Due to the different configuration of each module, thickness values, stringers number and the materials employed change accordingly.

In any case, the sizing loads are:

- static: due to \(\Delta p\) (hydrostatic pressure) between the internal atmosphere and the outer void and to the \(\Delta \rho\), height function;
- dynamic: coupling maneuvers between different items can occur during several phases of station’s life-time;
- acoustic: a meticulous attention must be paid to the Eigen shape of the thinnest walls, according to the damping ratio value (usually, \(\eta = 0.003\)). The loads applied to the structure are not totally absorbed during the load itself, but a propagation waves can occur on the whole structure;
- shocks: during the separation of the spacecraft from the rocket, punctual force - up to \(300g\) - can weigh on the structure.

As above-mentioned, the three main functions of the space qualities are: integrity, rigidity and dimensional stability.

The integrity - or resistance - of the structure is a long-life factor in its. Usually, once the analysis of the most important loads due to launch has been
performed, the structure will not carry greater mechanical loads during the THOR space station's entire life: however, in order to comply with the possibility of amplification of dynamic coupling during the orbital transfer and to deal with the necessity of having maintenance in a convenient location of the spacecraft, a local design and a particular sizing process is sometimes needed. Moreover, the range of temperatures ($-150^\circ C, +120^\circ C$) can overload both the primary structures and the deployable appendices (e.g. solar arrays, antennas, scientific payloads), whose deployment could be badly compromised.

The dynamic behavior of the thin shells - Eigen shape, natural and resonance frequency, modal analysis - highly affects the rigidity of the entire structure. The first goal during the launch is to dynamically decouple the module from the launcher; furthermore, some specific subsystems - antennas, GPS, AOCS - must be deeply analyzed, because a coupling can occur, and it can lead to serious problems for the whole structure and the operations themselves.

Due to the presence of many probes and items associated to the subsystems, dimensional stability must be achieved: no permanent deformations or even slight change in shape are tolerated when dealing with this kind of equipment. Both structural and thermal requirements must be guaranteed for as long as space station is in use.

VI.II Internal architecture

Design of the modules is strictly linked to the structural/material requirements and to on-board human presence. While designing the internal configuration of a spacecraft, it is necessary to deal with several constraints: among others, structural, functional and psychological are the most important.

Overall model

In the Figure 8 a 2D sketch of the Spacecraft is provided. All the data and the internal architecture of the modules (internal environments, position of corridors, docking system) are part of a first general design.

The functional areas in the space stations are: offices, kitchen, commons area, rooms, cult area, toilets, meeting area, Space Medical Center (SMC), Extra-Vehicular Activities (EVA) module, sports zone, work area (Figure 2).

The main axis of the station will mostly be parallel to Earth poles line: a North-South orientation is simulate in the spacecraft. The modules in the northern part of the space station are settled for private and leisure activities, while the others in the southern part have been dedicated to public and work activities: 'the aim is to create a psychological impression of traveling from home to work'[11].

The human factors, in a mission with such a long duration (up to two years), must not be underestimated. In fact, astronauts have a priority in mission, where the first goal is to explore and increase human presence in Deep Space. So, during the design phase, a special-effort has to be given to help recalling daily life on Earth and the working environment. An entire module is thus set up as a cult area - rooms and personal space, being compatible with all involved crew’s cultures - for people that are living in the space station a wide common area and a sports zone are furthermore taking vast volumes
of the spacecraft, in order to safeguard the scientist from possible psychological and physical strokes.

Another important key to the well-being of onboard people is the presence of floors within the modules: humans are used to creating mental images of their surroundings, in order to give themselves a consistent orientation[11]. Floors are useful to discriminate the modules’ up and down sides. Disorientation and space sickness thus can be overcome and the overall crew performance optimized.

What is the best passage configuration? The passages location are not defined yet. The lateral or central position can be used as a corrective factor in order to assure a space homogeneity within each module and the whole spacecraft. According to the type of assembly configuration that would be eventually chosen, it is possible to change the spot of the corridors in order to reduce dis-homogeneity as much as possible, in respect to the central axis of the space station. In fact, due to the different internal architectures - and probably mass - of each module, it is realistic to have a torque momentum that can highly influence the orbit of the space travel. Indeed, if the final assembly will be planned at EML2, the presence of lateral passages could be a more restrictive choice, and the position of the propulsive system can be moved according to the internal architecture of each the module. Furthermore, windows (in Lexan) ‘allow the crew-member to focus on objects, such as Earth, outside the space module’[11]: so this opening should be located near the workstations, the astronauts’ room and the area of boring activities.

The spherical module must perform different functions: hub for the spacecraft, junction point between different modules, work and experiments area, and loading zone for re-supplies cargoes. In order to adapt the internal space according to the different activities, a system of movable walls can be used within the spherical modules. An accurate structural and dynamical analysis will obviously be needed for this kind of thin unfastened walls, that must be kept fixed during the most critical phases of the station’s lifetime: launch and assembly.

**Interactive panels**

Modern mobile phones and monitor technologies are making leaps and bounds: nowadays, it is possible to use such devices just with motion control, moving one’s hands or using one’s voice without any physical contact perfectly feasible. These interactive panels could be the future of workstations In fact, it might be possible for them to replace old devices altogether, saving a lot of weight. With the simple flip of a hand, it is possible to change the screen/panel: in such a way many subsystems output screens could be stored in one monitor and it will be possible to call them back just when needed; furthermore, with the single use of face-recognition, it will be possible to store some crew personal data in these devices, in order to achieve privacy.

It is thus possible to save on both weight and space, allowing an increase of the space station’s payload.

One can also assume that while these panels are not used as workstations, they could display images that reproduce the meteorological conditions on Earth, making crew members feeling a little more ‘at home’.

**Art as human factor**

As the philosopher Dewey stated, art is the complement of science. In order to reach the optimum in the daily life, science and art should go hand in hand. Deep Space exploration requires to crew to spend so much time in the space station that it can have strong fallouts on their psychological balance. As already mentioned, the human factor of these missions cannot be neglected: all the efforts must be made to guarantee the well-being of all the people that live into the spacecraft.

How to? In order to optimize the role of art in the allocated space, it should be perfectly and positively adapted to the module’s structural and working aspects. As Walter Gropius, the founder of the German current Bauhaus, stated, all type of craft should be placed together, so as to merge utility and beauty.

One helpful expedient, could be the use of oeuvres in the modules. In fact, interrupting the monotony, by placing works of art on the space station’s walls, can result in a mood improvement, and consequently the bettering of the astronauts’ work abilities.

**VI.III Docking system**

For such a space station, the docking system is of vital importance. As above-mentioned, the rendezvous is presently in development. One option is to assemble the station at LEO, another one is to have the complete spacecraft put together only at EML2. The docking system will be fitted on the spherical modules, because their shape allow to have better possibility of storage of materials and it is optimal to house the visiting shuttles.

The design of the upcoming docking system is based on the prospect of having a ‘universal’ type of junction. For the sake of saving time and financial resources, the various national space agencies are willing to develop a docking system that can fit all the future spacecraft: thus, with the collaboration of the major space companies, the final goal will be a unique
type of connection between the stations and all the re-supply - manned or unmanned - shuttles[15]. How can it be designed?

The docking system must be designed to have the possibility to anchor all the visiting vehicles or modules at the same time, and consequently it must allow the unload of all the supplies stored in the external modules. Furthermore, the docking system must satisfy all the safety requirements to be able to dock the shuttles in any environmental conditions.

![Closed docking system](image1.png) ![Open docking system](image2.png)

(a) Closed docking system.  (b) Open docking system.

(c) Particular: adaptable docking pins

(d) Conceptual picture of a rendezvous.

Figure 9: First idea of an universal docking system: the size of the pins can be adapted to the different visiting vehicles/modules.

As above-mentioned, the type of assembly of the space station, is not final yet. In theory, the modules docks must answer all the structural/thermal/human constraints, bearing in mind the results would be different at LEO and at EML2. In fact, when the mooring takes place at EML2, there will be no problem due to orbital transfer, because the second Lagrangian point is the final destination. But, if the docking is to happen at LEO, there will be some structural problems due to the propulsion system, that, at first, has to move a greater mass, and, furthermore, has to deal with the different distribution of mass within the spacecraft. Probably, in this case, a more efficient attitude control system will probably be needed.

Another conceptual idea can be the opportunity to build the docking system by using inflatable materials. Their features allow to save space and mass, and the characteristic of being flexible and adaptable are advantages for their purpose. In fact, these materials can be easily stored in low volumes, and then deployed in the void.

The concept of universal docking system was already developed by the Russian Space Agency in the 60s. As ATV has this kind of docking system as reference, some ideas about a unique type of junction have already emerged. However, the ATV docking system is to this day not the best possible solution: a universal one should be further analyzed. It means that both active and passive docking systems can fit all types of modern space vehicles.

Its basic design requirements will be redundancy and safety: different technical cultures and standards must be taken into account. The main functionalities in the attached phase will be, as for the ATV, the following ones [5]:

- structural connection between THOR and external vehicles;
- transfer of fuel, power and data;
- passageway for pressurized cargo transfer;

The main differences between the new docking system and the one used for the ATV are: maneuverability and larger doors. In fact, as the visiting vehicles for this space station will be manned, there will be less safety requirements and the possibility of correcting the trajectory in the most critical phases of the mission - docking operation being one of these. Obviously, the astronauts must be thoroughly trained in order to be able to accurately drive the shuttles. However, an automatic docking procedure can be envisioned, in case of an emergency.

The modern spacecraft will be designed with wider spaces, in order to allow easier movements within the different modules. It is important to highlight that while the ATV is eventually detached, most of the vehicles of the space station will remain as permanent modules of the spacecraft - in the first part of the mission in any case.
Even so, the ATV docking system still remains a reference for the overall development of the THOR station design.

As the space station will be a reference point for manned space missions to Mars, other docking points - in the cylindrical modules - must be provided in order to allow visitor vehicles to anchor and to use the spacecraft as a spaceport. It also has to be understood that several supplies will be needed through the course of the station’s mission, and the docking system must be equipped to allow the loading form cargo shuttles.

VII. CONCLUSIONS

The design of a whole spacecraft is a very arduous task. All the subsystems must be integrated and all the respective constraints must be satisfied. It is very hard to focus attention to the complete architecture of a spacecraft, its systems and on its configuration. This of course escapes the scope of this paper.

The hypothesis at the basis of the research project come from an accurate analysis on the human aspect of the mission: the goal of Deep Space exploration must comply with the well-being of astronauts (scientists, engineers, mathematicians, artists, etc.). So, at first, all the constraints that might be satisfied were linked to the human field.

In order to save money and time, the general architecture of each module has characteristics similar to the ATV. Due to its good performances and overall qualities, this cargo-shuttle is a reference for the study and analysis of the station. Dimensions, mass, natural frequency consequently do not have to be deeply examined, because of their similarity with the European transfer vehicle.

During the project, the constraints relative to the structural perspective have been deeply analyzed, taking into account the different work environments in which the manned vehicle should work during its lifetime. The ground loads, the LEO and the EML2 pose all the structural and thermal restrictions that must be tackled in the accurate internal and external design of the spacecraft.

The general overview on the materials gives several ideas on their habitual use and on new possible conceptions. In order to satisfy all the restrictions due to the structural and thermal requirements, an accurate study of their purpose must be planned before starting the actual design of the space station. Furthermore, the new materials require a complete test phase, in which it must be verified that they can comply with all requirements. In the engineering field, the use of even more modern materials is always approved, but at first their relevancy must be proven. The final goal for the structural and materials engineers is to save money and weight, in order to increase the amount of payload.

The present ideas about design and the docking system are totally conceptual: only when the type of orbital transfer and the configuration of the final assembly is chosen, will it be possible to proceed to the final design stages of the space stations.

Additionally, many other elements must be designed. As previously mentioned, the general configuration of the spacecraft requires the integration of all its systems. They have to be analyzed and sized complying with all the requirements imposed by the constraints.

Here-in-after, several hints on the possible future analysis are listed:

- in-depth thermal and structural analysis;
- sizing and design of the mock-up;
- structural subsystems (interface with launcher, joints with antennas and solar arrays);
- solar arrays configuration, depending on the type of assembly of the space station: estimation of daily needs and size of surface of the panels;
- detailed scheme of docking system;
- design of the fuel tank;
- new ideas on how to make the life of astronauts in the space station more comfortable;
- the role of the art in the living-space.

At this moment, the way to the colonization of Deep Space is at an embryonic stage. Further and detailed studies must be performed in order to succeed in the space exploration. The constraints have been fully identified, the overall model is ready: the road to the future is not so faraway.

VIII. BIBLIOGRAPHY

REFERENCES


