Underwater Exploration Mission on Europa Jovian Moon

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Abstract— *NASA´s spacecraft, Galileo, discovered large amount of water on Europa, one of the Jupiter´s icy moons. Several works claim the existence of a liquid water ocean under the Europa icy crust. Europa is one of the most important regions in the Solar System and might reveal primitive forms of life in its oceans. At the present days, several technologies can be used to design the travel, prepare the landing and build the pressure hull of the submarine. A deep region of ice crust could be melted by an ice breaker, which would reach a liquid ocean and then a small submarine would be released. In this short communication, a preliminary design of both ice breaker and a small submarine for Europa's ocean exploration is considered. Additionally, communication between the submarine and a structure left over the icy crust will be discussed too. Results reveal that a small submarine with less than 80 cm and 2.4 m for diameter and beam, respectively, are required for moderate melting time. A submarine hull in ceramic composite is required to have adequate reserve buoyancy. Several alternatives are analysed for both submarine propulsion problems and underwater communication systems.*

Keywords— Spacecraft, submarine, Europa, ice breaker, pressure hull.

I. INTRODUCTION

Space exploration for outer planets and their moons has given the knowledge of both composition and structure of their atmosphere. Future missions planned, as the so-called ESA´s JUICE mission (JUpiter ICy moons Explores) will give the possibility of deeper exploration; it will focus on the study of the origin and evolution of habitable worlds in the Jovian System, especially Europa moon. NASA has recently required external concepts of instruments for an exploration mission to Europa Jovian moon. Both NASA/ESA missions could find Europa´s ice thickness, identifying regions for potential future in-situ explorations; short probes under tens of centimetres of ice could also be used to locate the liquid-solid interface. Several works present the possibility of a subsurface ocean in the Jovian moon Europa (Cassen et al., 1979; Squyres et al., 1983; Ross et al., 1987; Hussmann et al., 2002). Constraints on the Europa´s ice thickness are severely limited by surface observations and gravity data. Induced electrical current found by the magnetometer instrument data in Galileo's flyby on Europa moon had been interpreted as due to a limited amount of saltwater ocean. Empirical constraints of the salinity give less than fifteen kilometres of ice shell for near-saturation salt concentration (Hand et al., 2007). A viscous icy model proposed by Pappalardo et al. (1998) would imply no water layer, however.

In the proposed mission here, orbital probe might observe the surface of Europa identifying areas suspected to be connected to the ocean water. Additionally, identification of icy shell with less thickness would be important to reduce the melting/drilling time.

Following planetary protection requirements, landing mission on Europa is considered as category IV. The probability of contamination in Europa´s Ocean should be less than 10-4. Cleanroom technology is highly required for avoiding microbial and specific high-risk species contamination; all parts of the space probe and submarine must be clear before assembly.

Zimmermann et al. (2001) and Cardell et al. (2004) analysed a new type of thermal probe; hot water jets might be used as method of ice penetration. In order to work, the water expelled by the ice should be reused. Sublimation would occur in the low pressure ambient of Europa, making the reused water inefficient, however.

Since both mass and size of the submarine might be large, several space propulsion systems should be briefly discussed for an optimal orbit transfer from Earth to Jovian system; an electric solar sail (Janhunen, 2004; Sanchez-Torres, 2014), which is a promising propulsion concept for outer planet missions, might be used to reach Jupiter and its Europa moon. Both standard solar sails and ion thrusters might be another propulsion systems which might be considered. Finally, fission technology as the cancelled NASA´s JIMO mission might be considered too.

Submarine would allow in-situ exploration of the large ocean, determining a cartographic map of its structure and looking up the traces for prebiotic form of life. In addition, habitability in Europa´s salty ocean is possible; some terrestrial halophilic microorganism might survive. Methanogens are considered as a plausible microorganism living in the extreme Europa conditions.

The required time for melting a cylindrical hole with small radius in Europa´s icy crust for several values of depths is analysed in Section 2. Submarine design is briefly discussed in Section 3, studying hydrodynamic for navigation proposes, bridge fin, and the pressure hull requirements. Submarine propulsion and its power source are studied in Section 4. Both communication components sensors and transceiver structure are discussed in Section 5. Submarine constraints and navigation model are discussed in Sections 6 and 7, respectively. Finally, the conclusions are in Section 8.

II. ICE BREAKER

After probe landing over an icy surface, it is necessary to drill or to melt the Europa´s icy crust and to allow the submarine put into the water. An analysis of the ice surface is necessary to decide which method can be used. For both melting and drilling technology high power sources are required. For the melting method, which is considered here, a radioisotope heater unit should be considered. These devices use small samples of radioactive material (using a Polonium 210 heat generator) to produce heat directly, instead of electricity.

Since the thickness of the ice shell is not well known, this short communication studies the time required to penetrate the ice for a range of depths. The required power for ice melting with a penetration velocity v and temperature T is estimated by the following equation:

$$P_0 = \pi R^2 \rho_{ice} v \left[c_p \left(T_b - T \right) + L_m \right], \tag{1}$$

where R is the melting probe radius, Tb is the melting temperature of the ice, which is equal to 273.1 K. For temperatures from 0 to 273 K, the ice density varies as:

$$\rho_{ice} \approx 933.31 + 0.038 \cdot T - 3.63 \cdot 10^{-4} T^2 \ \text{[kg m}^{-3}\text{]}. \tag{2}$$

Following the work of Ulamec (2007), latent heat of sublimation is approximated by a quadratic interpolation:

$$L_m \approx 2636.77 + 1.66T - 0.0034T^2 \ \text{[kJ/kg]}, \tag{3}$$

whereas specific heat capacity at constant pressure reads:

$$c_p \approx x^3 \frac{c_1 + c_2 x^2 + c_3 x^3}{1 + c_4 x^2 + c_5 x^4 + c_6 x^8} \ \text{[J/kg/K]}, \tag{4}$$

where dimensionless component x is equal to T/Tb, and the values of the constants c1, c2, c3, c4, c5, c6 are equal to 1.84·105, 1.64·108, 3.55·109, 1.67·102, 6.46·104, and 1.69·106, respectively.

For a cylindrical probe of length L, the lateral conductive looses reads (Aamot, 1967).

$$P_{cond} = 2\pi R \frac{4\lambda \left(T_b - T \right)}{R \pi^2} \times I, \tag{5}$$

$$I = \int_0^\infty \frac{du}{u \left[J_0^2 \left(Ru \right) + Y_0^2 \left(Ru \right) \right]} \int_0^L \exp\left(-k u^2 s / v \right) ds, \tag{6}$$

where k=λ/(ρice cp) is the heat diffusion coefficient, λ is the thermal conductivity of ice, s is the spacial coordinate along the length L, and u is the integration argument for the Bessel functions J0 and Y0 for the first and the second kind, respectively. Carrying out the s-integral in (6) we have:

$$I = \frac{v}{k} \int_0^\infty \frac{du}{u^3} \frac{\left[1 - e^{-ku^2 L / v} \right]}{\left[J_0^2 \left(Ru \right) + Y_0^2 \left(Ru \right) \right]}, \tag{7}$$

which is numerically solved to obtain the net power:

$$P = P_0 \cdot \eta, \qquad \eta \equiv P_0 / \left(P_0 + P_{cond}\right), \tag{8}$$

where η is the efficiency of the initial power. Since ice proprieties; such as cp, ρice, Lm and λ vary with the temperature (Ulamec et al., 2007), a temperature model of the Europa´s ice crust is required. Vertical temperature profiles can be modelled with (Ruiz et al., 2002; Nimmo et al., 2003).

$$\frac{T(y)}{T_s} = \exp\left[\frac{\log\left(T_b / T_s\right)}{H} y\right], \tag{9}$$

where H is the thickness of the ice crust, y is the variable depth from the surface ice to the water layer, and Ts is Europa´s surface temperature, which is about 105 K. Fig. 1 shows the time of depth penetration versus thermal power for several values of diameter D, lengths and depths.

Additionally, melting experiments have evidenced that the penetration can be not as efficient as expected; low-porosity ice can re-freeze faster than the probe velocity, which lead to block the continue motion into the penetration path (Treffer et al., 2006). Regarding the re-freeze problem, a thermal conductive shell over the cylinder could be proposed for heating and melting lateral ice obstructions.

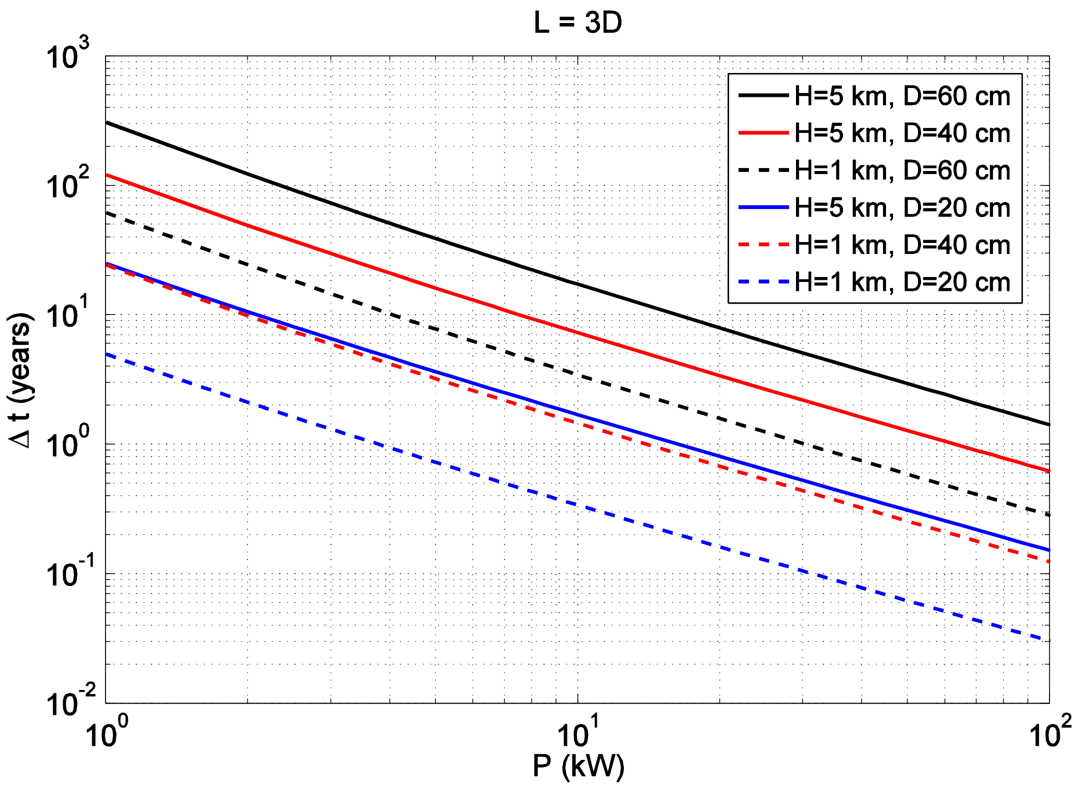

FIG. 1: TIME REQUIRED TO PENETRATE SEVERAL VALUES OF ICE THICKNESS AS A FUNCTION OF THERMAL POWER FOR SEVERAL VALUES OF DIAMETER AND LENGTHS. TYPICAL VALUES USED OF CP, ρICE, LM ARE FOUND IN (ULAMEC ET AL., 2007). NOTICE THE LOW EFFICIENCY OF MELTING FOR P0=1 KW

Considering larger values of depths for the icy crust, a hybrid melting/drilling technology might be needed. Conventional drilling using rotatory cutting would penetrate with a rate.

$$v = \frac{\varepsilon P_{mec}}{\pi R^2 E}, \tag{10}$$

where ε is the mechanical efficiency, E is about 5 MJ/m3 for ice, and Pmec is the mechanical power. Additionally to the power produced by the generator included in the cylindrical probe, power generator station above the icy crust, which is linked by a thin tether, might produce the extra current required. Tethered system has high risk due to the tidal flexing at Europa´s ice crust, however. Shielded tether could withstand both refreezing and tidal flexing.

III. SUBMARINE DESIGN

A small submarine for exploring the oceans of Europa Jovian moon is here considered. Europa´s peculiarities are particularly included in the design; hydrodynamic study will be carried out in the following subsections.

3.1 Hydrodynamic Study

Both beam B and total length L are the characteristic lengths of the submarine. Additionally, the external hull design and length-to-beam ratio will be used to characterize the hydrodynamic performance of a hypothetical submarine exploring Europa´s ocean.

The external hull should be designed to allow the pressure acting at right angle to every point of the surface, as it is shown in Fig. 2. Largest pressure supported at the submarine occurs in the domes, which is the stagnation point where the streamlines divide. Lower and higher pressure are found where the streamlines are converging and diverging, respectively.

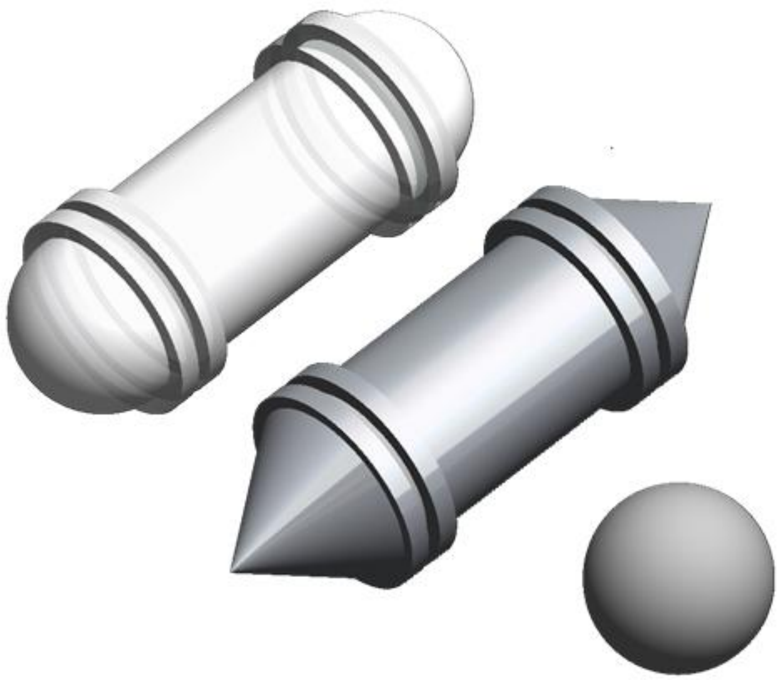

FIG. 2: IN THE CASE OF THE SUBMARINE DESIGNED FOR EUROPA´S EXPLORATION, THE PRESSURE HULL APPEARS IN THE FORMS OF CIRCULAR CYLINDERS AND DOMES. BUT OTHER OPTIONS FOR THE PRESSURE HULL HAVE BEEN ANALYZED

In theory, the pressure right at the tail would rise to the same value as that at the stagnation point on the dome for a fluid without viscosity. Considering Bernoulli's equation, the integral of all the pressures acting on the elemental areas would be zero. Unlike the theoretical case, in Europa's oceans, as well than in the Earth, the fluid flows with a viscosity. Both pressure and skin friction drag will be resistance produced against submarine. Normal and tangential forces, from drag and skin friction, respectively, are about equal in value on a streamlined body. The boundary layer initially quite thin thickens towards the tail and streamlines do not diverge as wide as they would in an in-viscid fluid, which effect causes the form drag.

All features affecting the resistance are discussed, including the boundary layer, laminar flow, transition, turbulence and separation, and how the flow over the bridge fin, where all the communication systems as well sonar, should be as quiet and smooth as possible. Added resistance from the two appendage flaps in the fore part for vertical navigation needs careful streamlining and attention in design.

Large length-to-beam ratio would make very high skin friction and extremely low pressure drag, whereas the contrary will occur for low values of length-to-beam ratio, i.e. very high pressure drag and very low skin friction. In this submarine, the optimal value for the length-to-beam ratio would be three; keeping low both skin friction and pressure drag. Since vertical velocities for a convecting, low-viscosity ocean are about 0.1 mm/s, a length-to-beam ratio of 3 would improve the submarine behaviour. For the submarine design a FEM analysis is carried out.

The volume of water displaced by the submarine has influence in the resistance of the submerged body. The prismatic coefficient for the volume displace by the submarine, V, reads:

$$C_p = \frac{V}{A_m L_W}, \tag{11}$$

where Am and Lw are the mid-ship area and the waterline length displaced, respectively. This parameter describes the amount of volume in the ends of the hull. The optimal value of Cp for this submarine should be about 0.6.

The ideal shape involves a continuously changing diameter along its length. This idyllic form implicates an elliptical fore and the aft would be parabolic. A cylindrical mid-body design is the proposed structure for the submarine. This would reduce the draft and the building costs without any severe drag and noise penalties. Advantages and drawbacks have been analysed, because different approaches from the last ideal form would not only increase the drag but also impose both speed and range limitations.

The skin friction drag on a flat plate parallel to the undisturbed flow U∞ may be laminar/turbulent or a mixture of both. Low friction layer generated by laminar flow occurs at low free-stream velocities and is rarely found at higher velocities in seawater.

The Reynolds number gives the inertial-to viscous force ratio:

$$R_e = \frac{\rho U_\infty L}{\mu}, \tag{12}$$

where μ is the water viscosity. The behaviour of submarine prototype should be examined in a wind tunnel, testing the flow conditions in Europa´s oceans. In the submarine designed for Europa´s exploration, the value of the Reynolds number is under 2300, as it is shown in Fig. 3.

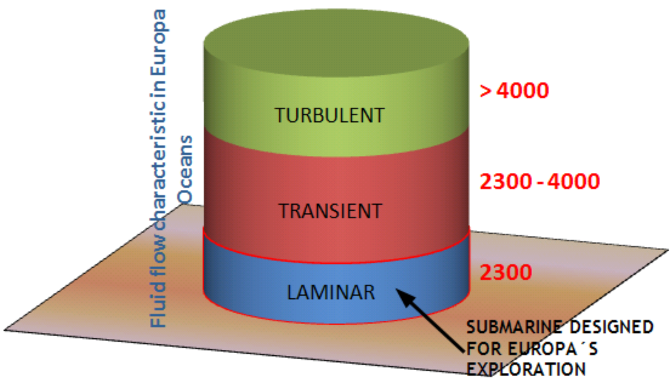

FIG. 3. THE REYNOLDS NUMBER IS A DIMENSIONLESS NUMBER THAT GIVES A MEASURE OF THE RATIO OF INERTIAL FORCES TO VISCOUS FORCES AND CONSEQUENTLY QUANTIFIES THE RELATIVE IMPORTANCE OF THESE TWO TYPES OF FORCES FOR GIVEN FLOW CONDITIONS

3.2 Bridge fin

The major appendage is the fin, which largely contributes to the overall drag. A large sail may contribute up to 30% of total resistance and a fully appended hull may have between 20% to 60% more resistance than a bare hull.

In this submarine design, the bridge fin has a number of important functions, it provides:

- Stowage and support for the apparatus.
- Underwater handling stability.

3.3 Pressure hull design

From section 2, the radius of the probe which contains the submarine should be smaller than 0.5 m for an affective melting in Europa´s icy crust. The length of the submarine is constrained than to 3 m for L/R=6. The characteristic lengths of the submarine might have an internal diameter and length of 0.5 m and 1.5 m, respectively.

The pressure hull must keep secure the submarine at the bottom of Europa´s oceans. The pressure supported by the submarine reads:

$$p = \rho \cdot g \cdot H_{oc} \tag{1}$$

where g is the Europa´s gravity surface, and Hoc and ρ are the depth of its ocean and density of its saline water content, respectively. Considering Hoc= 96 km of depth, and taking ρ= 1020 Kg/m3 and g = 1.32 m/s2, the maximum pressure would be about 131 MPa.

It is possible to define different pressures, according with the Europa´s depth. Fig. 4 shows the pressure that the submarine endures for a range of depths for both Earth and Europa conditions. Since gravity is about ten times smaller in Europa and maximum depths are ten times smaller in Earth, pressures at their surface ends are similar. The pressure is proportional with the dive depth. This dive depth cannot be increased effortlessly. Making the hull thicker increases the weight of the submarine, and it will require a reduction of the weight of on-board equipment. The design of the submarine should be studied to afford the objective to descend until the Europa´s oceans bottom. It is possible to reduce the submarine size, reducing the dive depth.

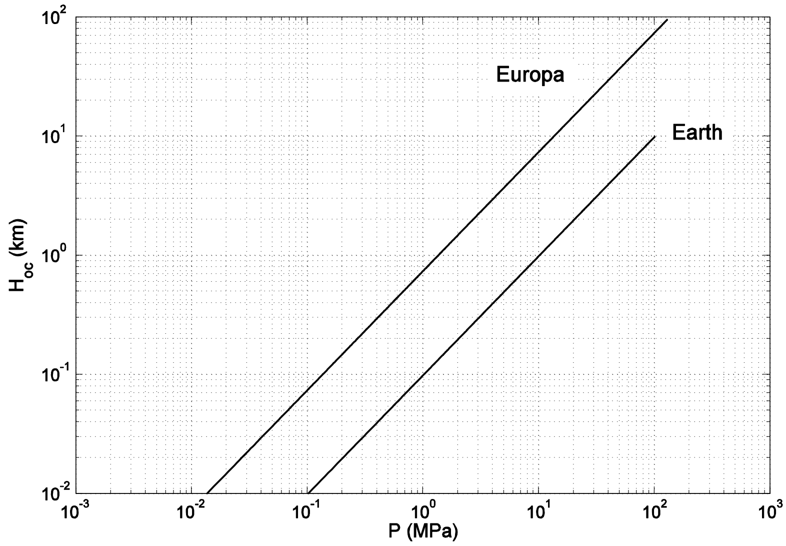

FIG. 4. DEPTHS VERSUS PRESSURES IN OCEANS FOR BOTH EARTH AND EUROPA. NOTICE THAT PRESSURES AT THEIR SURFACE ENDS ARE SIMILAR

Regarding the material of the pressure hull, a compromise between density and strength should be considered. The material used in the construction of the pressure hull might be metal matrix composite (MMC 6061 Al/alumina) or 6061 Al/SiC fiber because of their high strength-to-weight ratio. For the MMC 6061 Al/SiC, which will be the material considered here, the characteristic values of density, Young´s modulus and yield strength are 2700 kg/m3, 69 GPa and 3000 MPa, respectively. Considering ABS rules for underwater vehicles, systems and hyperbaric facilities the shell thickness is determined. With a safety factor of two and assuming 60 cm of internal diameter, the shell thickness would be 2.7 cm if the material adopted is MMC 6061 Al/SiC. If the size of the submarine is reduced the diving depth would be reduced too.

3.4 Diving Depth

Strong, heavyweight submarine hull should be designed to operate at high depth, leaving less available space for scientific instruments and both propulsion and communication systems. Submarine must dive over the safe depth. Between collapse and safe depth is required to use a factor of safety (sometimes called maximum designed operating depth) which may be 1.5 or higher and provides a margin of safety due to the inaccuracy of calculations of strength for the indeterminate structure of the submarine; the departures from the designed surface; stress concentrations from holes; to provide against fatigue; imperfect workmanship; reductions due to corrosion; dynamic loading and inadvertent travel below safe depth.

IV. SUBMARINE PROPULSION AND FUEL

As the vehicle is required to travel up to 96 km below the icy surface of Europa, it is suggested that the vehicle is initially put in a negative state of buoyancy, so that it will sink gently to the bottom of the ocean and thus not consume too much electrical power to reach these great depths. Additionally, the vehicle might have to be propelled backwards and forwards for in-situ exploration of interesting sites near a hydrothermal vent and it is suggested that this is achieved through traditional screw propellers. The submarine may also be able to control vertical movement through flaps, so that its motion can be three dimensional.

4.1 Propulsion

Due to upstream appendages the wake field entering the propeller disc is not uniform. There are shadows cast from the bridge fin and the aft control surfaces. In some cases a badly faired casing can leave not only velocity decrements but also large vortices that enter the propeller disc. These shadows can create a momentary increase in the lift coefficient on the blade in the shadow. The lift coefficient can double due to the momentary change in the angle of incidence, which it would cause beats. The propeller is a major source of low frequency noise emanating from a submarine.

Another concept, necessary to study is the noise. Is it really necessary to avoid the noise in this submarine? Is the noise contamination a problem in Europa? To cancel some of the noise produced by a submarine it is complicate and requires an expensive arrangement, a shrouded propeller. If a shroud is to be used then it has to be supported and a set of fixed pre-rotator blades are arranged to provide a pre-swirl in the opposite direction to the rotation of the propeller.

4.2 Fuel

Power source for propulsion is an efficient Radioisotope Power System (RPS), such as an improved Radioisotope Thermoelectric Generator (RTG). This fuel radioactive decay generates heat, which flows through thermoelectric devices. The well-known Seebeck effect will produce electrical power for the propulsion system. The radioactive material used in the submarine´s RPS must have several characteristics (Sanchez-Torres, 2011):

- Generate high energy radiation.
- Radiation easily absorbed and converted into alpha radiation. If it is transferred into beta radiation, the submarine will require extra shielding.
- Release energy at a permanent rate for a considerable amount of time. The measure of energy released per time of a given amount is inversely proportional to half-life.
- Produce a large quantity of power per density.

For large mission time a high life of the power source is required. RPS is useful for unmaintained situations needing a few hundred watts or less of power for durations too long for fuel cells, batteries, or generators to provide economically, and in places where solar cells are not effective, as it occurs in this Jovian moon far away of the Sun. Safe use of RTG requires containment of the radioisotopes long after the productive life of the unit. This point is very important in the future design of this submarine.

V. COMMUNICATION COMPONENTS, SENSORS AND TRANSCEIVER STRUCTURE

The submarine will carry oceanographic tools, as sensors to navigate autonomously and will create map features of the Europa´s oceans. The sensors should include compasses, depth sensors, sidescan and other sonar, magnetometers, thermistors and conductivity probes.

The sonar will be used to control and communicate with the spacecraft left in the surface. Images will be transmitted by means of sonar from the submarine to the first stage left in the surface. Alternatively, the data can be collected by the submarine and beamed to an orbiter-link which would transmit information back to Earth.

5.1 Components and other systems

The submarine apparatus are going to be situated alongside of the submarine, in a bridge fin designed for that purpose.

The bridge fin structure is designed in two parts, fore and aft, depending of the location. The components in forward are nosecone module, obstacle avoidance sonar, acoustic modem, acoustic imaging system, video camera and optical sensor, whereas the components in the aft part of the submarine would be control and communication module, sidescan sonar transducer, single or dual frequency sidescan sonar and propulsion and servo module.

The submarine will have different kinds of antennas: an antenna for linking the submarine with one or more devices using some wireless distribution method (probably radiofrequency), iridium antenna and a Europa Global Positioning System (EGPS) antenna; a future EGPS could be created positioning a few satellites around Europa, as the same way there are in the Earth.

5.2 Under-ice transceiver structure

Since the ice will refreeze behind the descending submarine, communications from submarine to the base at the surface might be difficult. Bryant (2002) shown a type of communication using ice-embedded transceivers; data would be sent through the ice crust with a fixed number of transceivers deployed at required intervals. The communication link margin will be given by the signal-to-noise power ratio.

5.3 Underwater transceiver structure

The underwater transmission of data is compound by bit streams, which will be transmitted organizing in frames. According with Choi, et al. (2003), the initial and the end code indicate the start and the end of a message frame, respectively. They are used by the receiver for the frame synchronization. There are sequences used by the adaptive equalizer in the receiver for optimizing the equalizer coefficients. The information-bearing data follow this sequence. The gap between the initial and the end sequence is for ensuring the completion of the frame synchronization in the receiver before the reception of the complete sequence.

VI. SUBMARINE SPECIFICATION

One of the main aspects in the design/specification of the submarine is the contamination problem. Primary, it is necessary to take special care for avoiding to introduce foreign organisms in the oceans of Europa and by all means not to produce any type of spill or escape from the submarine. For that reason, inoffensive systems for Europa environment will be used and innocuous devices with a clean-room technology will be designed for preventing the contamination of this important Jovian moon.

The submarine should be designed depending on the mission requirements. Table 1 shows the size of the submarine for a range of values and maximum depth requirements.

TABLE 1
SUBMARINE PROTOTYPE SPECIFICATIONS

Concept	Value
Total length	2.4 m – 1 m
Beam/External diameter	0.8 m – 0.3 m
Maximum depth	96000 m – 5000 m
Lifetime	≥14 years
Mass	140 kg – 30 kg
System efficiency	~ 30 %

The submarine design has been already described in previous sections, studying hydrodynamic for navigation proposes, bridge fin, and the pressure hull requirements. After several possible solutions, the final submarine hull or surface was defined as shown in this paper. The election of the submarine propulsion and its power source were also studied in previous sections.

VII. SUBMARINE NAVIGATION

The submarine can navigate using an underwater acoustic positioning system. When operating within a net of sea floor deployed baseline transponders, a set of three or more baseline transponders will be deployed on the sea floor, this is known as long baseline navigation. In Europa´s surface, the spacecraft will be used as a reference; ultra-short baseline or short-baseline positioning might be used to calculate where the subsea vehicle is relative to a future EGPS. The position of the surface craft will be created by means of acoustic range and bearing measurements. When it is operating completely autonomously, the submarine will surface and take its own EGPS fix. Between position fixes and for precise maneuvering, an inertial navigation system on board the submarine measures the acceleration of the vehicle and Doppler velocity technology is used to measure the rate of travel. A pressure sensor measures the vertical position. These observations are filtered to determine a final navigation solution. An emerging alternative might use an inertial navigation system in conjunction with either an EGPS receiver or an additional magnetic compass for dead reckoning whenever the EGPS signal is lost.

VIII. CONCLUSION

Low thermal power produces very slow melting. Faster penetration rate is obtained for larger values of P0, and smaller values of length L and diameter D.

Regarding the refreezing problem of the penetration path, thermal envelope over submarine might clean the obstructions. As it is shown in section 2, the design of the submarine is highly constrained for the radius of the probe which is used for melting the icy crust. In a future work the submarine will be designed for several length-to-beam ratios.

The design of a submarine shape with both minimum hydrodynamic drag and flow noise is considered. The combined effect of prismatic coefficient and both skin friction and pressure drag is designed to be minimum. Optimal length-to-beam ratio included here is about 3. New materials will improve the conditions of the pressure hull against the large column of water supported by the submarine. Future optimal designs should have smaller beam and larger length.

In the future, higher efficiency radioisotope power systems could be considered for melting icy crust. In addition nuclear reactor would solve the high power requirements.

In far future the sun will increase its temperature, heating and melting Europa´s ice. Assuming the viscous icy model without ocean, the submarine will work under these circumstances.

High number of transceivers should be left during melting process for obtaining high signal-to-noise ratio in the communications between the submarine and the base at Europa´s surface.

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REFERENCES

[1] Aamot, H. W. C. (1967). Heat transfer and performance of a thermal probe for glaciers. CRREL Special Report 194, Cold Regions Research and Engineering Laboratory Hanover, New Hamphire.

[2] Bryant, S. (2002). Ice-Embedded Tranceivers for Europa Cryobot Communications. IEEE, 0-7803-7231-X/01.

[3] Cardell, G. et al. (2004). The subsurface ice probe (SIRP): a low power thermal probe for the Martian polar layer deposits. 35th Lunar and Planetary Science Conference.

[4] Case, J.; Lord, C. and Ross, C. T. F. (1999). Strength of materials and structures. Butterworth-Heinemann, Oxford, U.K.

[5] Cassen, P.; Reynolds, R.T.; Peale, S.J. (1979). Is there liquid water on Europa?. Geophys Res. Lett., 6, 731-734.

[6] Choi, Y.; Kim, S. M.; Park, J. W.; Lim, Y. K. and Ko, H.-L. (2003). A Digital Acoustic Transceiver for Underwater Communication without PLL and DLL. Proceeding of IEEE Oceans Conference, Vol. 4, pp. 1781-1785.

[7] Choi, Y.; Park, J. W.; Kim, S. M. and Lim, Y. K. (2003). A Phase Coherent All-Digital Transmitter and Receiver for Underwater Acoustic Communication Systems. Proceeding of the 35th Southeastern Symposium on System Theory, pp. 79-83.

[8] Hand, K.P.; Chyba, C.F. (2007). Empirical constraints on the salinity of the europan ocean and implications for a thin ice shell. Icarus, 189, 424-438.

[9] Hussmann, H.; Tilman, S.; Wieczerkowski. (2002). Thermal Equilibrium States of Europa´s Ice Shell: Implications for Internal Ocean Thickness and Surface Heat Flow. Icarus, 156, 143-151.

[10] Janhunen, P.. (2004).Electric sail for spacecraft propulsion. Journal of Propulsion and Power, 20, 763-764.

[11] Joubert, P. N. (2004). Some Aspects of Submarine Design. Maritime Platforms Division, DSTO Platforms Sciences Laboratory, Australia.

[12] Nimmo, F.; Giese, B.; Tappalardo, R.T. (2003). Estimates of Europa´s ice shell thickness form elastically-supported topography. Geophysical Research Letters, 30, 5, 1233, 37:1-4.

[13] Pappalardo, R.T.; et al. (1998). Geological evidence for solid state convection in Europa´s ice shell. Nature, 391, 365-368.

[14] Ross, C.T.F. (2007). Conceptual Design of Submarine to Explore Europa´s Oceans. Journal of Aerospace Engineering, July, pp. 200-203.

[15] Ross, M.; Schubert, G. (1987). Tidal heating in an internal ocean model of Europa. Nature, 325, 133-144.

[16] Ruiz, J.; Tejero, R. (2002). Heat flow, lenticulae spacing, and possibility of convection in the ice shell of Europa. Icarus, 162, 362-373.

[17] Sanchez-Torres, A. (2011). Radioisotope Power Systems for Space Applications, in: Singh, N. (Eds.), Radiositopes, Applications in Physical Sciences. INTECH, Croatia, pp. 457-472.

[18] Sanchez-Torres, A. (2014). Propulsive force in an electric solar sail. Contributions to Plasma Physics, 54, 314-319.

[19] Squyres, S.W.; Reynolds, R.T.; Cassen, P.M.; Peale, S.J. (1983). Liquid water and active resurfacing on Europa. Nature, 301, 225-226.

[20] Tennent, R. M. (1971). Science data book. Oliver and Boyd, Edinburgh, U.K.

[21] Treffer, M.; et al. (2006). Preliminary studies concerning subsurfaces probes for the exploration of icy planetary bodies. Planetary and Space Science, 54, 621-634.

[22] Ulamec, S.; Biele, J.; Funke, O. (2007). Access to glacial and subglacial environments in the Solar System by melting probe technology. Rev. Environ. Sci. Biotechnol, 6,71-94.

[23] Weiss, P. et al. (2008). Study of a thermal drill head for the exploration of subsurface planetary ice. Planetary and Space Science, 56, 1280-1292.

[24] Zimmerman, W.; Bonitz, R.; Feldman, J. (2001). Cryobot: an ice penetrating robotic vehicle for Mars and Europa. IEEE Proceedings, 1, 10-17, 311-323.