Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Analysis of Nuclear Submarine in Europa Using the eVinci™ SMR: Welcoming Trump-Nomics for Space Industry Incorporated with SpaceX

Tae Ho Woo[1,*], Kyung Bae Jang[2], Chang Hyun Baek[1]
[1]*Department of Mechanical and Control Engineering, The Cyber University of Korea, Seoul 03051, Republic of Korea*
[2]*Department of Electrical Engineering, Gangneung-Wonju National University, Wonju 26403, Republic of Korea*
[*]*Corresponding author: thwoo@cuk.edu, thw_kor@hotmail.com*

***Keywords* :** Small Modular Reactor (SMR), Space, Cryobot

1. Introduction

This study investigates the application of a small modular reactor (SMR) with enhanced safety features for the utilization of nuclear energy. Specifically, the Westinghouse eVinci™ reactor, which uses the core technology of producing electricity and heat using the thermoelectric effect, is being examined for use on Europa, a satellite of Jupiter [1]. Key specifications are presented in Table 1 [2]. Notably, the modular, hermetically sealed design of these reactors provides robust safeguards against nuclear material leakage and core meltdown events, thereby demonstrating a substantial capacity to mitigate radiological contamination. The consideration of nuclear power's inherent high energy density, coupled with the projected energy release of Europa, informs the assessment of SMRs. Consequently, this analysis posits the potential for SMRs to facilitate future in-situ resource utilization, specifically the extraction of nuclear fuel on Mars or other extraterrestrial bodies.

The surface gravity of Europa is measured at 1.314 m/s^2, a value marginally lower than that of Earth's Moon of 1.622 m/s^2 [3]. A comprehensive overview of Europa's physical characteristics is presented in Table 2 [4, 5]. Specifically, Europa exhibits a mean radius and volume equivalent to 0.245 and 0.061 times that of Earth, respectively. Furthermore, its mass, which is 0.008 times Earth's mass and less than that of the Earth's Moon, significantly influences its gravitational field. Consequently, the exploration of Europa necessitates a thorough consideration of the satellite's fundamental physical properties. In particular, the dynamics of human locomotion will be critically affected by the ambient environmental parameters, including gravitational acceleration. The estimated thickness of Europa's ice layer ranges from 15 to 25 km [6]. For the purposes of this investigation, a thickness of 20 km is adopted; however, it is imperative to acknowledge the inherent uncertainties associated with this parameter.

2. Methods

The exploration of Europa necessitates the deployment of cryobots, wherein operational efficacy is contingent upon energy availability and mechanical actuation. Because it operates under the sea, it is also called a submarine. Fig. 1 illustrates a schematic representation of a typical cryobot design. Nuclear thermal energy, requisite for exploratory endeavors, can be generated through the utilization of Small Modular Reactors (SMRs) within a suitably dimensioned tunnel. The thermal output of these reactors facilitates the construction of substantial tunnel infrastructures. Furthermore, electrical power generation is achievable via the thermoelectric principle. As depicted in Fig. 2, the cryobot initiates penetration from the vacuum of space, traversing the Europan surface and subsequently entering the ice layer. The thermoelectric effect constitutes a phenomenon whereby a temperature gradient, induced by localized heating, drives the directional migration of internal electrons, resulting in the generation of an electric current [7]. At elevated current densities, particularly in graphene or nanowire/nanotube-based devices, Joule heating emerges as a critical design consideration, significantly impacting electron transport characteristics [8].

As the forces of the cryobot's movement, the configuration is seen in Fig. 3 where the Europa's central force is Mg and this is divided for a free body force as $Mg\cos\theta$ and $Mg\sin\theta$. So, the forces are described as [9],

$$\frac{dV}{dt} = \frac{\sum F_d - \sum F_{rs}}{dM} \tag{1}$$

where $\sum F_d$ is the total tractive forces, $\sum F_{rs}$ is the total resistance forces, and M is the vehicle's mass. Consequently, the cryobot's locomotion is influenced by gravitational forces, which are directly correlated with mass, gravitational acceleration, and resultant forces. Potential hazards within Europa's ice layer may arise from inaccuracies in sinkhole detection and malfunctions of safety mechanisms. A critical consideration for cryobot operation on Europa pertains to its energy provisioning and kinematic behavior. The primary power source is derived from nuclear energy, facilitating both thermal energy generation for ice layer ablation and electrical energy production for cryobot operation. Specifically, electrical power sustains the functionality of scientific instrumentation, avionics, communication modules, and other critical subsystems. For contingency power requirements, a radioisotope thermoelectric generator (RTG) is integrated into the system.

The detection of sinkholes within Europa's ice layer necessitates the adaptation of terrestrial sinkhole detection methodologies, as outlined in references [10, 11]. These procedures typically involve a multi-faceted approach, incorporating geophysical surveying techniques to identify subsurface anomalies indicative of potential sinkhole formation.

A. Data collection
B. Data processing
C. Identification of ice layer sinkholes
D. Sinkhole monitoring and prediction

The analysis of potential pyrobot malfunctions is conducted through a rigorous safety assessment encompassing both sinkhole detection inaccuracies and safety mechanism failures. Furthermore, the implementation of pyrobot startup failure modeling is achieved via the application of the System Dynamics (SD) methodology [13].

Considering, for example, time-dependent variables A(t) and B(t), where Stock(t) represents the quantity of a given stock at time t, the temporal evolution of Stock(t) can be expressed in differential form, as shown in the following equation [14]:

$$\frac{d(Stock\ \ (t))}{dt} = A(t) - B(t) \tag{2}$$

Fig. 4 (a) is the main modeling where Safety Systems, Accident Scenarios, Sinkhole Detections affect to Cryobot Operations. The others are models for Safety, Accident, and Detection Procedure for Sinkholes in Ice Layer.

3. Results

Fig. 5 presents the results of four distinct simulations: (a) Cryobot Operations, (b) Safety Systems, (c) Accident Scenarios, and (d) Sinkhole Detection. The graphical representations depict the behavioral trends over a 100-minute temporal interval. Cryobot Operations demonstrates a gradual, monotonic increase throughout the simulation period. Safety Systems exhibit relatively low values at the initial and terminal stages, indicating peak performance of safety mechanisms during the mid-operational phase. Accident Scenarios reveal a minimal performance capability at the simulation's conclusion. Sinkhole Detection displays a consistently increasing trend over the duration of the simulation."

4. Conclusions

The space development project based on the Trump administration's Trump-nomics, along with Elon Musk's SpaceX, can be seen as a signal of innovation in the commercial space industry. The proliferation of commercial space operations necessitates the immediate mitigation of numerous associated risks. However, the paramount consideration lies in the quantification of potential economic returns. Given Europa's distal location from the Sun, nuclear energy presents a highly efficacious method for ensuring a stable energy supply, even during resource extraction from the subsurface ice layer. Terrestrial commercially developed SMRs exhibit potential for successful deployment in space environments. This is attributable to their capacity for energy generation irrespective of vacuum and gravitational conditions. Notably, the consequences of radiation leakage incidents in space are not directly comparable to those on Earth. The primary concern revolves around the potential disruption of energy output. Should such a disruption occur, remedial measures can be implemented to restore and augment energy production. Therefore, safety protocols should be viewed as mechanisms to secure system reliability and operational success, rather than solely as safeguards against the direct deleterious effects of radiation on human life.

Acknowledgments

This study was supported by the Ministry of SMEs and Startups grant (RS-2023-00266376).

REFERENCES

[1] Westinghouse, eVinci™ Microreactor The Next Generation Nuclear Research Reactor, Westinghouse Electric Company LLC, Cranberry Township, USA, 2024, https://westinghousenuclear.com/data-sheet-library/evinci-microreactor-the-next-generation-nuclear-research-reactor/.

[2] Westinghouse, eVinci™ Microreactor, Westinghouse Electric Company LLC, Cranberry Township, USA, 2024, https://westinghousenuclear.com/energy-systems/evinci-microreactor/.

[3] Williams, M., Jupiter's moon Europa, Phys.org, Isle of Man, 2015.

[4] Blue, J., Planet and Satellite Names and Discoverers. USGS, USA, 2009.

[5] NASA, Overview of Europa Facts, National Aeronautics and Space Administration (NASA), Washington, D.C., USA, 2014.

[6] NASA, Thick or Thin Ice Shell on Europa? National Aeronautics and Space Administration (NASA), Washington, D.C., USA, 2017,

[7] Zhu, L.L., Ding, T.P., Gao, M.M., et al., Shape conformal and thermal insulative organic solar absorber sponge for photothermal water evaporation and thermoelectric power generation, Adv. Energy Mater., 9 (22) (2019), p. 1900250.

[8] Ravi. Chandran, K.S., Transient Joule heating of graphene, nanowires and filaments: analytical model for current-induced temperature evolution including substrate and end effects, Int. J. Heat Mass Trans., 88 (2015), pp. 14-19.

[9] Eddine, G.S., Tadjine, M., Boucherit, M.S., 2014. Model based Design of an Electrical Hybrid

Vehicle with Energy Management, Int. J. Comp. Appl., 97 (17) 35.
[10] Guinea, A., Playà, E., Rivero, L., Salvany, J.M., Geoelectrical prospecting of glauberite deposits in the Ebro basin (Spain), Engin. Geo., 174 (2014), pp. 73-86.
[11] Laurent, V.C.E., Schaepman, M.E., Verhoef, W., Weyermann, J., Chávez, R.O., Bayesian object-based estimation of LAI and chlorophyll from a simulated Sentinel-2 top-of-atmosphere radiance image, Remote Sensing of Environment, 140 (2014), pp. 318-329.
[12] Singh, V., McCarthy, C., Silvia, M., Jakuba, M.V., Craft, K.L., Rhoden, A.R., German, C., Koczynski, T.A., Surviving in Ocean Worlds: Experimental Characterization of Fiber Optic Tethers across Europa-like Ice Faults and Unraveling the Sliding Behavior of Ice, The Plan. Sci. J., 4 (1) (2023)1 (22pp).
[13] SDS, What is System Dynamics? System dynamics society (SDS), San Diego, USA, 2024, https://systemdynamics.org/what-is-system-dynamics/.
[14] Sterman, J.D., Business Dynamics: Systems Thinking and Modeling for a Complex World, Irwin McGraw-Hill, Boston, USA, 2000.

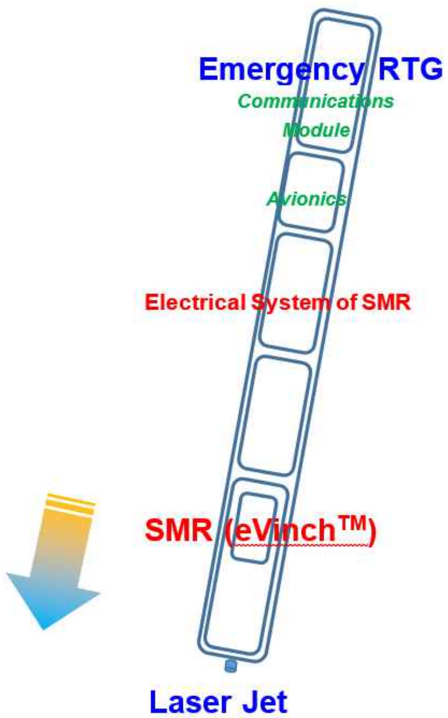


Fig. 1. Simplified configuration of Cryobot.

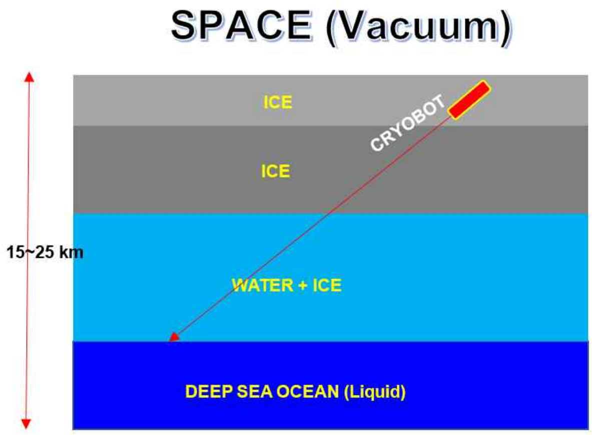


Fig. 2. Feature of Europa's surface layer [12].

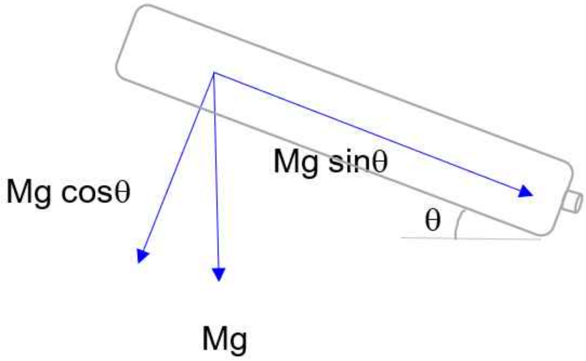
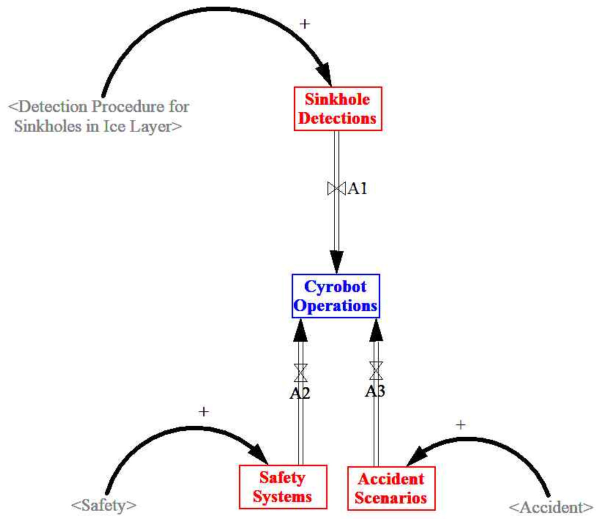
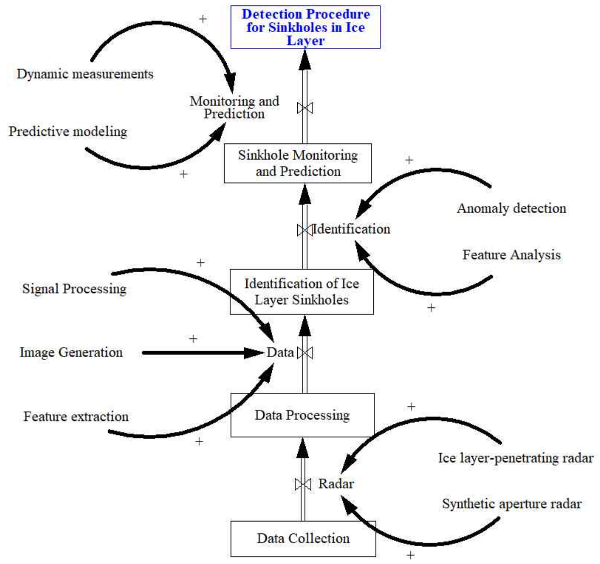


Fig. 3. Forces of the cryobot movement.



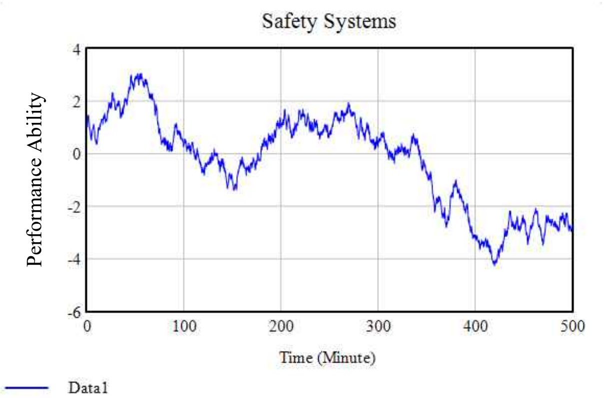
(a)

Performance Ability

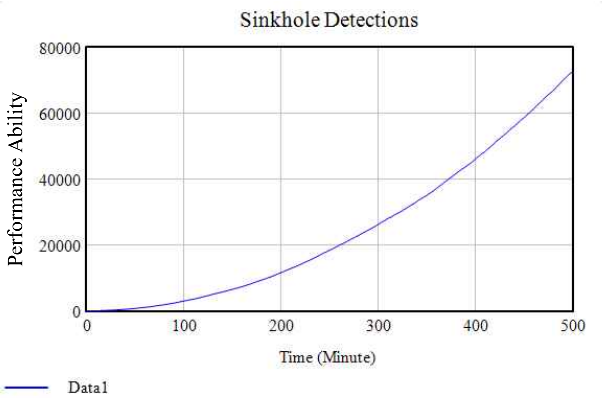


(b)

Fig. 4 Modeling for cryobot (a) Main modeling and (d) Detection Procedure for Sinkholes in Ice Layer.



(b)



(d)

Fig. 5. Results for simulations (a) Safety Systems and (b) Sinkhole Detections.

Table I: Specifications of eVinci™ Microreactor [1,2]

Classification	Content
Power	5MWe (6MWth)
Fuel Life	8+ years
Grid	Seamless pairing with existing grid
In-Core Flux	1×10^{13} n/cm^2
Coolant	No water required for operation

Table II: List of Europa's data [4,5]

Classification	Content
Surface Gravity	0.314 g (1.314 m/s^2)
Mean Radius	1,560.8 +/- 0.5 km
Surface Area	3.09×10^7 km^2
Volume	1.593×10^{10} km^3
Mass	4.799×10^{22} kg
Periapsis	664,862 km
Apoapsis	676,938 km
Mean Orbit Radius	670,900 km
Avg. Orbital Speed	13,743.36 m/s
Discovery	Galileo Galilei, Simon Marius (1610)