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Space Mining of Asteroid 52 Europa by Atomic Power Propulsions of Space Small Modular Reactor (S-SMR): Another Jackpot by Practicable Space Nuclear Technology

Tae Ho Woo[1,*], Chang Hyun Baek[1], Kyung Bae Jang[2]
[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*

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1. Introduction

Space mining using nuclear-powered rockets is analyzed. Asteroid 52 Europa is about 315 km across and has an elliptical shape, with an estimated width of 380 km, length of 330 km, and height of 250 km [1]. It has the same name as Jupiter's satellite Europa, and is a C-type metallic asteroid. 52 Europa is the 7th largest asteroid by volume and the 6th largest by mass, Table 1 has the list of asteroid type [2]. Like 16 Psyche, 52 Europa is thought to have deposits of nickel, iron, and gold. Located within the asteroid belt, 52 Europa is relatively accessible and is considered suitable for mining. The economic value of 52 Europa is estimated to be several hundred trillion dollars, and it is no exaggeration to say that it is a jackpot. [3].

The celestial body 52 Europa orbits the Sun at an approximate mean distance of 3.101 astronomical units (AU), completing an orbit in roughly 5.48 Earth years (2002 days) [4]. The general configuration of small Solar System bodies is illustrated in Fig. 1 [5]. A one-way transit to 52 Europa is estimated to range from 2 to 4 years. This duration is subject to variability based on several factors, including the precise orbital parameters of 52 Europa (e.g., eccentricity and inclination) and its relative position to Earth at the time of spacecraft launch. The anticipated duration for mining operations and subsequent waiting at 52 Europa is projected to be between 1 and 2 years. Consequently, the total round-trip mission time is estimated to be no less than 5 to 10 years.

2. Methods

2.1. Change in spacecraft velocity (delta-V(ΔV))

To analyze the thrust of a spacecraft, the velocity change required for the spacecraft to change its orbit or velocity vector is important. There are several factors that affect speed [6]. That is, the asteroid mining target orbit, moving gravity field, Oberth effect (maneuvering to maximize spaceflight fuel efficiency) [7], gravity assist effect, Earth's atmospheric resistance, and changes in orbital inclination.

2.2. Nuclear Electric Propulsion (NEP)

Converting thermal energy generated by Small Modular Reactors (SMRs) into electricity for a Nuclear Electric Propulsion (NEP) system, such as an ion or plasma engine, significantly enhances specific impulse compared to Nuclear Thermal Propulsion (NTP). This is achieved by ionizing and accelerating the propellant, leading to superior fuel efficiency [8]. Unlike NTP, which provides high thrust over a short duration, NEP systems are better suited for continuously generating low thrust over extended periods, enabling gradual spacecraft acceleration. The SMR assumes Westinghouse's eVinci™ SMR [9]. According to the company's guidance, it is applicable to space propulsion of nuclear reactors, etc.

2.3. Required Propellant Velocity

ΔV, representing the total change in velocity necessary for a spacecraft to achieve a desired orbit or trajectory, is directly correlated with propellant consumption [10]. The cumulative ΔV for a mission is determined by summing the ΔV requirements of each successive maneuver. Consequently, this parameter is a critical determinant of mission success and economic viability. Fig. 2 illustrates the required propellant velocity for various mission phases.

1. Achieving Low Earth Orbit (LEO) from the Earth's surface necessitates a ΔV of approximately 9,300 to 10,000 m/s.

2. To egress Earth's gravitational sphere of influence and initiate a heliocentric transfer trajectory towards 52 Europa, a ΔV of approximately 3,200 to 3,500 m/s is necessary.

3. Upon traversing the heliocentric transfer orbit, the ΔV required to approach 52 Europa, nullify relative velocity, and achieve rendezvous can range from several hundred m/s to over 1,000 m/s.

4. For long-term exploration or mining operations requiring orbital entry around 52 Europa, the required ΔV is relatively low, typically tens to less than 100 m/s.

5. For missions involving surface operations, such as mining, the ΔV required for landing on the asteroid's surface and subsequently liftoff to initiate a return trajectory is exceptionally low, ranging from a few m/s to tens of m/s.

6. The final phase of the mission, involving departure from 52 Europa with acquired resources, insertion into an Earth-return trajectory, and safe atmospheric reentry, necessitates a cumulative ΔV that can range from several hundred m/s to over 1,000 m/s.

2.4. Nuclear propulsion thrust calculations

In NEP systems, the thermal energy released from nuclear fission is transformed into electrical energy. This electricity is then used to accelerate a propellant, typically xenon, thereby generating thrust. The process involves ionizing the propellant to create positively charged ions, which are subsequently accelerated by applying a high voltage across a series of specialized meshes known as grids. This direct acceleration and expulsion of ions produces the desired thrust.

The fundamental relationship governing rocket motion is articulated by the Tsiolkovsky rocket equation [11]. This equation describes how a rocket's change in velocity (ΔV) is directly related to its effective exhaust velocity and the ratio of its initial to final mass. As a rocket expends propellant, its mass continuously decreases, a dynamic intricately captured by this foundational equation.

One can define the velocity of a rocket of mass m at time t. After the fuel is ejected at time $t + dt$, the mass of the rocket is $m + dm$. The momentum of the rocket system at t is mv. The momentum of the rocket at $t + dt$ is $(m+dm)(v+dv)$, and the momentum of the fuel is $dm - v'dm$. This means that the momentum of the rocket system at $t + dt$ is $(m+dm)(v+dv) - v'dm$. Then,

$$m\,v = (m + dm)(v + dv) - v'dm \tag{1}$$

Using $-u = v' - (v+dv)$

$$m\,v = (m + dm)(v + dv) + dm[u - (v + dv)] \tag{2}$$

So,

$$m\,dv = -\,udm \tag{3}$$

For integration,

$$\int_{v_i}^{v_f} dv = -\,u \int_{m_i}^{m_f} \frac{dm}{m} \tag{4}$$

If one organizes,

$$v_f = v_i + u \ln \frac{m_i}{m_f} \tag{5}$$

Then, v_i is the initial velocity of the rocket, v_f is the final velocity of the rocket, m_i is the initial mass of the rocket, m_f is the final mass of the rocket, and u is the fuel injection velocity.

If gravity is at work, such as when escaping from Earth, by the relationship between momentum and impulse,

$$[(m + dm)(v + dv) - v'dm] - m\,v = -\,m\,gdt \tag{6}$$

Using $-u = v' - (v+dv)$

$$m\,dv + udm \;-\; m\,gdt \tag{7}$$

So,

$$\int_0^{v_f} dv_f = \int_{m_i}^{m_f} \left(-\frac{g}{dm/dt} - \frac{u}{m_f}\right) dm_f \tag{8}$$

Then,

$$v_f = -gt + u \ln \frac{m_i}{m_f} \tag{9}$$

Here, m_i is the mass of the rocket when $t = 0$, and m_f is the mass of the rocket when time is t.

If one adds the mined material m_a, Eq. (5) becomes,

$$v_f = v_i + u \ln \frac{m_i}{(m_f + m_a)} \tag{10}$$

And Eq. (9) is,

$$v_f = -gt + u \ln \frac{m_i}{(m_f + m_a)} \tag{11}$$

So, the final velocity is obtained.

3. Results

Fig. 3 (a) is the rocket velocity (Gravity Considered), (b) rocket velocity (Non-Gravity Considered), and (c) rocket velocity comparison. The fuel injection velocity is assumed to be 5,500 m/s. While the specific impulse of conventional chemical propulsion rockets is usually 400 to 450 seconds, nuclear electric propulsion can reach the target from several thousand seconds to more than 10,000 seconds. However, chemical rockets are suitable for missions that require rapid acceleration or escape from the Earth's gravity by generating strong thrust in a short period of time, while nuclear electric propulsion generates low thrust continuously for a long time to gradually accelerate the spacecraft. Therefore, it must be launched from the Earth with the help of chemical rockets, and it is suitable for long-term space exploration missions such as space mining. Fig. 4 shows a comparison of rocket speeds for mined materials. Despite the presence of mined materials, speed increases due to the reduction in fuel. Chemical-propellant rockets produce large thrusts in the tens of kN to several MN units [12]. The Merlin engine of SpaceX Falcon 9 produces about 845 kN. In contrast, nuclear-electric rockets typically produce very low thrusts in the milliN to N units. The Hall-effect thruster (PPS-1350) used on the SMART-1 satellite produces about 68 mN. Fig. 5 shows that the rocket speed increases with the change in nuclear energy.

4. Conclusions

The features and advantages of the Space Small Modular Reactor (S-SMR), an SMR-powered spacecraft, are imaginable. Factory production of many SMR designs reduces costs and allows for flexible deployment in space missions, while their passive safety systems ensure they can automatically and safely shut down in an emergency without external power. This can be used for a variety of purposes in space, not just as a propulsion system. The challenges that need to be addressed in the overall system include the risk of radioactive leakage during ground launch, concerns about radioactive spread in the event of an accident in space, material durability in ultra-high temperature environments, and the need for technologies to miniaturize and lighten the reactor.

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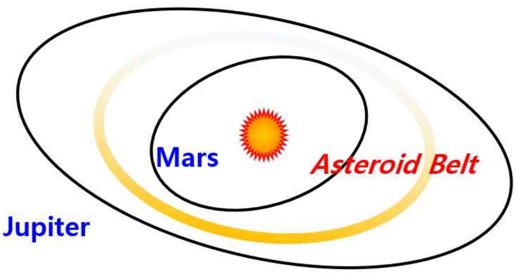


Fig. 1. Configuration of Small Solar System body [5].

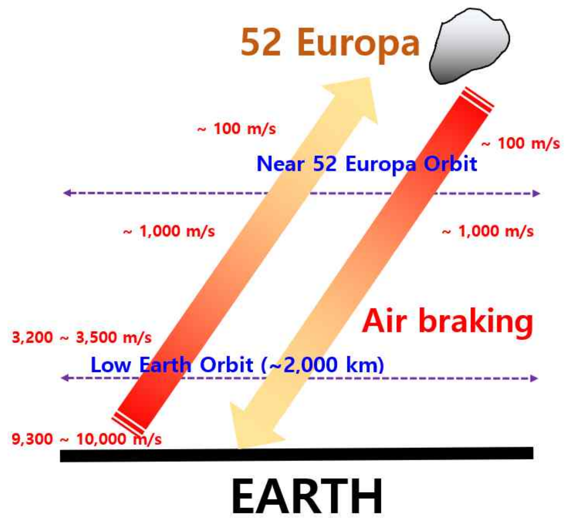
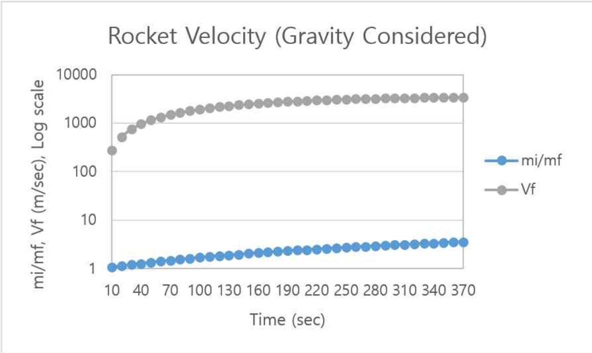
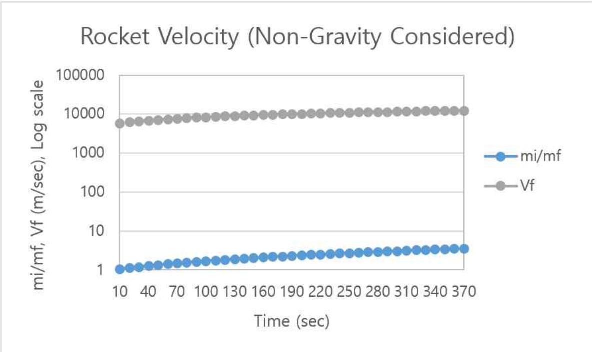


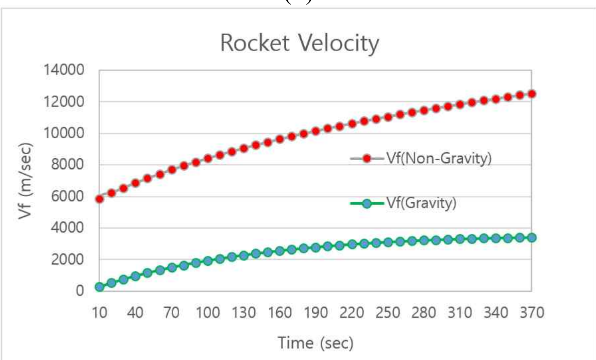
Fig. 2. Required Propellant Velocity.



(a)



(b)



(c)

Fig. 3. Comparisons of rocket velocity (a) Rocket Velocity (Gravity Considered), (b) Rocket Velocity (Non-Gravity Considered), and (c) Rocket Velocity comparison.

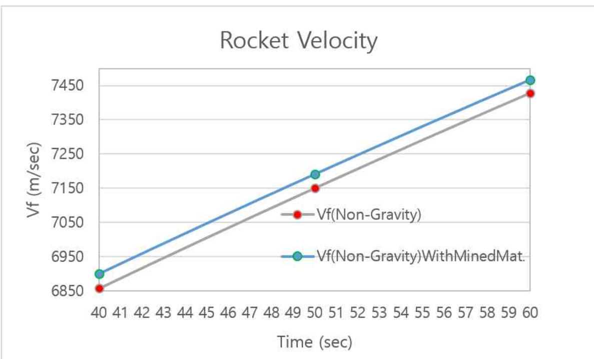


Fig. 4. Comparisons of rocket velocity for mined material.

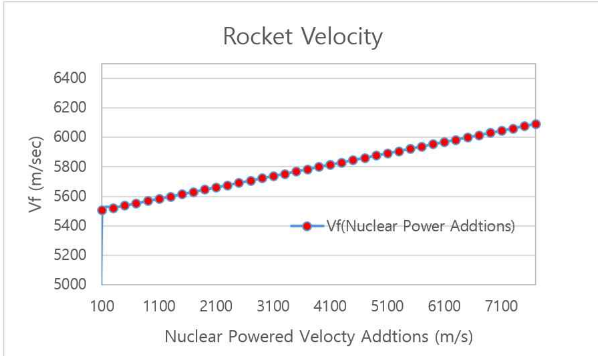


Fig. 5. Rocket velocity by nuclear power variations [5].

Table I: List of space mining market (Fortune Business Insights, 2024) [2].

Classification	Content
Asteroid	C, S, M Types
Nations	USA, EU, RUSSIA, Asia Pacific etc.
Phase	Space Vehicle, Launch, Thrust, Operation
Applications	Resource harvesting, Construction, 3D Printing