A THERMAL-SOLAR SYSTEM FOR DE-ORBITING OF SPACE DEBRIS

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ABSTRACT

This paper presents a system for removal of space debris, which can be placed on geocentric, heliocentric or Sun-synchronous orbit. The system is composed of two parabolic mirrors, a large one and a small one. The concave face of the large parabolic mirror is oriented toward the concave face of the small parabolic mirror. Sunlight is focused by the large parabolic mirror in its focal point. Then, the light rays are reflected by the small parabolic mirror (which has the same focal point as the large parabolic mirror) and form parallel rays directed along the axis. A guide-tube having a honeycomb structure plated with gold is attached to the convex side of the large parabolic mirror within a spherical articulation. Elastic lens filled with liquid are placed at the end of this guide tube. The guide-tube is normally closed by a gold platted shutter. When the shutter is opened, the light coming from Sun is focused by lens in one focal point onto target debris. The high power of focused light locally vaporizes/ionizes the debris material. The thrust created in this way de-orbits the space debris pushing it toward the Earth surface.

KEYWORDS: space debris de-orbiting, removal

NOMENCLATURE

E_e, irradiance in proximity of Earth, [W/m^2]
E, energy, [W]
$\dot{m}$, mass flow, [kg/s]
P, power, [W]
r, radius, [m]
R, reflectivity, dimensionless
t, temperature, [°C]
T, absolute temperature, [K]
T_f, thrust force, [N]
c, heat capacity, [J/kg·K]
c_f, heat of fusion, [J/kg·K]
c_{ion}, heat of ionization, [J/Kg·k]
c_v, heat of vaporization, [J/kg·K]
C_m, coupling coefficient, N/W

1. INTRODUCTION

Currently, there is no reliable and efficient system for removing space debris. Today, space debris represents already a great danger becoming one of the main threats for safety of space exploration and exploitation. Most of space debris is concentrated in the near-Earth space region, particularly in the Low Earth Orbit (LEO, Fig.1 [1]) and Geostationary Earth Orbit (GEO, Fig.2 [2]) regions. Space debris is composed of non-functional boost stages of rockets, spent rocket upper stages, paint flakes, chunks of slag from solid rocket motors, remnants of old science experiments, non-functional satellites, various fragments which are the result of collisions, materials detached from International Space Station, components of satellites destroyed by missiles etc. [3]
Depending on size, there are three main categories of space debris: [4]

Category I (<1cm)-causes significant damage to vulnerable parts of a satellite; no shielding may protect the satellite
Category II (1-10cm)-seriously damages or destroys a satellite by collision, there is no effective shielding
Category III (>10cm)-destroys a satellite by collision, can be tracked, evasive maneuvers can protect the satellite.

Figure 1: Space debris in LEO region [1]

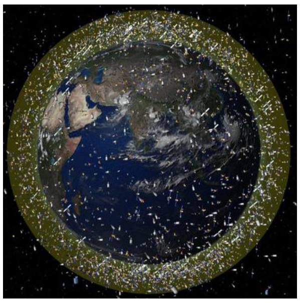

Figure 2: Space debris in GEO region [2]

2. DESIGN OF THE NEW SOLAR-THERMAL SYSTEM FOR SPACE DEBRIS DE-ORBITING

In a previous paper, the authors presented a system for deflecting asteroids from collision trajectories with Earth [5].
In the present paper, the authors present a similar system which can be used for de-orbiting of space debris. The system is composed of two parabolic mirrors, a large one and a small one (Fig.3).

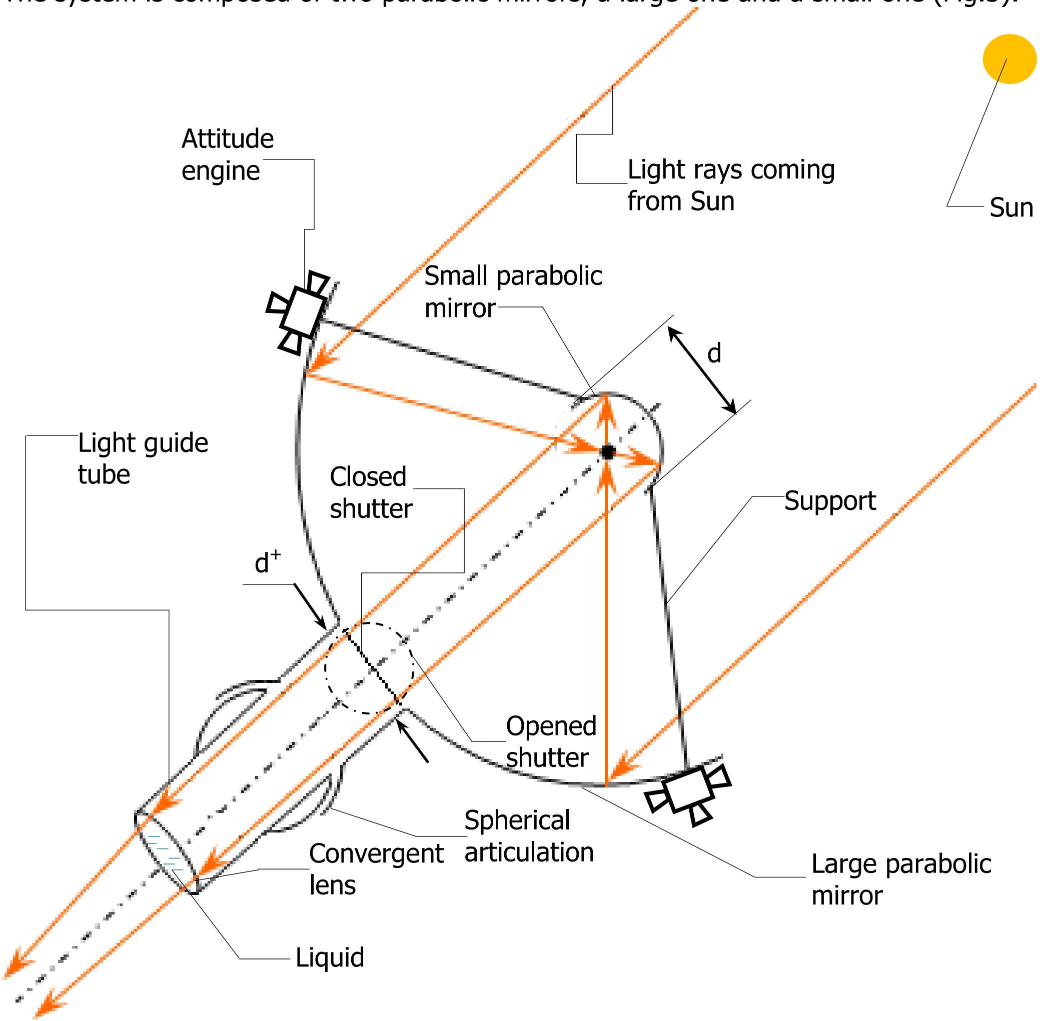

Figure 3: Design # 1 of solar thermal system for space debris de-orbiting

The mirrors are made from very thin composite material (based on graphite fibre) plated with a very thin gold layer or Mylar on the concave face.
The concave face of the large parabolic mirror is oriented toward the concave face of the small parabolic mirror. The mirrors have a common focal point.
The solar light rays which are parallel to the axis of the large parabolic mirror are reflected into this focal point. Then, the light rays are reflected by the small parabolic mirror and form parallel rays which are directed along the common axis (because, as said above, the mirrors have a common focal point).
The diameter of concentrated light beam is the same as the diameter of small parabolic mirror ('d'). This light beam passes through one hole (with diameter 'd$^+$') placed in the centre of the large parabolic mirror. A light guide-tube having a fine honeycomb structure made of composite material with graphite fibre base, which is plated with gold is attached to the convex side of large parabolic mirror using a spherical articulation. Elastic lens filled with liquid are placed at the end of light guide tube. The hole having diameter 'd$^+$' placed in the canter of the large parabolic mirror is normally closed by a gold plated shutter.
The system operates as follows:
First, the system is oriented with the large parabolic mirror to the sun using the attitude thrusters (the shutter is closed). Then, the light guide tube is directed to the space debris and the faces of lens are curved at the appropriate radii for focusing the light on the surface of space debris. (Fig. 4). When the shutter is opened, the light coming from Sun is focused by the large parabolic mirror into the common focal point and then is reflected by the small parabolic mirror toward the hole 'd+' and the light guide tube. At the end of the guide tube, the light is focused by lens filled with liquid in a focal point which is positioned onto space debris. The focused light locally vaporizes/ionizes the space debris material. The thrust force created in this way pushes the space debris toward the Earth surface. Thus, the space debris is de-orbited and subsequently burns in the atmosphere.
When the light shutter is closed, the light rays are sent back toward the small parabolic mirror, focused to the common focal point then reflected back toward the Sun.

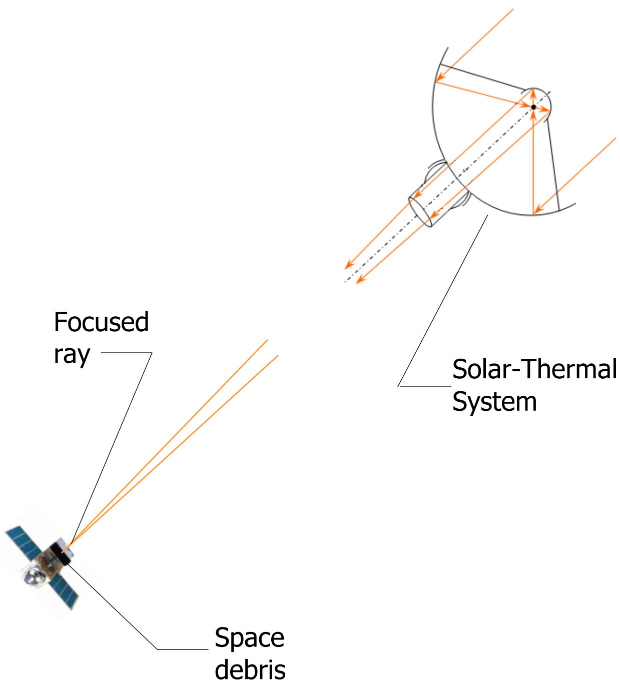

Figure 4: Striking space debris using the Solar-Thermal System

The system can be launched as a whole by the Ariane 6 launcher. In this case, the large parabolic mirror is a hexagon which can be inscribed in a 5 m diameter circle when folded (Fig.5), small enough to pass through the Ariane 6 launcher fairing (5.4 m). When unfolded, the large parabolic mirror is a hexagon which can be inscribed in a 10 m diameter circle (Fig.6).

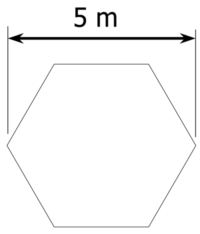

Figure 5: The large parabolic mirror in folded state

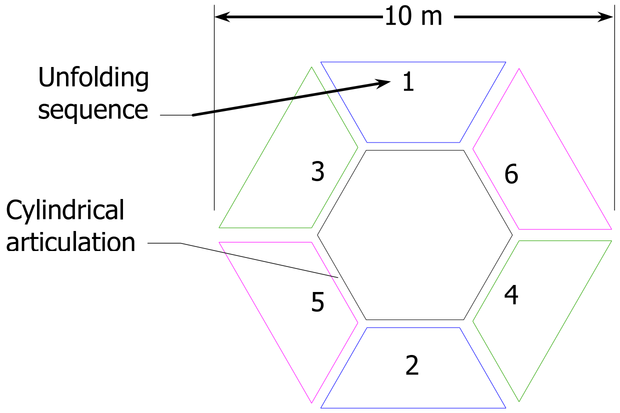

Figure 6: The large parabolic mirror in unfolded state

The surface area of parabolic mirror in this case is about 65 m^2 being able to collect a solar power of P=88.4kW (for solar irradiance on Earth's orbit, E_e=1360W/m^2).
Alternatives to this system are Cassegrain or Gregorian type solar-thermal systems. These systems are used in manufacturing of optical telescopes or radio antennas. [6]
A Cassegrain reflector (Fig. 5) [7] is a combination of a large concave and a small convex (hyperbolic) mirror. This design permits placing of the focal point at a convenient location behind the large parabolic mirror using a compact mechanical system.
The Gregorian reflector [8] uses a small concave (parabolic) mirror having a focal point that does not coincide with the focal point of large parabolic mirror (Fig. 6).
Although the Cassegrain and Gregorian type solar-thermal systems can focus the light in a single point placed behind the large parabolic mirror, it is more difficult in these two cases to change the focal point distance and direct the concentrated light beam to the space debris.
When a higher power is necessary for de-orbiting space debris, the large parabolic mirror can be decomposed in hexagonal pieces and launched together with the small parabolic mirror assembly, spherical articulation assembly, light guide tube and lens assembly and then the system is assembled on orbit using NASA's SpiderFab robot. [5]

3. ORBITS FOR SOLAR-THERMAL SYSTEM FOR SPACE DEBRIS DE-ORBITING

The system can be placed on a geocentric orbit, heliocentric orbit or sun Sun-synchronous orbit.
The most advantageous is the Sun-synchronous orbit (helio-synchronous orbit) [9] because the satellite is placed in constant sunlight. For example, heavy military or weather satellites are placed on Sun-synchronous orbits.

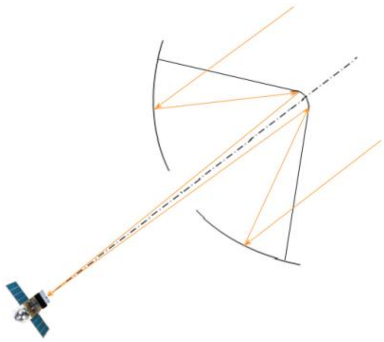

Figure 7: A Cassagrain type Solar-Thermal system

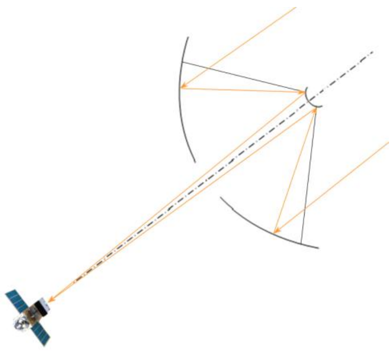

Figure 8: A Gregorian type of Solar-thermal System

4. CALCULATIONS

4.1 Power range

Some simple calculations were done to evaluate the energy of focused light and the de-orbiting force exerted on space debris by the expanding vapours and ions.
Near Earth, the solar irradiance is quite high, E_e=1360 W/m^2. Sun can be assimilated with a black body having surface temperature of 5800 K . [10] The emitted light has a broad band of wavelengths, from 250 nm to over 2500 nm (Fig. 9). [11].

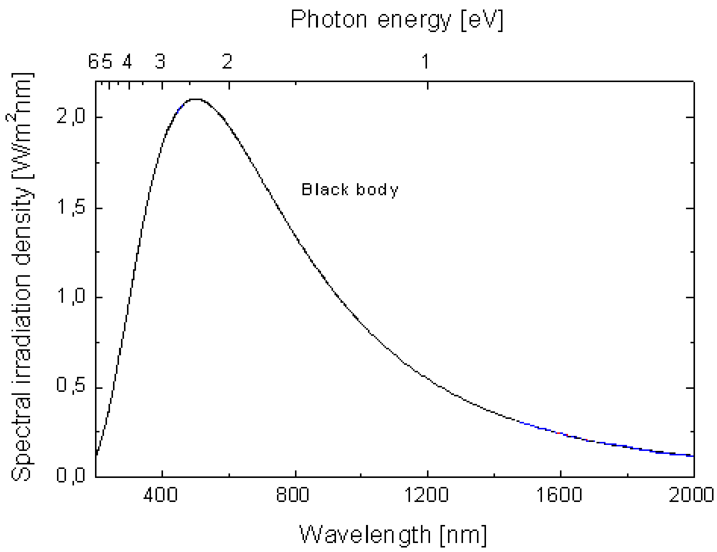

Figure 9: The spectrum of Sun [11]

If Mylar is applied on both mirrors, their reflectivity is remarkable. Fig. 10 [12] shows that gold has a coefficient of reflectivity R_g=0.98 for most of frequencies.
The best design of solar thermal systems for de-orbiting space debris is to apply several microns of gold directly on graphite fibre composite plates after forming them in parabolic shape. Gold confers maximum reflectivity, while graphite fibre maximizes heat transfer through conductivity and highest emissivity coefficient.

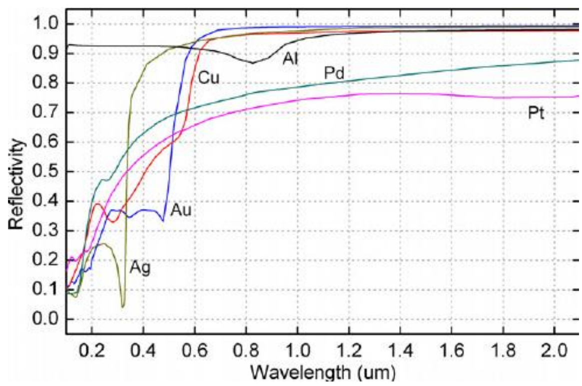

Figure 10: Reflectivity of metals [12]

As it was shown above, for the system presented in Fig. 6 where the area of the unfolded large parabolic mirror is 65 m^2, the total collected power is P=88.4kW.
If the small parabolic mirror has radius r_{spm} = 0.144 m, the intensity of concentrated light beam created by the small parabolic mirror, E_{spm}, will be about 1000 times more intense than the intensity of light coming from Sun i.e.,

$$E_{spm} = \frac{P}{\pi \cdot r_{spm}^2} = \frac{88400}{\pi \cdot 0.144^2} = 1360\ kW/m^2 \qquad (1)$$

When the radius of large parabolic mirror increases, the collected power increases (Table 1)
Such parabolic mirror can be easily assembled in space where gravitation is balanced by inertia forces. [5]

Table 1: Sun power collected by the large parabolic mirror

Case. no.	Radius of large parabolic mirror, r_{lpm} [m]	Collected solar power, P [kW]*
1	5	88.4
2	7.5	240.3
3	10	427.3
4	15	961.3
5	20	1709.0
6	25	2670.3

*Note: The effective power which can be used is smaller if reflectivity coefficient of mirrors is taken into account.

4.2 The effect of concentrated light on space debris

The space debris is made of various materials (aluminium, titanium, carbon fibre composite, steel etc.). For example, considering space debris is made of aluminium,

-melting temperature is: t_m= 660,3 ^oC; T_m=933.3 K;
-boiling temperature is: t_b=2470 ^oC; T_b=2743 K;
-heat capacity for solid aluminium is: c_S=0.9 kJ/kg·K;
-heat capacity for liquid aluminium is: c_L=1.18 kJ/Kg.K;
-heat of fusion: c_f=10.71 kJ/mol (398 kJ/kg)
-heat of vaporization is: c_v=284 kJ/mol (10518 kJ/kg)
-first ionization energy is: c_{ion}=577,5 kJ/mol (21388kJ/kg)

For simplicity, the values of above physical characteristics are considered constant in the given range of temperatures.
The quantity of heat necessary for vaporizing of 1 kg of aluminium is given by:

$$E_{vap} = 1 \cdot c_S \cdot (T_b - T_0) + c_f \cdot 1 + 1 \cdot c_L \cdot (T_b - T_m) + c_v \cdot 1 = 0.9 \cdot 2743 + $$
$$+ 398 + 1.18 \cdot (2743 - 933.3) + 10518 = 15520\ kJ/kg \qquad (2)$$

where the initial temperature of space debris T_0 was assumed to be 0 K.
The total energy needed to ionize aluminium atoms after vaporizing is

$$E_{ion} = E_{vap} + c_{ion} = 15520 + 21388 = 36908\ kJ/kg \qquad (3)$$

In one second, the heat collected by the parabolic mirror of the system can vaporize or ionize the amount of aluminium listed in the Table 2.
Table 2 shows that the quantity of metal which can be vaporized/ionized in just one second is remarkably high.

Table 2: The quantity of aluminium vaporized by system in one second

Case. no.	Radius of large parabolic mirror, r_{lpm} [m]	Collected solar power, P [kW]	Flow of aluminium vapours per second, g	Flow of aluminium ions (first level) per second, g
1	5	88.4	6	2
2	7.5	240.3	15	7
3	10	427.3	28	12
4	15	961.3	62	26
5	20	1709.0	110	46
6	25	2670.3	172	72

4.3 Lens Design

The lens role is to focus the light on a very small area in order to assure very high power density . Theoretically, the energy can be focused on a geometric point. In reality due to chromatic aberration and shape errors light is not focused quite so tightly. The lens is shown in Fig. 11. It is composed of elastic transparent material filled with liquid.

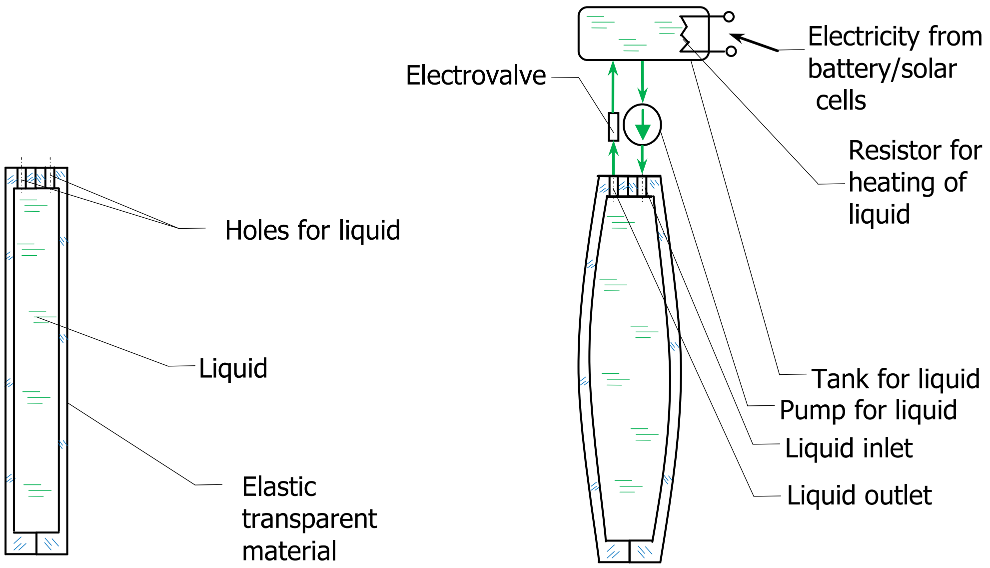

Figure 11: Design of Lens filled with liquid

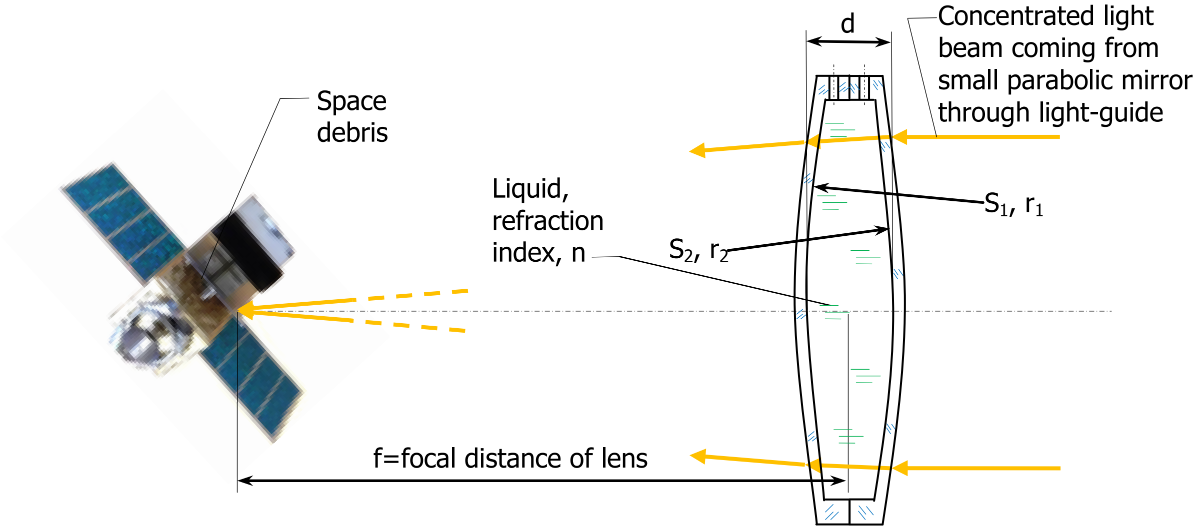

Figure 12: Operation of lens filled with liquid designed to eliminate space debris

Approximating surfaces S_1 and S_2 with spheres having radii r_1 and r_2 respectively, assuming thickness of liquid lens is d, and neglecting the optical effect of transparent elastic material (which is very thin) if the refractive index of liquid is n, the focal distance f of lens is given by the Eq.4 and Eq.5. [13]

$$\frac{1}{f} = (n-1)\cdot[\frac{1}{r_1} - \frac{1}{r_2} + \frac{(n-1)\cdot d}{n\cdot r_1\cdot r_2}] \quad (4)$$

For the simple case when $r_1 = r_2 = r$

$$\frac{1}{f} = (n-1)\cdot[\frac{1}{r} - \frac{1}{r} + \frac{(n-1)\cdot d}{n\cdot r\cdot r}] = \frac{(n-1)^2\cdot d}{n\cdot r^2} \quad (5)$$

Eq. 5 shows that for a given n and d, when r-->∞ (i.e. low pressure of liquid inside the lens), f-->∞, i.e. theoretically the system can hit the target (space debris) at any distance. However, due to aberration and imprecision of lens dimensions this distance is limited. Lens operation is illustrated in Fig. 12.
The temperature of liquid must be kept in an appropriate range for preserving the liquid state (avoiding of freezing). A resistor fed by battery charged by solar cells heats the liquid which is circulated permanently by pump with a low speed. The electro valve is normally opened. When hitting of space debris is necessary, the electro-valve is closed and the liquid bends the lens to the necessary curvature. Some suitable liquids and refractive indexes are given in the table 3. [14]

Table 3: Some liquids suitable for lens

No.	Liquid	Refractive index (n)
1	Aniline	1.586
2	Benzyl benzoate	1.568
3	Ethylene glycol	1.43
4	Glycerine (Glycerol)	1.47
5	Water	1.333

The transparent elastic material can be polydimethylsiloxane (PDMS). PDMS has good optical properties a large elongation and is highly transparent (over 96%) in the range of visible wavelengths. PMDS refractive index is $n_{PDMS}=1.410$. In a terrestrial application, such elastomeric membrane having thickness of 60 microns was used in manufacturing of a convex lens. [15] The refractive liquid used in that design was water.

4.4 Specific impulse and thrust

The process of generating a reaction force due to material ablation is very complex. This effect was observed during interaction of laser ray with a material surface. [16] In the present case, the process should be similar.
In the case of laser ray, ablation takes place when material is removed from a substrate through direct absorption of laser ray energy. As a first condition, the radiation energy must exceed a given threshold, which is less than 10 J/cm^2 for metals, 2 J/cm^2 for insulating inorganic materials and 1 J/cm^2 for organic insulator materials [16].
The solar-thermal system discussed here satisfies this requirement because, even when the power of the smallest mirror is 0.98x0.98*88.4 kW=84.9 kW (see case no. 1 from Table 2 where the coefficient of reflection for each parabolic mirror was considered 0.98), it provides an energy of 10 J in 1.18x10^{-4}s. [17]

Another condition is related to the absorption mechanism of energy. Chemical composition, microstructure and morphology of material strongly influence absorption of heat.
Heating of debris must be sufficiently fast for homogenous nucleation and expansion of vapour bubbles and ions.
Some simulations were done for interaction of a laser rays shown that: [18]

a- The degree of absorption of light increases as the cavity deepens.
b- Maximum energy absorbed by the cavity is around 80% of the total energy of radiation.
c- The radiation is multiply reflected by cavity. As a result energy is highly concentrated at the centre and bottom of the cavity and forms the final conical shape of cavity.
d- The surface temperature is much higher than the normal boiling point.
e- The power intensity must be over 108 W/cm^2 for having a homogeneous boiling regime and evaporation as the dominant mode of material removal.
In the case of the solar-thermal system, one can see that the condition (e) is accomplished even for even for the smallest mirror (case 1 from Table 2).
Note: The mentioned simulations were done only for iron, not for aluminium or other materials currently used in manufacturing of satellites and space equipment but the effect on such materials should be similar.
The result of focused ray is shown in Fig. 13. [18]

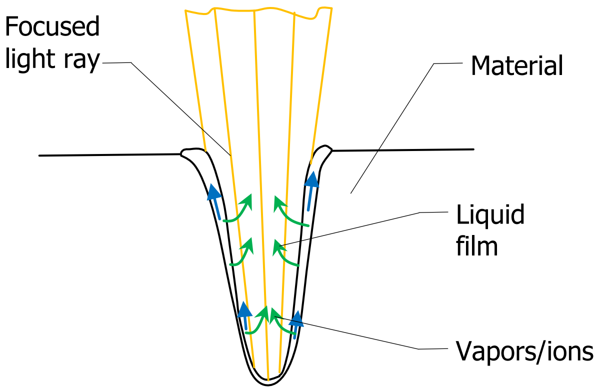

Figure 13: Action of focused ray on debris material

In some experiments a specific impulse of about 4000s was measured for carbon and aluminium in ionized state produced by the laser ray. [19]
During those measurements the following observations were noted:

a'-The speed of ejected atoms and implicitly I_{sp} is inversely proportional to the square root of the atomic mass of ablated material; the lighter the element, the higher the specific impulse I_{sp}
b'-Thrust tends to increase with the atomic mass of ablated material
c'-The speed of atoms was independent of angle at 22 cm by target
d'-The ablation time was of 1,5 μs
For the case when I_{sp} is known, the thrust force can be evaluated using Eq.6:

$$T_f = g_0 \cdot I_{sp} \cdot \dot{m} \quad (6)$$

where g_0 is the gravitational acceleration at Earth's surface (g_0=9.81m/s^2) and $\dot{m}$ is the mass of ions ejected in one second.
Momentum coupling coefficient C_m is another method for thrust evaluation. [20]
This coefficient characterizes thrust production efficiency. The coefficient is determined as the ratio of the thrust T_f to the laser power P, i.e.,

$$C_m = T / P \quad (7)$$

This parameter determines the minimum light power required to produce a 1N thrust.
According to the above reference, $C_{m\ max\ Al}= 6 \cdot 10^{-5}$ N/W for aluminium and $C_{m\ max\ Cu}=10 \cdot 10^{-5}$ N/W for copper.
That means that in the case of ablation of space debris made of aluminium using the solar-thermal system from case 1 of Table 2 when power P_1=88.4 kW (losses due to reflection by mirror were neglected) the thrust force is

$$T_{1Al} = P_1 \cdot C_{m\,max\,al} = 88400 \cdot 6 \cdot 10^{-5} = 5.3N \quad (8)$$

For case 6 from Table 2 (large mirror diameter r_{lpm}= 25m), the thrust force is

$$T_{6Al} = P_6 C_{m\,max\,Al} = 2670300 \cdot 6 \cdot 10^{-5} = 160.2N \quad (9)$$

Obviously both these calculated forces are remarkably high and can de-orbit space debris with a few strikes.

4. CONCLUSIONS

▪The Solar-Thermal system for space debris deorbiting has a simple design – the main components are a large parabolic mirror, a small parabolic mirror and a lens filled with liquid.
▪The mirrors are made from graphite fiber base composite material with graphite fiber base plated with gold or Mylar.
▪The lens are made of elastic transparent material filled with liquid. When liquid pressure is increased by a pump, the curvature of lens faces is changed and the focal distance changes accordingly. In this manner, the solar light is theoretically focused on a single point on space debris.
▪Deorbiting of space debris is done by vapors/ions ejected from the cavity created by the concentrated/focused solar light.
▪The deorbiting force is considerably high and the space debris can be deorbited through multiple strikes.
▪The system can be transported on orbit by Ariane 6 launcher as a single assembly (in folded state) or can by assembled on orbit.
▪The system can be placed on a geocentric orbit, heliocentric orbit or sun Sun-synchronous orbit.

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