Satellite propulsion

Canada, EU, Norway, and other stakeholders (IPEN and ZMWG)

1. Category of mercury-added product	Ion engines for satellites and spacecraft
2. Further description of the product	**<u>Alternative names</u>:** Ion thruster; mercury ion thruster; mercury bombardment ion thruster; Hall thruster
3. Information on the use of the product	**Canada** • Canada has been made aware of potential uses of mercury in rocket propulsion systems in other jurisdictions[1]. This is a concern to Canada because of the atmospheric fallout and distribution of mercury into the air. Most atmospheric mercury deposited in Canada comes from foreign sources, and the addition of rocket fuel to existing mercury sources would only exacerbate this issue. **EU** • Ion thrusters are used for spacecraft propulsion and create thrust by accelerating ions using electricity. Ion thrusters ionize a propellant by adding or removing electrons to produce ions. This is mostly achieved through electron bombardment, where a high energy electron collides with a propellant atom to release electrons and create a positive ion. • Mercury has been used as a propellant in the past, up to around 1980 (Fazio et al., 2018). Concerns related to mercury toxicity led to its abandonment. • Manufacturers of mercury ion thrusters include Apollo Fusion (USA). • Consumption: 20 kg of propellant for a representative configuration ideal for a low-orbit satellite (Bloomberg, 2019). • According to information from the website of Apollo Fusion, the company intends to produce up to 500 thrusters between 2019 and 2023. This would result in a consumption of around 10 t mercury in five years (Apollo Fusion 2019). • Plans for satellite constellations are expected to increase the number of satellites in Low Earth Orbit by a factor of 10 in the next 10-20 years (Fourie et al., 2019). It has been estimated that 2000 satellites would emit approximately 20 t of mercury per year over a 10-year lifetime which would largely be deposited in oceans. • There is no manufacture/use in the EU.

	Norway • At 20 Mg/yr., mercury emissions from satellites would represent about 1% of global anthropogenic mercury emissions. The vast majority of mercury emissions from satellites in Low Earth Orbit with Hall thruster propulsion will reach the turbopause (about 80 km altitude), and about 75% of the mercury reaching the turbopause is deposited in the oceans. (Fourie et al., 2019) **ZMWG** According to the Apollo Fusion's website (accessed 27 April 2020), it expects to have its "first thruster in flight operation in 2020; over 100 thrusters in flight operation by the end of 2022; and over 500 thrusters in flight operation by the end of 2024." **Information from experts** • Mercury was used as a propellant back in the 60s, primarily because of its high storage density (a lot of kilograms of mercury can be stored in a very small volume) which is attractive for the spacecraft. There were, however, a great deal of technical difficulties with mercury and health and safety concerns, for which NASA, the primary developer, abandoned the use of mercury and started using non-mercury alternatives. • Mercury will be expelled possibly in the low earth orbit, and according to the expert predictions, this exhausted mercury is likely to travel back to earth's atmosphere and eventually to the surface of the earth over several years. • A NASA Review report "State-of-the-art small spacecraft technology" was released in October 2020. On page marked 76 it states that the Astro Digital Ignis Satellite will carry the Apollo Fusion ACE engine which carries 1.1 kg of "a proprietary high density propellant." The satellite launch date is given as 2020. • An Astro Digital Ignis Satellite Orbital Debris Assessment report was filed with the US FCC in 2019 as a requirement to launch. On the page marked 7 it states, "the ACE propulsion system utilizes a high density proprietary inert propellant (see Proprietary Information Exhibit for details)." On the page marked 10 it states that "a rupture of the propellant tank would release gaseous nitrogen and up to 1.1 kg of liquid propellant….Droplets of propellant would be expected to leak out of vent holes in the spacecraft body, but would reenter quickly due to their high area to mass ratio."
4. Information on the availability of mercury-free (or less-mercury) alternatives	**Canada** Alternatives to mercury-based propellants are available and have been used for many years.

	EU Non-mercury alternatives include Xenon (Xe), Krypton (Kr), Argon (Ar), Neon (Ne), Helium (He), Hydrogen (H_2), Iodine (I_2), Buckminsterfullerene (C_{60}), Adamantane ($C_{10}H_{16}$), and Air (nitrogen/oxygen). **ZMWG** Mercury-free alternatives have been available and almost universally used in recent decades (Kieckhafer and King, 2005)
5.(i) Information on the technical feasibility of alternatives	**EU** A heavy element, such as mercury and iodine, offers the best engine performance among the alternatives, as they allow a higher payload/propellant ratio than for example xenon. **IPEN** Non-hazardous alternatives are currently available and achieve high performance levels (xenon gas) and have been in commercial use for decades as a propellant for satellite thrusters. **ZMWG** Fazio et al. (2018) published a comparative overview of the properties of various propellants suitable for electric propulsion, comparing the physical properties and performance, and concluded that the only viable alternative would appear to be Krypton if all of the selected impacts are taken into consideration; however, Iodine and Mercury have the best performance but could be eliminated because of compatibility issues, especially in terms of spacecraft contamination and toxicity. Nevertheless, it should be noted that the former [Iodine] is current [sic] being actively pursued both in Europe and the USA as an alternative propellant despite these issues and that the latter [Mercury] was in the past (up to around 1980) the preferred propellant choice, only being replaced by Xenon due to spacecraft interactions. Additionally, the low storage density of Krypton has important effects on the storage system, i.e. need for a bigger and/or heavier propellant tank system.
5.(ii) Information on the economic feasibility of alternatives	**Norway** Fourie et al. published the study that characterizes the potential environmental impact of widespread mercury used as a satellite propellant. "Concerns related to toxicity led to the abandonment of mercury as a propellant in the 1980s in favor of noble gases, predominantly xenon (Rawlin 1982). However, the high price of xenon ($2000/kg) coupled with burgeoning commercial space development has recently renewed interest in alternative, low-cost propellants such as mercury for electric propulsion (Kieckhafer and King 2007, Holste et al 2015, Saevets et al 2017,

	Elgin 2018)." The study concludes that "the environmental impact of mercury propellant is not worth the satellite cost savings of moving away from existing non-toxic propellants."
6. Information on environmental and health risks and benefits of alternatives	**EU** • Risk of spillage/ contamination on the ground. • Emission of mercury in orbit over the period of 5-7 years, at the height of 300 km to 1,200 km above the Earth. Due to the weight of mercury, it is expected to travel back to the surface of the Earth over several years. **Norway** • Satellite electric propulsion using mercury propellant, if launched, would be a major environmental concern. • The most common propellants, for example xenon, are NOT an environmental concern. **Information from experts** • There is a risk in launch vehicle accidents. The satellites full of mercury will get a ride into the orbit on top of a large launch vehicle, possibly 100 satellites on each vehicle. Launch vehicles, such as SpaceX Falcon 9, fail at a rate of approximately 2%, which means one in every 50 rockets will fail in some way, which could be an explosion on the launch pad or a mid-course abort that sends it down into the ocean somewhere. In those instances, thousands of kilograms of mercury would very directly be deposited on earth, around the launch-sites or in the oceans.
7. If any, additional information being submitted on mercury-added products pursuant to Article 4.4 of the Convention not addressed above (e.g. manufacture, general trade information, etc.)	NA
8. Other relevant information pursuant to Decision MC-3/1	NA

9. References

1 Bloomberg. (2019). This Silicon Valley Space Startup Could Lace the Atmosphere with Mercury. Available online at https://www.bloomberg.com/news/articles/2018-11-19/this-space-startup-could-lace-the-atmospherewith-toxic-mercury

Apollo Fusion (2019): http://apollofusion.com/

Bloomberg. (2019). This Silicon Valley Space Startup Could Lace the Atmosphere with Mercury. Available online at https://www.bloomberg.com/news/articles/2018-11-19/this-space-startup-could-lace-the-atmosphere-with-toxic-mercury

Fazio et al. (2018). Alternative Propellants for Gridded Ion Engines. Available online at https://www.researchgate.net/publication/326571233_Alternative_propellants_for_gridded_ion_engines

Fourie et al. (2019). Are mercury emissions from satellite electric propulsion an environmental concern? Published in Environmental Research Letters. Available online at https://iopscience.iop.org/article/10.1088/1748-9326/ab4b75/pdf

Fourie et al. (2019). Are mercury emissions from satellite electric propulsion an environmental concern? Published in Environmental Research Letters. Available online at https://iopscience.iop.org/article/10.1088/1748-9326/ab4b75/pdf

Kieckhafer and King (2005). A Kieckhafer and LB King, Energetics of Propellant Options for High-Power Hall Thrusters, Proceedings of the Space Nuclear Conference, San Diego, California, June 5-9, 2005, Paper 1092. Available online at http://aerospace.mtu.edu/__reports/Conference_Proceedings/2005_Kieckhafer_1.pdf

Ames Research Center (2020). State-of-the-art: small spacecraft technology.

Astro Digital US Inc. (2019) Astro Digital Ignis Orbital Debris Assessment Report (ODAR)