The designs of the space stations Salyut, Skylab, Mir, the International Space Station, and Tiangong-1 shared key considerations to survive the launch and keep crews alive with sophisticated life support systems. However, we seldom consider what happens when those massive structures re-enter the atmosphere and plummet back into our pale blue dot. In this column, we looked back through some notable spacecraft re-entries, discuss their impacts and risks, and, ultimately, consider a different future where we can prolong or re-use spacecraft.

Ad adstra,
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BACK IN 2018, in anticipation of the uncontrolled orbital re-entry of the first Chinese space station, *Tiangong-1*, the Argentinean space agency, la Comisión Nacional de Actividades Espaciales, published warnings in local papers advising citizens to stay away from windows during the six potential re-entry passes over its territory [1]. The articles included maps showing the trajectory of each pass as well as the time and duration so that people could be prepared. Furthermore, they warned individuals that if they did encounter a piece of debris, they should alert the authorities and stay at least 20 m away from it at all times in case the objects had sharp edges or toxic chemicals such as hydrazine, which is often used for propulsion systems.

Tiangong-1 (Figure 1) was launched in September 2011 and visited by two groups of taikonauts before it was put into sleep mode. The engineers intended to collect data for some period before decommissioning the station through a controlled re-entry. However, things did not go as planned, and, on 16 March 2016, the station ceased functioning at an altitude of 349 km, with a daily decay rate of approximately 160 m/d. The Chinese government issued a warning through the United Nations and stated its intentions to monitor the re-entry through the Inter-Agency Space Debris Coordination Committee [2]. Many tracking stations monitored the orbital decay and attempted to predict when and where the station would plunge to the surface (Figure 2).

Since two-thirds of Earth is covered by water, the chances of any piece of space debris landing over a populated area are very slim. In fact, the Aerospace Corporation estimates the probability of being hit by orbital debris that reenters the atmosphere as one in a trillion [3]. However, despite those statistics, the Argentinean government was not taking any chances. The country learned its lesson after fragments of debris from the Russian *Salyut-7* station (*Mir*'s predecessor) overshot its entry point and were scattered over the town of Capitán Bermúdez.

Whether we want to accept it or not, pieces of human-made objects in low Earth orbit (LEO) reenter the atmosphere on a regular basis. Canadian artist Brandon Vickerd captured the "modern-day Icarus" nature of these technological wonders through his powerful and dramatic sculptures displaying space objects crashed on top of cars or on the ground (Figure 3). For us engineers, these thought-provoking art pieces remind us to consider the entire lifecycle of a space mission, from launch until it is fully decommissioned. In actuality, most components from small satellites burn up due to the heat generated by the interaction between the space objects travelling at 7 km/s in a vacuum and particles encountered as they enter Earth's atmosphere. Only the components designed to withstand high temperatures can pose a threat to both people and property during re-entry.

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This is not a new concept. The first account of space debris landing in

Figure 1: China's *Tiangong-1* space station. The main cylindrical body was 10.4 m long and had a 3.35-m diameter, comparable in volume to a school bus. (Source: China Manned Space Engineering Office.)

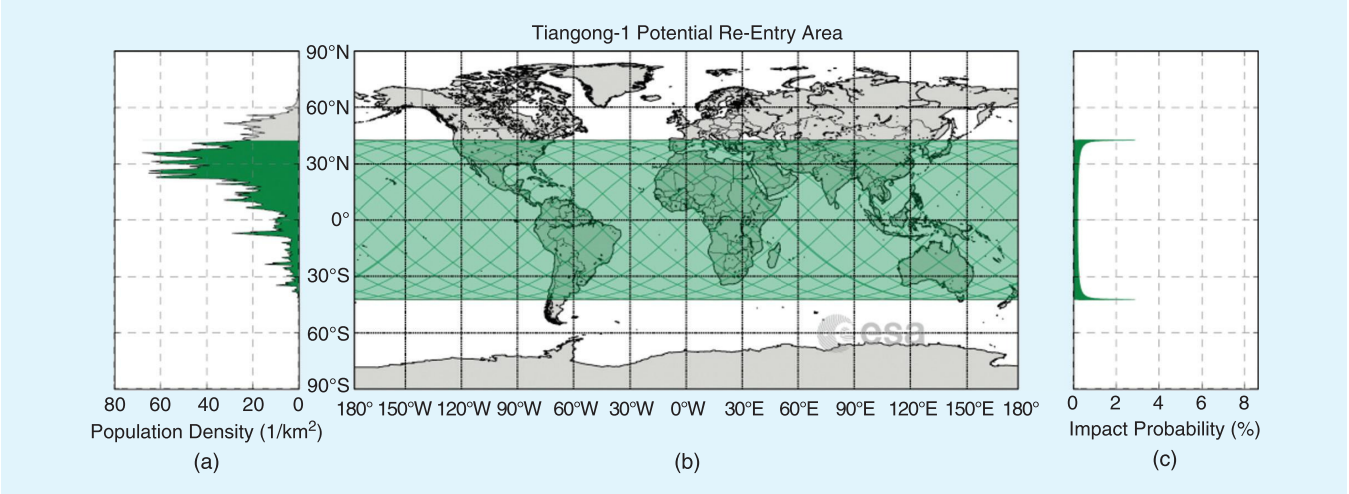

Figure 2: The *Tiangong-1* re-entry predictions, showing that, despite uncontrolled re-entry, there is a very low chance of debris landing in a populated area when considering the orbit and the distribution of people on our planet. (a) The population density by latitude. (b) The ground track for the last 24 hours before re-entry. (c) The impact probability by latitude. (Source: European Space Agency.)

populated areas dates back to the night of 6 September 1962, when a circular piece of metal crashed on the streets of Manitowoc, Wisconsin. Originally kicked off the curve by police officers patrolling the streets who thought it was just a scrap that fell off a garbage wagon, people later realized it was a piece of the Soviet *Sputnik-4* spacecraft. The town commemorated this illustrious event with a plaque on the street [4], a duplicate at the local museum, and an annual Sputnikfest street party. Another notable example involves the large pressurized tanks from the first U.S. space station, *Skylab* (Figure 4), which fell over the town of Esperance in Australia in 1979. Although they did not cause any damage, the town issued a gag $400 littering ticket to NASA, which was paid in 2003 through a collection organized by disc jockey Scott Barley from a radio station in California.

Canada's geographical position and wide spread are considered both advantageous and disadvantageous with respect to its space assets. Many LEO spacecrafts are launched with low inclinations—meaning that the satellite does not cover areas at high latitudes—so our fellow Canadians in northern communities cannot reliably depend on satellite communications or navigation like those living closer to the 49th parallel. Near-polar inclinations are used by a handful of nations with shared interest in monitoring the Arctic and by Earth observation missions flying in a sun-synchronous orbit. Still, there have been cases of debris landing in Canada, with the two most notable examples being the Soviet reconnaissance satellite *Kosmos-954* (1978) and NASA's *Upper Atmosphere Research Satellite* (2011). These types of events scatter debris over large areas spanning hundreds of kilometers and cost millions to clean up.

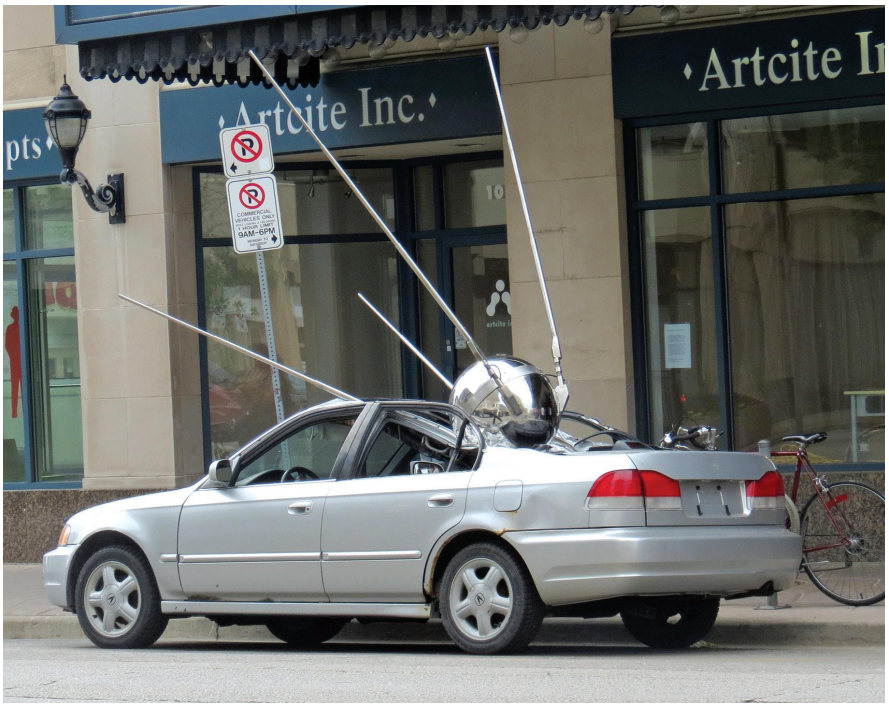

Photo: Brandon Vickerd

Figure 3: An artist's rendition of hypothetical satellite re-entry if no parts were burned up in the atmosphere: *Sputnik Return 2* by Brandon Vickerd, 2015; 3.2 × 3 × 2.4 m; stainless steel, Acura sedan.

With all of these examples of uncontrolled re-entries over populated areas, it is a wonder that there is only a single case of a person reported to have been struck by space debris.

With all of these examples of uncontrolled re-entries over populated areas, it is a wonder that there is only a single case of a person reported to have been struck by space debris. That unfortunate individual was Ms. Lottie Williams, who was hit by a small piece of a *Delta II* rocket fuel tank while walking through a park in Tulsa, Oklahoma, on 22 January 1997 [5]. As

Figure 4: The U.S. *Skylab* space station. The main cylindrical body was 25.1 m with a 6.6-m diameter—a volume an order of magnitude larger than that of *Tiangong-1*. During the 1973 launch, a micrometeoroid hit the station, jamming one of the main solar panels before it could be deployed. The crew was able to recover and use the station as shown until its decommissioning in 1979. (Source: NASA.)

luck would have it, the object glanced her head, and she did not sustain any serious injuries from the incidence.

Obviously, uncontrolled re-entries are not anyone's first choice. Large missions in LEO budget their propellant to ensure they have enough for a deorbiting maneuver aimed at the spacecraft graveyard known as *Point Nemo* in the South Pacific. Named after Jules Verne's Captain Nemo from *Twenty Thousand Leagues Under the Sea*, this point is farthest away from any landmass. Its precise location was calculated to be at 48.88° S and 123.39° W, making it more than 2,500 km away from the three closest coasts of Ducie Island, Motu Nui (part of the Easter Island group), and Maher Island. As an added bonus, this area is not biologically diverse, so the debris has a very limited impact on the environment compared to other potential oceanic targets.

To date, more than 300 spacecrafts have plummeted to the ocean floor at Point Nemo. The largest object to take the "ice bucket challenge" was the *Mir* space station in 2001, weighing 120 tons. (Not all of it survived re-entry.) Notably, Taco Bell, the fast food chain, used the re-entry as part of a publicity stunt, advertising that if *Mir* landed within a 40-ft × 40-ft bullseye labeled "Free Taco Here," the company would offer coupons for free tacos to everyone in the United States. Although this is unrealistic, given that space debris is often scattered over a large area and it is impossible to pinpoint the exact location, it did make national news. Even though there is no fixed date, at some point in the next decade, the record-setting MIR deorbiting maneuver will be surpassed by the *International Space Station* as it is decommissioned after many years of service.

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Ultimately, neither controller or uncontrolled re-entries are the ideal solution due to the risks for humans and waste of materials. Better approaches are being tested and investigated for reusable booster rockets, such as those demonstrated by Space X, and serviceable spacecraft that can prolong their operation for years to come. Definitely an exciting challenge for engineers. ■

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