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IMPLICATIONS OF A GROWING SPACEFLIGHT INDUSTRY: CLIMATE CHANGE

MARTIN N. ROSS AND KAREN L. JONES
THE AEROSPACE CORPORATION

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MARTIN N. ROSS

Dr. Martin Ross is senior project engineer for Civil and Commercial Launch Projects. In this capacity, he leads research concerning the effects of space industry emissions, including launch and reentry on global climate and stratospheric ozone. He is developing new interagency strategies to better understand the scientific, economic, and policy implications of environmental sustainability for a growing space industry. Ross conceived and implemented the Rockets Impacts on Stratospheric Ozone (RISO) program for the U.S. Air Force, managing simultaneous airborne and remote sensing measurements of stratospheric rocket plumes. He also served as mission scientist for the joint NASA/NOAA/Air Force Atmospheric Chemistry of Combustion Emissions Near the Tropopause (ACCENT) project and is a contributor to the World Meteorological Organization's Quadrennial Scientific Assessment of Ozone Depletion reports. He has written more than 50 publications and holds a Ph.D. in planetary and space physics from UCLA.

KAREN L. JONES

Karen L. Jones is a senior project leader in the Center for Space Policy and Strategy at The Aerospace Corporation. In her role as a space economist and technology strategist, she has been responsible for performing and managing a variety of projects, including federal R&D, research grants, internal R&D projects, commercial space engagements, new space architectures for the Office of Director of National Intelligence, and R&D portfolio management for the Department of Homeland Security. Prior to joining Aerospace, Jones worked as a management consultant for IBM Global Services focusing on the telecommunications industry, and later e-business strategy for commercial companies and the federal sector. Prior to IBM, Jones worked as a management consultant with Arthur D. Little where she was focused on international privatization projects, technology commercialization, environmental consulting, and risk management. Jones has a bachelor's degree in geology from Louisiana State University and an M.B.A. from the Yale School of Management.

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Summary

The global impacts of the spaceflight industry have historically been viewed as limited in scope, without significant change, and therefore not requiring regulatory attention. As a result, little scientific attention has been paid to the impacts of rocket launches and space debris reentries on global climate and stratospheric ozone. The space industry has recently seen revolutionary change and growth with development of heavy lift rockets, deployment of large satellite constellations, and the introduction of new space-based services and rocket propellants. As the profile of the modern space industry rapidly increases, so too will the public interest in understanding how spaceflight affects the atmosphere and the role it plays in the broader scope of global greenhouse gas emissions and climate change mitigation. Though recent scientific research has answered a few outstanding questions about spaceflight's climate impacts, space technology advancements and growth have raised many more. In a relative sense, knowledge of spaceflight's climate impacts has declined. Scientific uncertainties, coupled with increased rocket launches and space debris reentries, mean that a space policy based on an assumption of limited global impacts is no longer appropriate. Policymakers will require a comprehensive assessment of the global consequences of spaceflight in order to make effective and informed regulatory decisions regarding industrial emissions and fossil fuel use. Stakeholders across the space enterprise should recognize the urgency of the need to organize and properly fund a comprehensive assessment of the global impacts of spaceflight. A policy based upon scientific research would forestall unwarranted regulation and ensure regulatory impartiality where regulation is unavoidable.

Once is a Mistake, Twice is a Policy

Climate change is emerging as the most significant geopolitical concern of this century. The scientific community unanimously predicts that Earth's atmosphere, oceans, and surface will suffer increasing change, the severity depending on the policies taken by humanity with regard to greenhouse gas (GHG) mitigation and adaptation. The federal government is organizing around a multipronged strategy reflecting this reality, including:

- Appointment of a Special Presidential Envoy for Climate in a newly created cabinet-level position serving on the National Security Council and leading the administration's efforts to combat global climate change.

- Creation of a National Climate Task Force that includes every White House cabinet secretary and heads of all federal agencies, emphasizing that every part of government is required to deal with climate change.

- The Department of Defense recently issued a comprehensive National Climate Risk Assessment[1] and the Army has released the first service strategy to achieve net-zero emissions by 2050.[2]

The commercial sector is also adopting fundamental changes in corporate governance and finance that presume a global response to climate change. Financial institutions, for example, are reducing financial support to hydrocarbon (HC) extraction and investments at risk to a changing climate. The aviation industry is making foundational investments assuming that it will be HC-free by 2050. In some ways, commercial investors that deal with decades-long financial commitments must be the most forward-looking of all institutions.

Accumulation of greenhouse gases (GHGs) in the atmosphere is the principal cause of climate change. Carbon dioxide (CO_2) and methane (CH_4) emissions associated with HC extraction, storage, and combustion account for 80 percent of human-caused climate forcing. CO_2 has a long atmospheric lifetime (hundreds of years) and increased CO_2 levels become an essentially permanent feature of the atmosphere. CH_4 has a shorter lifetime (tens of years) but has a greater specific climate forcing. Most of the concern of climate mitigation strategies is focused on controlling the concentrations of CO_2 or CH_4 in the atmosphere. Other sources of climate change, such as stratospheric particle pollution, are being studied with increasing attention. Stratospheric particles can have natural and human-produced sources such as aviation, geoengineering, and spaceflight, the focus of this paper.

Aerosols and particles in the stratosphere can cause global temperature changes comparable to changes from GHGs.[3] The ability of major volcanic eruptions to inject aerosols into the stratosphere, shade the Earth's surface, and significantly reduce surface temperatures has been known for many years. The climate-changing potential of stratospheric particles was first explored in detail in the 1980s within the context of the "nuclear winter" concept.[4] The stratosphere has not suffered a major volcanic injection (Mt. Pinatubo in 1991, for example) in several decades and so the present-day stratosphere is in a relative baseline state where continuous particle sources are in a quasi-steady state with particle removal processes. The baseline stratosphere is of particular interest to climate scientists since the number and types of proposals for stratospheric transport, and associated particle emissions, are rapidly increasing.

It is About the Particles

Concern about pollution of Earth's sensitive stratosphere by spaceflight-generated particles is relatively new. Until recently, only gas emissions from rocket launches were of interest to scientists and policymakers. Recent calculations unmistakably showed that, between the gases and particles released during launch and reentry, the particles unmistakably have the greatest impact on climate.[5] The turn of attention toward spaceflight particles as a result of those calculations is underscored by increasing use of soot particle-emitting HC rockets and atmospheric disposal of low Earth orbit (LEO) satellites and space debris. Both present the stratosphere with the prospect of an increasing source of directly injected particles. But this recognition is arriving into a policy void without direction, analogous to the recognition that space debris presented a serious hazard to newly launched spacecraft.

For many years now space debris has been acknowledged to present a serious risk to continuing space operations and industry growth.[6] Nevertheless, policy and practice to decisively deal with the problem is not yet in place, even as the number of LEO spacecraft grows without obvious bound, the frequency of debris collisions increases, and a sense of crisis emerges. If early space stakeholders included visionaries who could imagine a future with thousands of LEO satellites and accumulations of hundreds of derelict rocket stages, perhaps policy and regulatory actions would have mitigated orbital debris. If international space traffic management standards had been enacted then, when there were only a few spaceflight actors with limited interests, space debris would not have become the existential crisis faced today.

With hindsight, we can appreciate the formidable technical, geopolitical, and national security obstacles that prevented early identification and resolution of the problem. Regardless of the cause of early inaction, space debris was not addressed, and the situation evolved into a classic example of a "Tragedy of the Commons." Half a century ago, a potential problem clearly presented itself, but a lack of vision prevented good policy from being established when the problem was in its nascent stage. The result is that some regions of Earth's orbital space present hazardous conditions due to debris accumulation and the future use of LEO more generally is in some question.

Ozone Depletion and Climate Change: Inadequate Research

Today, emissions from rocket engine combustion and space debris reentry vaporization (colloquially, "burn up") present a distinctive echo of the space debris predicament. Rocket exhaust plumes and reentry burnup dust emitted into the middle atmosphere negatively impact the global atmosphere through two main effects. First, spaceflight emissions deplete the ozone layer.[7] Historically, this has been the foremost concern because solid rocket motors inject chlorine gas directly into the ozone layer and ozone protection has been subject to strong international regulation since 1987.[8] Second, particles emitted during launch and reentry affect the flow of radiation and global circulation in the atmosphere.[9] These thermal and dynamical changes result in a change in Earth's energy balance between incoming solar radiation energy and outgoing thermal infrared energy. This radiative forcing causes changes in temperature at the surface and in the stratosphere which, in turn, contributes to ozone depletion.[10]

Like space debris 60 years ago, spaceflight emissions have not been a priority for the research or policy communities. The literature on launch emissions is sparse and the present state of understanding is poor; reentry emissions are understood even less. A modest airborne science campaign 25 years ago[9] added important new data on the impact of launch emissions on stratospheric ozone that helped remove Solid Rocket Motors (SRMs) from regulatory consideration. That new data, coupled with falling launch rates in the 1990s, permitted a conclusion that ozone depletion and climate forcing caused by spaceflight emissions was only "small,"[11] though the limits of small were not defined.

Today, the situation has changed. The global launch rate has recently been growing 8 percent per year and is expected to accelerate further. By most estimates and analyses from space planners, the pace and size of launches and reentries, and therefore emissions, will rapidly increase in coming years.[12] The rate of destructive reentries that inject particles into the stratosphere from above will dramatically increase as recently launched LEO communication satellites reach end of life[13] and active removal of the most hazardous space debris begins.

Potentially harmful emissions that are both rapidly growing and poorly understood—as spaceflight emissions are today—present policymakers with hard regulatory choices. Regulators must protect against worst-case impacts within the uncertainties presented to them. This can result in overly restrictive or even inappropriate regulation with the potential to cause harm to the industry in question. The potential harm includes misallocation of investment, uninformed public discussion, and operational limitations that might compromise performance and profitability without achieving the intended regulatory benefit. Today, the elevated sense of urgency to avoid a future climate crisis suggests that spaceflight is under increasing scrutiny for regulation. A conflict between continuing fast-growing launch and reentry emissions, on one hand, and increasing control of atmospheric pollution, on the other, seems inevitable in the long term. This predicament was first pointed out in the context of reusable launch vehicle profitability and protection of the ozone layer.[14] The timing of the conflict will be determined by the aggressiveness of international regulators and their confidence in the science of launch emissions.

The next section briefly describes how rocket engine combustion and reentry vaporization affect the atmosphere. While some progress has been made understanding these emissions in recent years, more questions have been raised than answered as new atmospheric processes are discovered and new space technologies widen the scope of potentially important emissions.

Space Vehicle Emissions and the Global Atmosphere

Space industry operations emit gases and particles that affect the composition and temperature of the atmosphere from the surface to the upper atmosphere, where satellites orbit.[15] Rocket engines emit combustion products into every layer of the atmosphere according to propellant combinations used. Derelict spacecraft and spent rocket stages reentering the atmosphere emit a burst of gases and particles into the mesosphere that drift downward and join the launch particles in the stratosphere.

At first glance one might think that spaceflight emissions could not possibly be an important pollution source compared to other industries such as aviation. Rockets burn about 0.01 percent of the fuel that aircraft do each year. But this comparison is misleading. The special nature of spaceflight emissions makes them incomparable to aviation or any other industry. Spaceflight is the only human activity that injects pollution directly into the sensitive middle atmosphere where the overturning circulation lags and emissions take half a decade to wash out. By contrast, aviation emissions wash out in weeks. And compared to jets, rocket engines can be prodigious soot producers, emitting hundreds of times more soot than jet engines, per kilogram of fuel.[16] And of course, aviation has no equivalent to the enigmatic dust particles produced during reentry. Finally, spaceflight alone emits directly into altitudes overlapping important atmosphere features, such as high-altitude clouds and the ozone layer. Comparing spaceflight and aviation emissions is like comparing apples to oranges.

Gas Emissions

More than 90 percent of rocket engine exhaust is composed of carbon dioxide (CO_2) and water vapor (H_2O) for every propellant type. (Alternate carbon and hydrogen forms, such as CO and H_2, are also emitted but are presumed to oxidize.) CO_2 is a well understood, long-lived GHG that produces a global climate forcing. The annual CO_2 emission from rockets is a vanishingly small fraction of all GHG emissions and so, without any doubt, spaceflight does not play a significant role in GHG climate forcing. H_2O emissions, in contrast, are short-lived and its accumulation and impact are more complicated. H_2O emission altitude determines the impact; only stratospheric H_2O accumulates to a steady state to produce a small climate forcing. Climate models show that rocket H_2O will also cause increased high altitude (noctilucent) clouds[17], though their climate impact is not significant. The models show unambiguously that the climate and ozone impact of rocket CO_2 and H_2O emissions are not significant. The space industry could double many times over and the CO_2 and H_2O impact on both climate and ozone would remain within the bounds of normal atmospheric variability.[18]

Other gases emitted by rockets include hydrochloric acid (HCl), that is of concern for ozone depletion. Control of chlorine pollution in the stratosphere was the original concern of the Montreal Protocol when chlorofluorocarbons (CFCs) were banned. SRMs are widely used in various configurations and at all altitudes though only stratospheric emissions affect ozone. Present-day SRM chlorine emissions account for about 1 percent of the ozone loss caused by the long-banned CFCs. The ozone layer is healing from the CFC era so that smaller sources of stratospheric ozone loss, natural and human-produced, may see increased attention in coming years. The launch industry will increasingly be dominated by liquid-fueled propellants, however, so that chlorine emissions are not likely to be a significant future concern. SRMs do have unique rocket propulsion applications though and they will continue to play a role in the global launch industry. SRM emissions should be better understood and monitored with appropriate focus in coming years.

Nitrogen oxide (NO_x) gas produced by rocket engine combustion or heating of the atmosphere during spacecraft or space debris reentry plays a role controlling stratospheric ozone levels. Rocket and reentry NO_x sources are thought to currently cause relatively small ozone depletion, similar to the global loss from SRM chlorine.[19] In contrast to stable SRM emissions, reentry NO_x emissions are likely to greatly increase through LEO constellation maintenance and active space debris removal.[13] Though small today, the potential for growth suggests that spaceflight NO_x emissions should be better understood.

Particle Emissions

The climate impact of surface transport is dominated by CO_2. For aviation, CO_2 and particles (contrails) have impacts with comparable amplitudes. For spaceflight, particles uniquely play the largest role.[5] Spaceflight emissions are composed of three particle types: (1) Soot particles (black carbon or BC) mainly from hydrocarbon fueled rocket engines; (2) Alumina (Al2O3) particles from SRMs; and (3) A complex mix of particles produced during destructive reentry burn up. Currently, BC and alumina are the largest sources. In the future, the reentry particles may become the largest source.

Spaceflight particles accumulate in the stratosphere to a steady state as new ones from recent launches and reentries replace older ones removed by sedimentation and mixing. These particles form distinct (limited in altitude and latitude) layers, too thin to see without instruments, according to their size and composition.[20] Stratospheric particles scatter and absorb a small amount of sunlight, heating or cooling the atmosphere depending on composition and also serve as surfaces that promote specific chemical reactions involving ozone. Some characteristics of rocket particles in the stratosphere have been measured from high altitude aircraft in fresh and aged plumes[21] and in the stratospheric background accumulation. The details of these radiative and chemical processes for spaceflight particles remain unclear.

It is known that particle surfaces convert background inactive chlorine into active forms, causing ozone depletion. Available research, while inadequate to support a detailed assessment, suggests that present-day global ozone loss from SRM alumina surface is comparable to the losses from the associated SRM chlorine gas emissions, about 1 percent of CFC loss, though with larger unknowns. BC and reentry particles also have the potential, though speculative, to support ozone-destroying chemical reactions on their surfaces. Until the microphysics of each of the spaceflight particle types is measured from aircraft in stratospheric plumes, ozone loss remains a puzzle, with uncertainties pointing to larger values.

The most important way that spaceflight emissions affect the global atmosphere is by absorbing or scattering a portion of downward solar radiation.[22] Conceptually, spaceflight particles convert solar visible energy into thermal energy, warm the stratosphere, and cool the surface a small amount. In this way, rocket emissions are thought to act similarly to particle-based solar radiation management (so-called geoengineering) techniques.[10] Calculating the climate forcing from the various particles is complex, requiring the application of sophisticated climate models that take into account complex feedback processes in the atmosphere.

The newest research shows that an idea that particles act as a kind of "umbrella" to cool the Earth's surface[22] has turned out to be only partly correct. The most recent model of rocket BC emissions[20] shows that rocket BC particles change the Earth's albedo more effectively than the surface temperature. According to this up-to-date view, the surface climate forcing and temperature change is smaller, and the stratospheric forcing is larger, than previously thought. Whether the same ideas hold true for alumina and reentry particles is not known; these particles have not yet been modeled. The total climate impact of all spaceflight particles presents, like ozone depletion, a potential for surprise in the direction of greater impacts.

The stratospheric climate forcing from BC particles causes a warmer stratosphere, which means ozone depletion. Since the 1990s, it was assumed that only solid-fueled rockets cause ozone loss and this bias has informed decisions about where to focus the limited research resources: to SRM emissions. But the new models emphatically show that stratospheric heating associated with BC-producing liquid-fueled rocket engines also cause ozone depletion. Preliminary calculations show that HC BC particle ozone loss is comparable to SRM chlorine gas ozone loss.[20] The stratospheric heating phenomenology associated with particles is general so that reentry particles also could reasonably cause ozone loss. Whether reentry particle heating and ozone loss could be comparable to launch is anybody's guess.

Adding it Up

There is a commonly held interest to simply describe the impacts of space travel in order to compare to aviation or promote policies affecting rocket launches.[23] These efforts aim to consider only CO_2 emissions in a single, easily understood parameter, such as a "carbon footprint." But as shown in previous sections, climate forcing is not easily comparable for emissions with different altitudes and timescales. Proper spaceflight metrics could be crafted by researchers (aviation emissions have a number of different metrics) but this requires direction from policymakers.

The actual climate forcing and ozone loss from spaceflight emissions are not well enough understood (aside from CO_2 and perhaps H_2O) to evaluate metrics with confidence in any case. Climate models have not been applied with a consistent methodology to consider each compound from all propellant types and the reentry particle problem remains an enigma. Using specific terminology developed by climate scientists to express confidence levels about facts and understanding[24] current assessments of present-day or future ozone depletion and radiative forcing have Low Confidence, meaning less than a 50 percent chance of being correct. This level is not consistent with the level that policymakers will need when they turn their attention to spaceflight.

The Current Policy Environment

The global perception of risk has undergone revolutionary change in recent years. The COVID-19 pandemic and European security situation make clear the need for global risk event planning. This includes climate change. Nearly every economic sector recognizes the risk presented by climate change and has begun to plan for a future without fossil HCs. The need to avoid a climate crisis has affected the transportation sector more than any other. Spaceflight represents a small, and yet manifest, form of transportation that is growing more rapidly than any other.

The perceived "smallness" of spaceflight's impacts, a result of past policy, has helped spaceflight develop relatively free of regulation. But this freedom also presents a kind of policy void. Though regulation undeniably presents a challenge to spaceflight's long-term future, current policy is not providing clear-cut direction for future development. Automobiles and aviation, for example, have clear policy direction to be carbon-free by 2050. Such policy direction allows for ample time to adapt and innovate appropriate alternatives. Spaceflight has no direction of this kind. Indeed, the industry is investing in liquid natural gas-fueled launch vehicles that will considerably increase the space industry's use of HCs.

Still, spaceflight does not take place in a policy mix that entirely ignores environmental impacts. But current policy is based on a half a century old regulation that is to a great degree unenforceable, does not extend beyond national boundaries, and is not as scientifically rigorous as possible. The following section paints a rough sketch of the current regulatory levers with an eye towards anticipating the future.

National Environmental Protection Act (NEPA)

Current national policy towards spaceflight emissions is based on the National Environmental Protection Act (NEPA)[25], established in 1974 to evaluate the impact of proposed government activities. For any major federal action, The Act requires that a federal agency analyze the impacts and prepare a report[*] that describes how the action will affect the environment, including the atmosphere, and what mitigation measures are required to allow the federal agency to comply with a range of environmental laws and move forward. The NEPA process is procedural and has no direct regulatory power. Instead it drives authority through identification of environmental statutes, federal licensing or permitting processes. Since NEPA is engaged at the federal agency level, its application has been seen as variable, depending on agency politics, and NEPA actions have been often challenged in the court system.[26] Advanced technologies are difficult for NEPA; it was written during a time of relatively slow innovation and tech investment. The comments below illustrate weakness in the NEPA process related to space systems.

Consider, for example, a large LEO constellation that includes a launch element and a satellite element. NEPA analysis of the launches is required by the FAA in order to obtain a launch license. Analysis of radio frequency spectrum use is required by the FCC to obtain an operating license. But a launch license does not assess satellite disposal and the FCC does not require any NEPA analysis, though there are legal arguments that it should.[27] By this fragmented process, the global impact of atmospheric disposal falls through the

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[*] The NEPA review can involve three different levels of analysis: Categorical Exclusion determination (CATEX), Environmental Assessment/Finding of No Significant Impact (EA/FONSI), or a longer Environmental Impact Statement (EIS) which involves public participation.

cracks without environmental analysis. Because the NEPA process is organized by agency function, as if satellite launch and end-of-life disposal are uncorrelated, one is covered by NEPA and the other is not. In reality, of course, launch emissions imply reentry emissions and NEPA should account for this correlation. But "enterprise" level-analysis was not yet a concept in 1974 when NEPA was made law.

NEPA documentation is usually prepared by technical or environmental consultancies, at the behest of the license applicant, without direction from the scientific community that best understands the impacts of pollution. NEPA documentation is subject to public review, but not scientific review. Relatedly, NEPA does not require that new scientific research be done even if gross uncertainties were recognized in documentation. An applicant's EIS may simply note uncertainty and make no effort to reduce it, even for required items. As a result, NEPA documentation often ignores important climate and ozone impacts.

Finally, NEPA regards each system under review as uncorrelated and requires only analysis of emissions directly associated with the specific system under review. NEPA, therefore, is unconcerned with cumulative and global impacts. Even as systems claim a "finding of no significant impact" (FONSI), according to NEPA, the cumulative impact of that class of system remains unexamined. Proposals to improve NEPA and bring it up to date after half a century are seeming unlikely to succeed[28], bringing further uncertainty to the environmental information needs of future systems.

The Montreal Protocol

The Montreal Protocol is unquestionably credited with saving the ozone layer[29] and is widely seen as the most successful international agreement of its kind. Despite changes in the political situations among the party nations, the Montreal Protocol has remained a strong regulatory force since its inception in 1987. As evidence of continuing strength, in 2021, the Montreal Protocol banned a class of compounds known as hydrofluorocarbons (HFCs).[30] Importantly, HFCs were not banned because of ozone depletion (they were replacements for CFCs), but rather because of predicted future climate impacts. These are important points: Though the ozone depletion problem is considered solved, the Montreal Protocol still regulates globally and is doing so based on predicted climate scenarios, not present-day impacts.

Regulations associated with the Montreal Protocol have not specifically addressed rockets (or aircraft) that emit directly into the stratosphere. Compounds are identified for global phase-out based on a calculated Ozone Depletion Potential (ODP), a metric that compares a compound's ozone depletion (per unit mass) to the ozone depletion caused by a standard compound. ODP is strictly defined only for gases released at the Earth's surface, however, so that rocket emissions cannot formally be assigned an ODP for assessment. Instead, ozone depletion assessments[11] adopt subjective descriptions (such as "small") based on analyses in the scientific literature which, as noted, has not kept up with space technology developments.

Coupling qualitative analysis such as "small" with Low Confidence scientific understanding of rocket emissions leads to a clear policy gap that presents a risk for space launch. That is to say, rocket emissions impacts are ill-understood while the regulatory metric is ill-defined. This policy gap appears at a time when the Montreal Protocol remains an influential multilateral instrument, regulating compounds based on global ozone protection and climate forcing. And while the Montreal Protocol saved the ozone layer from severe degradation, the problem of ozone depletion is not fully solved. Ozone levels are still declining in some regions.[31] This suggests that the Montreal Protocol might yet be applied to small impacts that have large uncertainties, such as spaceflight emissions.

Weakness in the understanding of rocket emissions, lack of formal metrics, and the continuing influence of the Montreal Protocol present an obvious risk of sudden and unanticipated change in the status of rocket emissions with respect to international regulatory attention.

Space Law

Finally, International Space Law, as promulgated through the Outer Space Treaty of 1967[32], has nothing to say about the atmospheric emissions problem. Article IX relates to activities in space that would “cause potentially harmful interference with exploration and use of space” and has been interpreted as the treaty’s hook to orbital debris concerns. Article IX also could be linked to launch emissions and their potential for “harmful interference” with launch activities, but this would stretch Article IX beyond its original intent even farther than in the case of orbital debris. Rocket emissions from upper stages do add to the debris problem in low Earth orbit (mainly slag from SRMs), though this is a separate issue from stratospheric pollution.

The Committee on the Peaceful Uses of Outer Space at the United Nations (COPUOS) is the body that helps manage the terms of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, more commonly known as the Outer Space Treaty. The document pointedly notes that signatories of the treaty, which include the U.S., are responsible for the actions of any nongovernmental activities based within their borders. This could happen most obviously with collisions and reentry debris reaching the surface, but it is not a stretch to consider COPUOS applying to cases of emissions that affect the atmosphere in specific ways that have greater amplitude for one country (e.g., latitude) than another. At the least, spaceflight’s climate and ozone impacts are part of the entire scope of international discussions and are always, if only in a small way, on the negotiating table.

Space travel has enjoyed a special standing that began with national Cold War imperatives at the beginning of the Space Age. Spaceflight activities were considered beyond the reach of the kind of environmental considerations that helped sideline other activities, such as supersonic transports. This status is, to some extent, the result of policy inattention from the scientific and regulatory communities. Research has been minimal and inconsistent. The hint of regulation due to ozone depletion has been a faint, but always present (e.g., SRMs), concern as the Montreal Protocol continues to protect the ozone layer. Situations of this kind are inherently unstable and prone to a sudden change in status, thus posing a risk to space launch. The next section discusses developments that might precipitate such a change.

Agents of Change

The current laissez-faire regime of space industry regulation is unlikely to persist indefinitely. Emissions growth is significant and unpredictable just as the global imperative to protect Earth’s climate also increases.[33] The spaceflight community, no matter how distasteful government intervention might seem, should formulate a strategy that acknowledges the risks posed by a sudden change in regulation and manage them as for any other risk. Policy experts understand abrupt change in terms of a “tipping point” where sudden changes in public perception occur after a consolidation of small changes that have taken place over a long period of time.[34] A previous review of space industry environmental policies[35] predicted that the space industry “…must prepare for a ‘tipping point’ wherein the scientific and regulatory communities become aware that space industry emissions are rapidly and abruptly growing yet have not been seriously included in regulatory efforts to protect Earth’s atmosphere.”

Such a tipping point is certainly at hand with respect to space debris.[23] Spacefaring nations are coming to agreement that the cost of doing nothing about space debris is higher than the cost of addressing the problem. Initial diplomatic moves by the United States to establish space debris norms is indicative of reaching a tipping point. A global discussion to define debris production regulations and collision avoidance norms has started, if only haltingly so far. Creation of an international body to define norms and obligations and monitor compliance will be difficult, but once established, such a body could serve wider regulatory goals.

While it is not possible to predict when or how a tipping point will be triggered, thought experiments about the circumstances that precipitate such changes are useful. Consider the following circumstances that might precipitate widespread changes in awareness of the kind that leads to change:

- Change in perception
- Entanglement with climate intervention
- Net-zero
- New propellants
- Ubiquitous reentry plumes

Change in Perception

It is often supposed that, with regard to public policy, reality equals perception. A change in the public perception of an industry can generate a harmful regulatory environment—nuclear power or supersonic transport for example. Spaceflight has benefited from the perception of being a special case, scientific rather than industrial, done "for all mankind," and therefore out of the reach of regulation. But as the space industry grows and becomes commercialized, it is increasingly perceived as a normal part of the economy, no longer a special case. The long-held protection from regulation afforded to spaceflight may not survive a change in perception.

It is often the case that when a change in perception does occur, the change overshoots the facts of the matter.[23] In just a few years, the perception of spaceflight has gone from the "final frontier" to that of a new "Wild West." Increasing awareness of military threats, space debris, elite space tourism, and light pollution all add up to a highly competitive and growing industry without few norms or regulation. While this view might be an overshoot and not grounded in careful technical analysis, the perception of a need to tame the LEO "Wild West" could lead to wrongly motivated regulation, with unintended consequences, that could negatively affect national space systems.

Entanglement with Geoengineering

Atmospheric processes that control how spaceflight particle emissions affect the atmosphere are analogous to those that control stratospheric particles associated with geoengineering. Geoengineering is supposed to mitigate climate change by purposefully adding particles into the stratosphere to create a "designer" particle layer that, like spaceflight particle layers, increases the albedo of the Earth and cools the Earth's surface.[10,20] The basic processes of plume dispersion, particle accumulation, and light scattering and absorption are essentially the same for geoengineering and spaceflight particles. Indeed, BC and alumina have even been studied in the scientific literature as geoengineering agents.[36] The mass of a geoengineering particle layer would be hundreds of times greater than the present-day spaceflight layer. Nevertheless, the similarities are striking at first glance.

The risk to spaceflight is that geoengineering attracts a hornet's nest of scientific, policy, and ethical concerns. It is controversial and there is no formal policy regarding its deployment, even in an experimental context. Policies and regulations to ban geoengineering have been proposed and the concept is often condemned.[37] Nevertheless, its acceptability grows with the perception of a climate crisis and preliminary experiments are moving forward with particle releases that are controversial, yet tiny, compared to the particle releases from a single launch or reentry.[38] If spaceflight particle emissions become too closely identified with geoengineering, regulation of the latter could affect the former by similarity.

A wide-ranging global ban on geoengineering[39] could present a problem for spaceflight and would have to be formulated in a way that preserves the privilege of rockets and space debris to emit particles into the atmosphere. Indeed, the future of spaceflight existentially depends on unchecked freedom to dispose of space debris and end-of-life satellites by reentry vaporization. Maintaining a clear separation of spaceflight from geoengineering requires strong engagement with the science and policy communities which, in turn, requires a much higher fidelity understanding of spaceflight emissions than is now available.

Net-zero

The global launch industry depends on access to inexpensive HC, mainly kerosene and (in the future) methane. Launch uses a minuscule fraction of the HC fuel used by aviation which, in turn, is only a few percent of all HC consumption. Nevertheless, there is a widespread assumption in the aviation industry that low-cost HCs will not be available for aviation use after mid-century.[40] Financial institutions have started to reduce capital investment in HC exploration and drilling. And the conflict in Ukraine has apparently nudged some countries to turn away from HCs even faster than previously planned. Meanwhile, the space industry continues to push toward ever greater dependence on HC-fueled (methane) launch vehicles. Biomass or renewable electric hydrogen or methane production might be possible for rockets, though a net-zero approach has never been proven for launch.

Despite the failure of international agreements to definitively reduce GHG emissions, there is widespread belief that the global economy will move away from HCs by mid-century. In fact, global regulation of the Montreal Protocol type may not be needed to reduce GHG emissions if a market-based pathway emerges. Fundamentally, the risk to spaceflight is that low-cost and low tax kerosene and methane will not be available, regulation or not, by mid-century. It is not overly speculative to imagine that launch will have to move toward renewable propellants, or an exception will need to be specified in order to guarantee HC access. Either case depends on improved and expanded rocket propulsion technology developments and global impacts data will be needed.

New Fuels

Technological novelty can be the trigger for a tipping point in regulatory attention. The primary four propellants used by launch vehicles have not changed since the start of the Space Age. Kerosene, the most widely consumed propellant today, powered the moon race half a century ago. The revolutionary super heavy lift rockets now in development use methane as fuel and they will enter the global launch fleet soon[41], possibly accounting for a significant portion of launches by 2030. As the second most important and fastest growing GHG, methane was recently subject to surprising new regulations on storage and venting[42] that may apply to launch site propellant handling operations. Spaceflight is switching to a novel propellant just as it becomes the focus of new scientific and regulatory interest.

Bright Reentry Plumes

When space debris or deorbiting spacecraft reenter the atmosphere, they vaporize and produce bright plumes that are visible over wide areas, attracting widespread attention. Historically, bright reentry plumes have been rare, and so the cumulative public reaction has been small. But the upcoming disposal of defunct satellites from newly deployed (and planned) large LEO constellations will change that. When these constellations reach an operational steady state, with old satellites being deorbited at the about the rate that they were launched, the number of bright reentry plumes seen each day will increase dramatically.

The effect on public perception could mimic the recent controversy about the sudden appearance of hundreds of bright LEO constellation satellites during twilight. Serious light pollution concerns have been raised in the astronomical community, which has generated more general concerns about the sustainability of these constellations in the scientific and lay communities. Commonplace bright reentry plumes may bring a similar notoriety with respect to pollution of the atmosphere with reentry dust and the sustainability of spaceflight systems in general.

Act Now for the Future

Any of these factors could be the tipping point that brings sudden awareness of emissions from a dynamic and rapidly growing space industry to the attention of the public and regulatory community. If a perception of "too small to pay attention" becomes "too large to ignore," the space community will need to be ready to respond. How can an updated space policy do that?

History informs us that the best course of action anticipating a realignment in perception is to acknowledge the inevitability of change and gather scientific data and expertise before a tipping point is triggered. The original spacefaring nations missed the opportunity to deal with space debris when regulation would have been relatively easy. The recent loss of dozens of satellites due to unforeseen space weather effects illustrates the potential for unplanned and unimagined space debris problems in LEO. Rocket and reentry emissions present an opportunity to avoid the failure of the past to imagine the future by increasing the level of understanding so that the global impacts of future development scenarios can be reliably predicted.

Achieving the required level of understanding will require cooperation and collaboration across the space enterprise from launch emissions to end-of-life disposal emissions. The United States could take the lead by providing research funding and other incentives to its stakeholders and by inviting international participation in a research program focused on space industry environmental impacts to the atmosphere and climate. On the other hand, advantage may be gained by the United States in becoming the lone world expert on these matters; information can be used to promote national and corporate interests directly on space or through linkage to other international policy goals. Either way, being proactive has consistently been shown to be a good policy.

"Proactive," in this case, means application of scientific research to the twin problem of launch and reentry pollution. The research community, to perform the required research, could quickly be assembled through the network of federal laboratories, universities, and corporate resources that support atmospheric science.

Such a research program would include the following components:

- Measure rocket engine BC and alumina emissions from high altitude aircraft, across the different propellant and engine types, characterize launch plume chemistry and diffusion.

- Measure gas and particle production during reentry using remote sensing, determine reentry particle composition and size distribution, characterize particle sedimentation in the mesosphere.

- Measure test stand rocket combustion composition, correlate and validate combustion models and stratospheric data collects.

- Develop spaceflight emission inventories and emissions scenarios using models and data using (1-3), predict potential future emissions for global model inputs.

- Predict the global climate and ozone impact of spaceflight using validated models of the global atmosphere using validated data (1-3) and emission scenarios (4).

Avoiding the Space Debris Experience

International concern for space debris provides a history lesson. During 1990s, DOD and NASA devised national debris mitigation guidelines that were then proposed to the international community. By 2007, a modified version of the guidelines was adopted by the U.N. Committee on the Peaceful Uses of Outer Space, and, ultimately, by the U.N. General Assembly. A detailed history is beyond the scope of this work. But these guidelines were ineffective for a great many reasons. One main factor was a lack of imagination with regard to what would come about in the future. If policymakers could have predicted the rise of national and corporate space, perhaps they could have made appropriate regulation to maintain the LEO environment.

Recent space debris incidents and calculations of rising collision risks have pushed stakeholders to consider international regulation of space traffic management. It may be too late for regulation, however, since commercial interests now dominate the LEO satellite population.[43] The lack of an international framework means that corporate space traffic management algorithms have become the standard. The regulators have become the regulated.

In contrast to the situation that has developed for space debris, spaceflight emissions are still at a stage where information-gathering can effectively influence the future. A complete understanding of launch and reentry emissions can be used to create scenarios for the future that can be used to avoid unnecessary concern and, if it cannot be avoided, to develop good regulation that avoids limitation on present systems and promotes the space industry. As for space debris, a proactive United States could be a primary driver of this activity while seeking international collaboration at the same time. The alternative, waiting for others to take the initiative, would not yield the most satisfactory results for the promotion of national and corporate interests.

Conclusion

Climate change is becoming the greatest long-term focus of political and economic attention across our planet. The recent upending of the world order by the COVID-19 pandemic and military actions only reinforces this view. Energy production, national self-sufficiency, and geopolitical interests become ever more important in a changing world. In the long term, humanity must manage Earth’s climate and avoid a crisis by reducing the accumulation of GHGs. This will be achieved primarily through elimination of hydrocarbons—including production, handling, and use as fuel. Another climate concern is pollution of a normally clean stratosphere. A climate crisis cannot be avoided without controlling emission of particles into the stratosphere.

The space industry, as all industries, will eventually need to deal with the elimination of hydrocarbons. While spaceflight’s GHG emissions are much smaller than other industry specific sources such as aviation, future regulation is unlikely to be carried out on a “by industry” basis. Even if a specific industry like spaceflight can define and demonstrate that its climate impact is too small to regulate, continued availability of low-cost hydrocarbon fuel will be at risk as the world decarbonizes, the global fossil fuel infrastructure declines, and taxes are levied on remaining users. Climate change presents a serious threat to the long-term viability of hydrocarbon-based spaceflight whether or not kerosene and methane fueled rockets are regulated directly. The space industry strives to be more like the aviation industry and this desire should extend to climate policy.

Spaceflight will also need to deal with stratospheric particle emissions. Stratospheric particles have a smaller impact than GHGs and can even be negative for some kinds of particles in some situations. But the desire to maintain the integrity of the ozone layer and a clean stratosphere, free from unregulated particle injections regardless of intent, will lead to increased attention on stratospheric emissions. The space industry alone directly pollutes the middle stratosphere and above by injecting rocket exhaust and reentry dust, and not much is known about their impacts on climate and ozone.

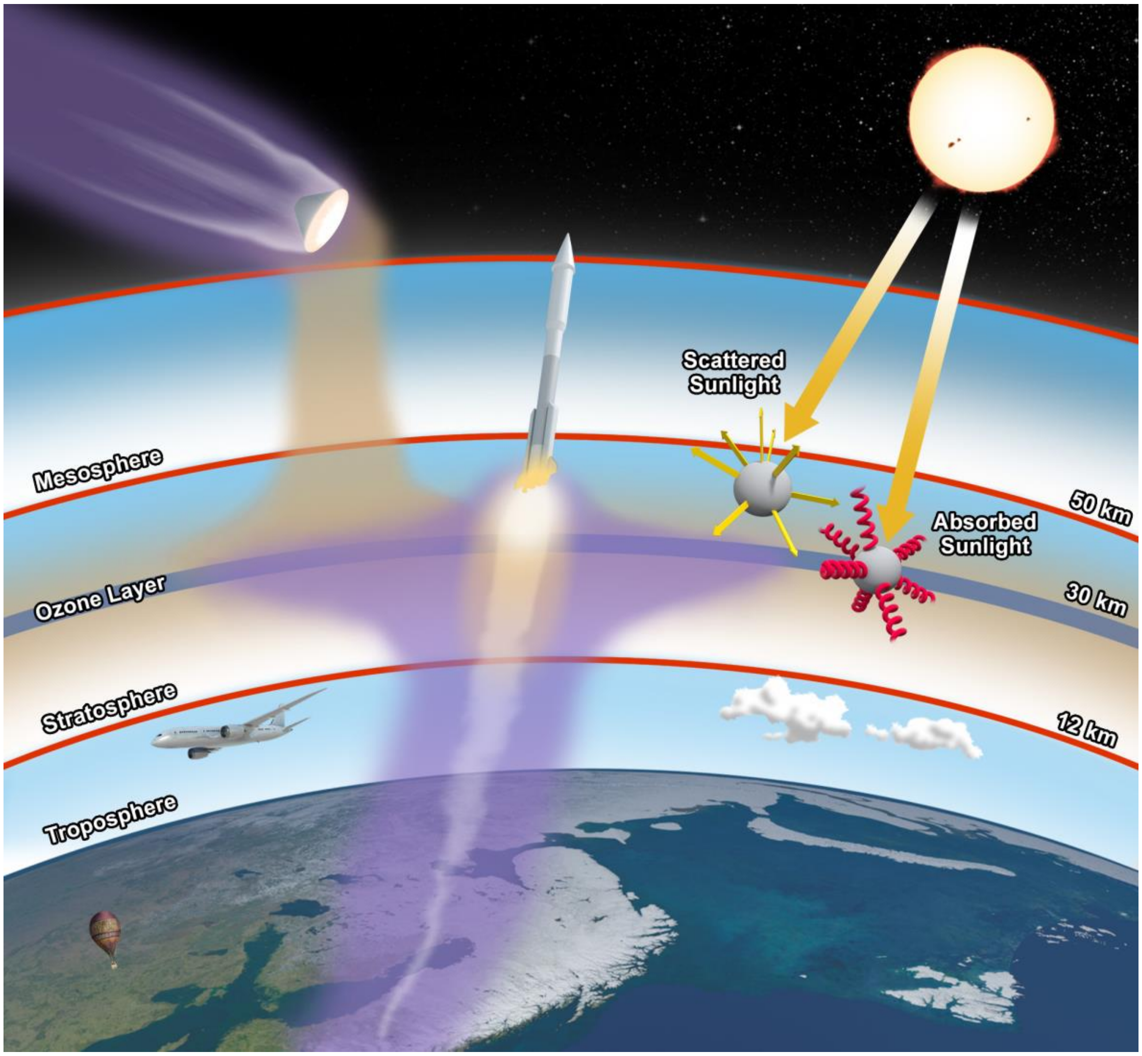
Other atmospheric impacts unique to spaceflight are recently becoming obvious, too. Ionospheric holes[44], upper atmosphere clouds, and changes in upper atmosphere composition are human produced "space climate change" that may cumulatively present hazards to space systems.[45] Changes in radio propagation, high altitude cloud radiance, and LEO air density changes caused by spaceflight emissions present potential risks that will require further study beyond what are usually considered "global impacts" on climate and ozone.

Past space policy to deal with spaceflight's influence on the atmosphere assumed that spaceflight emissions could not be at risk of regulation. This policy is no longer viable. The new factors of rapid growth, commercialization, and realization of routine reentry emissions render the old "too small to notice" approach untenable. A new policy that acknowledges the inevitable intersection of growth in spaceflight emissions and growth in regulatory aggressiveness is needed. The new policy would be motivated by an acknowledgement of a significant risk that climate change mitigation and ozone protection will impact spaceflight sooner or later.

What is the risk? Regulation could limit or eliminate the use of some propellants, reduce their availability, or heavily tax or regulate production and use. Some propellants that present technical challenges, such as cryogenic, could receive regulatory and research privileges if they could be produced using renewable energy. Biofuels might be appropriate for use by rockets. The use of Earth's atmosphere for defunct satellite disposal could be limited or specific disposal guidelines be imposed. All of these potential regulations present significant cost and schedule risks to space industry goals and developments.

Spaceflight growth and concern for Earth's climate and ozone are not necessarily exclusive of each other. But spaceflight's impacts are not zero and the foundation of understanding is becoming less secure over time. Emissions need to be understood so that policymakers can properly assess how to maximize spaceflight's benefits while minimizing global impacts. At the same time, entanglement with the regulation of other industries, such as decarbonization or geoengineering, is a risk. All of these potential future conflicts indicate that the spaceflight community should tackle the question of launch and reentry emissions while it is still manageable, and spaceflight should prepare to be involved in the regulatory discussion. The lesson learned with space debris mitigation urges an executable course of action: act when problems are small in order to prepare for the most enthusiastic possible future. For launch and reentry emissions, that means initiating an aggressive scientific research program in order to proactively engage regulatory forces.

Rocket engine exhaust is mostly carbon dioxide and water vapor, and neither have much of an impact on the atmosphere. Much more importantly, rocket exhaust contains soot and alumina particles that are emitted directly into the climate-sensitive stratosphere. Reentering space debris emits a chemical zoo of particles as it burns up in the mesosphere. These particles drift downward into the stratosphere to join rocket particles where they form thin cloud layers that scatter and absorb a small fraction of incoming sunlight. The particles warm the stratosphere, cool the troposphere, and accelerate chemical reactions that cause ozone depletion. The combined impacts of the rocket and reentry particles are not very well understood but are unlikely to be the cause of important changes to the atmosphere at the present time. The concern is that the current level of scientific understanding is insufficient to reliably predict what the impacts from a future and larger space industry will be. Policymakers will need a very much-improved understanding of spaceflight impacts in order to avoid overly restrictive and unwarranted regulation that could harm the space industry.



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